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HANDBOOK ON SMART HEALTHCARE ENGINEERING



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FOREWORD

This handbook presents the main concepts, technologies and practical challenges related to smart healthcare engineering. The book starts from a simple idea: a hospital is not only a medical institution, but also a complex technical system. Safe healthcare depends on reliable infrastructure, medical equipment, clean water, controlled air, energy supply, digital networks, materials, maintenance and correct waste management. For this reason, engineers have an important role in the daily operation, safety and development of modern hospitals.

The chapters bring together several fields that are usually studied separately, such as medical devices, hospital infrastructure, stainless steels and copper alloys, hazardous waste treatment, IT systems, biomedical imaging, seismic safety and hospital case studies. The handbook also connects engineering theory with real hospital needs, showing how technical decisions can influence patient safety, infection prevention, continuity of care, sustainability and resilience.

The material was developed within the Smart healthcare engineering project, with the purpose of supporting students, teachers and healthcare professionals. It is intended as a practical educational resource for engineering students who need to understand how their knowledge can be applied in hospitals and healthcare facilities. The handbook also supports interdisciplinary cooperation between universities and hospitals, helping future engineers to see healthcare as a field where technical competence must be combined with responsibility, communication and respect for clinical work.

The authors

Target group

The main target group of the handbook is students and professionals from EU countries (aged 18–65), specifically:

- **Managers and employees** of different healthcare facilities, who will apply the knowledge acquired from the handbook to make their organizations better in managing and maintaining the infrastructure of hospitals.
- **HEI (Higher Education Institutions) teachers/educators** (all categories of teaching staff), who will transfer the knowledge gained from the handbook to their students.
- **Students** from various BSc engineering education programs, who will be better prepared to address and face future challenges in healthcare engineering jobs or careers.

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CHAPTER 1

CONCEPT OF HEALTHCARE ENGINEERING

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This chapter introduces the concept of healthcare engineering and highlights the importance of engineering in hospital facilities.

1.1 INTRODUCTION

A hospital is a place for care, but it is also a dense technical system. Behind the medical act there are water networks, ventilation units, heating and cooling systems, medical gases, electrical installations, emergency power, elevators, sterilization units, laboratories, imaging equipment, data networks and waste circuits. Most of these systems stay in the background. When they work, they are almost invisible. When they fail, clinical activity can stop in a few minutes.

This explains why healthcare engineering has become important. Modern medicine depends on technology at almost every step. Diagnosis uses imaging systems, laboratory equipment, sensors, software and data. Treatment uses

operating rooms, intensive care devices, infusion pumps, ventilators, sterilization systems, clean water, medical gases and reliable energy. Patient safety depends on the medical act and on the technical environment where this act takes place.

The basic idea is direct and practical. Engineering knowledge must be used inside the healthcare system.

The engineer has to understand the hospital as a living technical organism. It must be designed, operated, inspected, maintained and improved. It must remain safe, clean, resilient and sustainable. Healthcare engineering sits between industrial engineering, materials science, biomedical engineering, electrical engineering, automation, information technology, energy systems, hospital logistics and clinical practice.

For many years, technical work in hospitals was treated mainly as support work. The technical department repaired installations, replaced damaged components and helped when something stopped working. That reactive view is too limited today. Hospital systems are complex, connected and critical for safety. Hospitals need engineers who can plan, prevent, monitor and explain risk. They need people who can speak with physicians, nurses, managers, suppliers, public authorities and maintenance teams. A small technical decision can reach the patient faster than expected.

Digital health is now a strategic direction at international level. The World Health Organization states that digital health needs governance, resources, standards and coordination, not isolated tools added to an old system [1]. Patient safety remains a major worldwide challenge as well. The WHO global patient safety report published in 2024 presents safety as a system issue that needs organized action [2]. These two directions meet inside the hospital. Technology is useful when it is introduced, maintained and used in a safe system.

Connected devices and artificial intelligence make this need even stronger. Medical equipment is no longer only mechanical or electrical. Many devices contain embedded software, sensors, communication modules and algorithms. Some collect data continuously and send information to hospital platforms or cloud services. In the European Union, AI used for medical purposes can fall under high-risk requirements linked to risk management, data quality, transparency and human oversight [3]. Engineers in healthcare therefore need technical knowledge and regulatory awareness. Climate pressure also changes hospital engineering. Hospitals use large quantities of energy, water, materials and chemicals. They produce normal and hazardous waste. The World Health Organization connects climate-resilient and environmentally sustainable healthcare facilities with safer communities, better use of resources and reduced environmental impact [4]. For engineers, this means daily work has a wider responsibility. Keeping systems running is necessary. Reducing waste, improving resilience and limiting environmental damage are now part of the same task.

Healthcare engineering is wider than the classical image of biomedical engineering. Biomedical engineering remains essential, especially for medical devices, implants, instruments and health technologies. Clinical engineering focuses on healthcare technology management and medical equipment inside healthcare organizations. The approach used in this handbook is broader. It covers medical equipment, hospital infrastructure, materials, energy, digital systems, maintenance, logistics and safety. It prepares engineers to work with the whole technical environment of healthcare.

A modern hospital is a technical ecosystem. The engineer does not replace the medical staff. Engineers support their work by keeping the environment safe, reliable and efficient. This support can be quiet, but it is essential.



Simple examples: A failure in the medical gas system can affect surgery and intensive care. Poor ventilation can weaken infection control. Hot water that is not monitored can create microbiological risk. Imaging equipment that is not maintained can delay diagnosis. A weak information system can expose patient data and clinical decisions. The cause may be technical, but the effect is clinical. The healthcare engineer must see the full chain between a technical system and a patient outcome. A pipe has a different meaning when it transports oxygen, sterile steam or hot water in a hospital. A surface has a different meaning when it is cleaned many times a day in an area with infection risk. A software update has a different meaning when it changes how a device stores, sends or interprets patient data. This way of thinking is the basis of healthcare engineering.

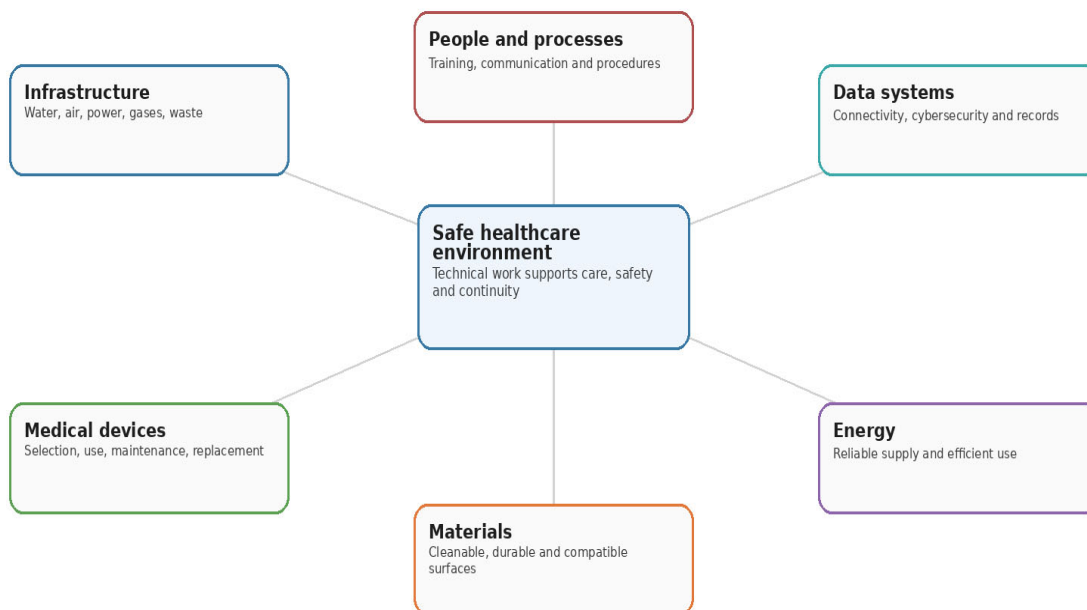


Figure 1.1 Main dimensions of healthcare engineering

The terminology differs between countries. Some hospitals use clinical engineer. Others use biomedical engineer, healthcare technology manager, facilities engineer, hospital engineer or maintenance engineer. The name matters less

than the role. Hospitals need engineers who understand healthcare needs and who can manage technology responsibly.

Healthcare engineering can therefore be described as an applied field that uses engineering to improve safety, quality, continuity and sustainability in healthcare. This definition is simple, and it is close to hospital reality. Every hospital depends on technical systems every day. As healthcare becomes more complex, this engineering role becomes more visible and more necessary.

1.2 WHY HEALTHCARE ENGINEERING IS NEEDED

Healthcare engineering is needed because modern healthcare depends on technical systems. A hospital cannot function with medical knowledge alone. It needs clean air, safe water, stable electricity, medical gases, working elevators, sterile instruments, reliable equipment, data networks, waste circuits and trained technical staff. These services may be invisible to patients, but they are part of the healthcare process.

Patient safety is a central reason. Safety is often discussed through diagnosis, medication, surgery and clinical procedures. These aspects are essential. The physical and technical environment also influences safety. A wrong alarm setting, poor electrical protection, a contaminated water system, a badly maintained ventilator, a failure of emergency power or an uncontrolled indoor environment can create serious risks. Technical systems need the same discipline that hospitals apply to clinical protocols.

The WHO patient safety report describes safety as a system issue, not just a problem of individual error [2]. This view is close to engineering thinking. Engineers are trained to understand systems, identify failure modes, reduce risk and improve reliability. These skills are useful in hospitals because many risks



are created by interactions between people, equipment, infrastructure and procedures.

Hospital infrastructure is more complex than the infrastructure of most public buildings. Hospitals work continuously. They need to remain operational during emergencies. They contain areas with different technical requirements, such as operating rooms, intensive care units, laboratories, imaging rooms, sterilization units, pharmacies, kitchens, laundry areas, technical rooms and outpatient departments. A single technical rule cannot fit all these areas.

An operating room needs controlled air, pressure relations, filtration, temperature and humidity control, sterile instruments, medical gases and reliable electricity. An imaging room needs shielding, cooling, electrical quality, space planning and equipment safety. A laboratory needs ventilation, water quality, waste control and biosafety. A normal patient room needs comfort, hygiene, call systems and safe installations. The engineer must understand the difference between these spaces before proposing a solution.

Medical devices add another layer of complexity. The handbook describes the evolution from simple instruments to imaging systems, life-support devices, IoT-based applications and AI-supported equipment. New devices bring benefits, but they also create risk. The more complex the device, the more important are procurement, training, maintenance, calibration, documentation and life cycle management.

A device must remain safe during its whole life. Safety does not end after purchase. Equipment has to be installed correctly, tested, used by trained staff, maintained at suitable intervals, updated when needed and removed from service when it is no longer safe or efficient. WHO guidance on medical equipment maintenance presents maintenance as part of health technology management [5]. This is a planned safety activity, not simple repair work.

Infection prevention has a strong technical side. Ventilation, water systems, surface materials, waste flows, sterilization systems, drainage, isolation areas and maintenance work can all influence infection risk. Healthcare ventilation standards, such as ASHRAE Standard 170, address ventilation for health care facilities and support environmental control in sensitive areas [6]. Air systems are therefore part of the safety chain.

Water systems are just as important. Cold water, hot water and technical water circuits can become sources of deposits, corrosion, biofilm and microbiological risk when they are poorly designed or maintained. Material selection, temperature control, stagnation reduction, maintenance quality and cleaning procedures all matter. Engineers need to work with infection prevention specialists and hospital managers because the technical and clinical problems are connected.

Continuity of care depends on engineering. A hospital must not stop when a device fails or when power is interrupted. Backup systems, spare equipment, preventive maintenance, emergency procedures and clear communication are needed. This is critical in intensive care, surgery, emergency departments and diagnostic units. Healthcare engineering reduces downtime and prepares the hospital for predictable and unexpected failures.

Digital transformation changes almost every medical process. Hospitals use electronic records, imaging archives, laboratory information systems, connected monitoring, telemedicine, AI tools and cybersecurity systems. The WHO global strategy on digital health stresses that digital tools need strategy, governance, resources and coordination [1]. A new digital tool should enter the hospital because it solves a real problem and can be integrated safely.

Digital systems also need human understanding. A remote monitoring platform is useful when data are reliable and responsibilities are clear. An alarm system



reduces risk when alarms are meaningful. An AI tool can help diagnosis when its limits are understood and human oversight remains in place. Poorly integrated digital systems can create new risks instead of reducing old ones.

Sustainability is now part of responsible hospital operation. Hospitals consume energy, water and materials every day. They must remain safe and comfortable while reducing waste and environmental impact. WHO guidance on climate-resilient and environmentally sustainable healthcare facilities links resource efficiency with the ability of facilities to protect communities in a changing climate [4]. Energy efficiency, water efficiency, waste reduction and resilience are practical engineering tasks.

Cost control also requires engineering. Medical equipment and hospital infrastructure are expensive. A hospital cannot afford to buy technology that is difficult to use, difficult to maintain or poorly matched with local needs. Engineering analysis helps compare life cycle costs, maintenance needs, consumables, spare parts, energy use and expected lifetime. A low purchase price can become expensive when failures are frequent or maintenance is complicated.

Communication is another need. Physicians and nurses describe clinical needs. Engineers describe technical limits. Managers describe costs, deadlines and regulations. Suppliers describe equipment features. The healthcare engineer helps these groups understand each other. This translation role prevents many small problems from becoming expensive or unsafe.

Engineering education also has a gap to close. Many students learn materials, mechanics, electronics, automation, energy or production systems, but they rarely see how these subjects are used in hospitals. Healthcare engineering gives these subjects a direct human meaning. Materials science appears in hygienic surfaces and pipelines. Electrical engineering appears in emergency

power for operating rooms. Automation appears in HVAC and medical gas monitoring. IT appears in connected devices and data protection. Industrial engineering appears in maintenance planning and patient flows.

A hospital oxygen pipeline can look like a normal technical installation. In reality, it is a clinical safety system. Material compatibility, cleanliness, pressure, leakage, maintenance access, alarms and emergency backup all matter. A small fault can affect patients in surgery or intensive care. This example explains why healthcare engineering is risk management applied to real hospital systems.

Hospitals also suffer when responsibility is fragmented. Buildings, devices, IT systems and clinical departments are often managed by separate teams. That separation is normal, but gaps appear at the borders. A connected medical device may need medical approval, cybersecurity review, electrical safety testing, network configuration, user training and maintenance planning. Coordination reduces risk.

Resilience is now a daily planning issue. Hospitals must prepare for heat waves, storms, fires, floods, pandemics, cyberattacks and supply chain problems. A backup generator is only one part of resilience. Engineers have to identify critical services, map dependencies, define alternatives and set priorities before a crisis starts.

Innovation needs the same practical discipline. Hospitals may be interested in AI, robotics, additive manufacturing, smart sensors or digital twins. These technologies can help, but only when they fit the hospital context. Useful questions are simple. Who will use the technology? What problem does it solve? Is it safe? Can it be maintained? Are data protected? What happens if it fails? Engineering turns attraction into responsible use.





Figure 1.2. Why healthcare engineering is needed in hospitals

1.3 WHAT IS A HEALTHCARE ENGINEER

A healthcare engineer is an engineer who applies engineering knowledge to improve the safety, quality, reliability and sustainability of healthcare services. This professional works at the interface between technical systems and clinical needs. The healthcare engineer does not diagnose or treat patients. The work creates and maintains the technical conditions that allow diagnosis and treatment to be performed safely.

The definition is close to the clinical engineer definition used by the American College of Clinical Engineering. In that definition, the clinical engineer supports and advances patient care by applying engineering and managerial skills to healthcare technology [7]. This is important because the role goes beyond repair. It includes management, risk control, communication and support for patient care through technology.

The World Health Organization also describes the role of biomedical engineers across the medical device life cycle, from conception to use [8]. This life cycle view is useful for healthcare engineering. A hospital system starts as a need, then becomes a specification, a purchase, an installation, a tested system, a

maintained asset and later a replacement decision. Engineering judgment is needed at every stage.

In this handbook, healthcare engineer has a broad meaning. The role includes elements from clinical engineering, biomedical engineering, hospital facilities engineering, industrial engineering and healthcare technology management. This broad approach is useful for students because real hospital problems rarely respect university disciplines. A water problem may include chemistry, corrosion, infection control, costs, staff training and maintenance access at the same time.

Technical knowledge is the base. The healthcare engineer needs to understand materials, mechanical systems, electrical systems, electronics, medical equipment, automation, data systems, energy and maintenance. No person can be an expert in every technology. Still, the engineer must understand the principles well enough to communicate with specialists and make responsible decisions.

Hospital understanding is just as important. A hospital is different from a factory, a school or an office building. The users include patients, medical staff, technical staff and visitors. Some patients are vulnerable, immobile or connected to life-support equipment. Some spaces need sterile conditions. Some activities cannot be interrupted. Technical solutions must respect this environment.

Risk thinking is part of the professional mindset. Engineers in healthcare must ask what can go wrong, how severe the consequence could be and how the risk can be reduced. This way of thinking appears in equipment management, infrastructure design, maintenance planning, emergency preparedness and digital systems. It does not mean fear of technology. It means responsible use.



Communication has a high value. A physician may describe a clinical problem without knowing the technical cause. A supplier may explain a device without understanding the hospital workflow. A manager may focus on budget and deadlines. A technician may know the practical details that no manual contains. The healthcare engineer listens, translates and helps the group reach a safe solution.

Documentation is part of safety. Hospitals need inventories, procedures, maintenance logs, risk assessments, training records, certificates, test reports and compliance documents. When documentation is clear, it becomes the memory of the system. It proves what was done, when it was done and why a decision was made.

Ethical responsibility cannot be separated from technical work. Engineering decisions in hospitals can affect vulnerable people. A connected device can improve monitoring, but it can create data protection risks. An AI tool can support diagnosis, but it must not remove human responsibility. A cost reduction may help the budget, but it cannot reduce safety. Patient safety, privacy and dignity must guide technical decisions.

Continuous learning is also necessary. Healthcare technologies change quickly. Standards change. Devices become more connected. Materials and software evolve. New risks appear. A healthcare engineer has to learn from training, incidents, maintenance data and the daily experience of clinical staff.

The role can be compared with a bridge. On one side are engineering disciplines, such as mechanics, materials, electronics, automation, IT and energy. On the other side are clinical needs, such as diagnosis, treatment, comfort, infection prevention and continuity of care. The healthcare engineer connects these sides in practical decisions.

It is useful to distinguish related profiles. A biomedical engineer may work in design, research, implants, biomaterials or medical device industry. A clinical engineer usually works in a healthcare organization and focuses on healthcare technology management. A facilities engineer focuses on building services and technical infrastructure. A healthcare engineer, as used here, can combine parts of these profiles, especially in hospitals where one problem crosses several technical domains.

Consider a robotic surgery system. The medical technology has to be evaluated. Power and electrical safety must be checked. The system may need a network connection. Space, cooling, structural needs, training, cost and maintenance must be considered. The healthcare engineer helps connect these requirements so that the hospital does not treat them as separate problems.

A sterilization unit gives another example. It includes steam, water quality, materials, drainage, ventilation, workflow, validation, maintenance and staff training. One narrow specialization is not enough. The healthcare engineer understands the system and knows when each specialist is needed.

This role is different from the role of a repair technician, although both are essential. The technician often performs direct maintenance and repair. The engineer plans systems, analyzes risk, defines procedures, evaluates performance, improves reliability and supports management decisions. A good hospital needs both. The technician brings daily practical knowledge. The engineer connects this experience with design, standards, data and planning.

Hospitals are human systems. A technically correct solution can fail if users do not understand it or if it does not fit the workflow. A complex alarm system can create alarm fatigue. A digital form can slow down care. A new material can be



difficult to clean if cleaning staff are not trained. The engineer must consider usability, training and daily practice.

The professional identity of the healthcare engineer is still developing in many countries. This is normal for an interdisciplinary field. The direction is clear. Healthcare systems need engineers who can work responsibly inside hospitals and who understand the relation between technology and care.

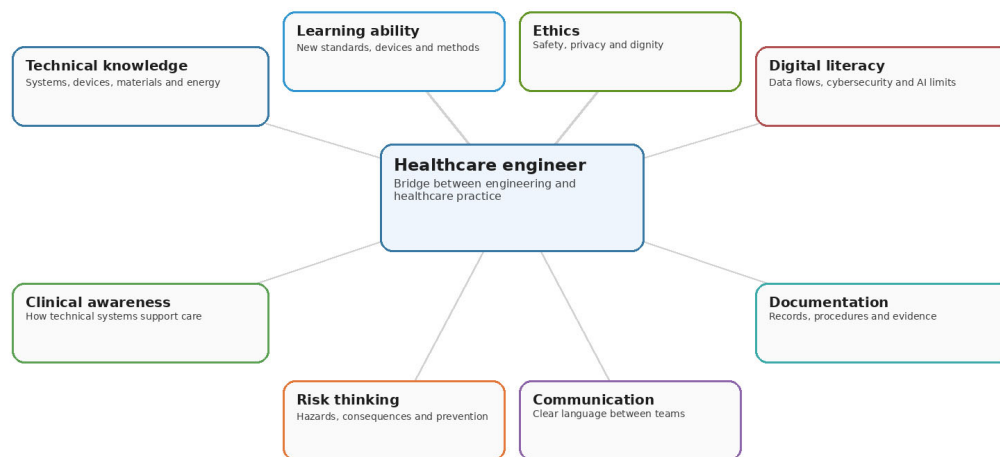


Figure 1.3. Competence profile of the healthcare engineer

Table 1.1. Competence profile of the healthcare engineer

Competence	What it means in practice	Why it matters
Technical knowledge	Understands infrastructure, devices, materials, energy and digital systems	Supports correct decisions and communication with specialists
Clinical awareness	Understands how technical systems support diagnosis, treatment and patient comfort	Links engineering decisions with healthcare needs
Risk management	Identifies hazards, estimates consequences and defines prevention measures	Protects patients, staff and hospital continuity
Life cycle thinking	Plans selection, procurement, installation, use, maintenance and replacement	Reduces failures and improves value for money
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Communication	Translates between clinical, technical, managerial and supplier language	Reduces misunderstandings and improves cooperation
Documentation	Maintains inventories, procedures, records and technical evidence	Supports quality, traceability and compliance
Digital literacy	Understands connected devices, data flows, cybersecurity and AI limits	Supports safe digital transformation
Ethics and responsibility	Balances innovation, cost, safety, privacy and patient dignity	Keeps technology aligned with healthcare values

1.4 THE ROLE OF ENGINEERS IN MODERN HOSPITALS

The role of engineers in modern hospitals can be understood by following the life of a system from planning to daily use. Engineers are needed before a hospital is built, when it is renovated, when equipment is purchased, when systems are commissioned, when staff are trained, when maintenance is planned and when incidents are analyzed. Their work is continuous because a hospital is never technically finished. It changes with new needs, new risks and new technologies.

Planning and design support begins with technical requirements. Engineers help define what a new space or system must do. A technical room, an operating room, a laboratory and an intensive care unit have different needs. Design must include capacity, safety margins, maintenance access, redundancy and future flexibility. Decisions made on paper can help or disturb the hospital for decades.

Good design prevents problems that are expensive to correct later. A poor position of technical shafts can make maintenance difficult. A weak electrical



design can limit future equipment. Poor ventilation can create infection control problems. Bad material selection can create corrosion or cleaning difficulties. Lack of space around equipment can make maintenance unsafe. Engineering input in the early stage saves time, money and risk later.

Procurement support is also important. Hospitals buy many types of technology, from simple devices to very expensive systems. Engineers help prepare technical specifications, compare offers, verify compatibility and estimate life cycle costs. Purchase price is only one part of the decision. Consumables, spare parts, maintenance contracts, training, energy use, software updates, cybersecurity and expected lifetime must be considered.

Clinical staff may ask for a device because it offers useful medical functions. The engineer checks if the hospital can support it. Does it need special power? Does it need cooling? Can it connect to the network safely? Does it need medical gases or special water quality? Can local staff maintain it? Does the supplier provide training and documentation? These questions protect the hospital from buying technology that later becomes difficult to use.

Installation and commissioning turn a purchased system into a safe clinical asset. A device is not ready because it arrived in the hospital. It must be installed, connected, tested and accepted. Commissioning verifies that the system works according to requirements before routine use. In medical environments this step is critical. Safety tests, calibration, alarms, user training, documentation and integration with existing systems need to be checked.

Operation and maintenance remain the visible part of technical work, but they need planning. Maintenance includes repair after failure, planned preventive work, condition monitoring and performance analysis. WHO guidance treats medical equipment maintenance as part of a wider management programme

[5]. Critical systems need priorities based on risk. An office printer and a ventilator cannot receive the same attention.

Hospital utilities are hidden clinical systems. Electricity, emergency power, water, hot water, steam, cooling, ventilation, compressed air, vacuum, oxygen and other medical gases must be available when needed. Engineers monitor these systems, plan maintenance, verify alarms, prepare emergency procedures and coordinate interventions. The patient rarely sees this work, but care depends on it.

Infection prevention support is another daily role. Engineers are not infection control doctors. Their systems still influence infection risk. Ventilation, pressure relations, filtration, water temperature, stagnation control, surface cleanability, waste flows and maintenance procedures are technical issues with clinical effects. Even opening a ceiling in a clinical area can create dust and contamination risk if work is not planned carefully.

Materials selection matters in hospitals. Stainless steel, copper, polymers, ceramics, glass, coatings and composite materials can all appear in healthcare facilities. These materials face cleaning agents, humidity, temperature changes, mechanical wear and sometimes aggressive chemicals. They must be easy to clean and inspect. Materials science is therefore connected with hygiene, durability and safety.

Energy and sustainability management require balance. Hospitals must reduce consumption without weakening safety or comfort. Ventilation, heating, cooling and sterilization can use large amounts of energy. Engineers identify losses, improve control schedules, monitor consumption, recover heat where possible and evaluate alternative energy systems. Better energy use reduces operating costs and can strengthen resilience.



Digital and smart systems integration is now part of engineering work. Engineers work with IT specialists to connect devices, protect data, manage sensors and support digital workflows. IoT and AI can help monitor equipment, predict failures, optimize energy use and support clinical decisions. These systems need cybersecurity, data quality, clear responsibility and human oversight. The European approach to AI in healthcare shows why this attention is necessary [3].

Safety and regulatory compliance give structure to daily work. Hospitals must follow many rules and standards, depending on the country and the type of system. Engineers translate requirements into procedures, tests, inspections, training and records. The Joint Commission environment of care resources show the importance of controlling risks linked to the physical care environment [9]. The exact standards may differ from one system to another, but the principle remains useful.

Emergency preparedness is practical engineering. Hospitals must continue essential services during failures and crises. Engineers help prepare for power loss, water interruption, oxygen supply problems, equipment failures, fire, flood, extreme heat and cyber incidents. They identify critical systems, define backup solutions and test plans. A plan that is never tested is weak.

Training and communication reduce incidents. Many technical events are linked to incorrect use, lack of training or poor communication. Engineers can train medical staff on safe device use, basic troubleshooting, alarm meaning and reporting procedures. They can also train technicians on clinical risks and sensitive areas. Shared training reduces the distance between technical and medical teams. Data analysis can improve quality. Modern hospitals produce data about downtime, maintenance costs, energy use, alarms, water temperatures, user reports and incidents. Engineers can use these data to find

patterns. Repeated failures in one device family may show a procurement problem. High energy use may show a control problem. Frequent alarms may show a training or configuration problem. Data become useful when they lead to action.

Innovation support must stay realistic. Hospitals may test 3D printing, digital prototyping, remote monitoring, robotics, AI or non-destructive testing of installations. Engineers help prepare pilot projects, check risks, evaluate results and decide what can be scaled. The final measure is simple. Does the technology help care, safety, continuity or sustainability? If not, it remains interesting but not useful.

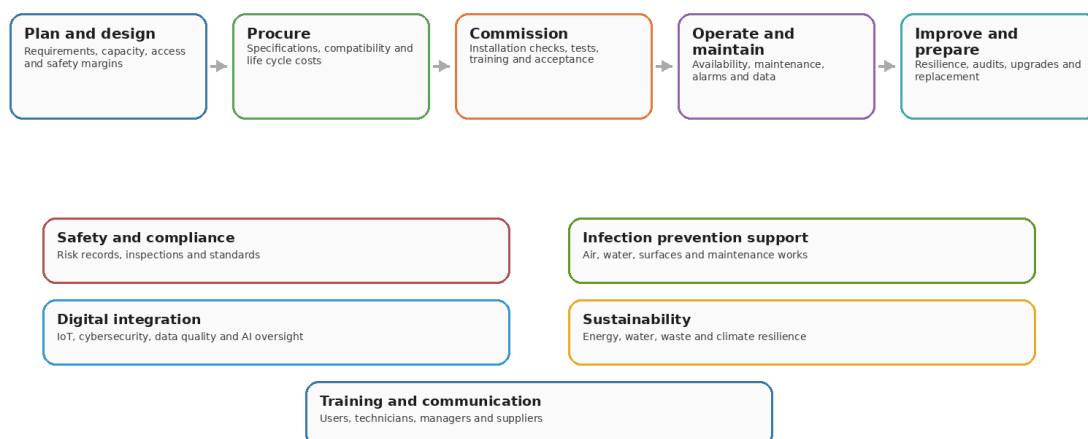


Figure 1.4. Engineering roles across the life of a hospital system

The engineer also makes technical risk visible to management. Managers must decide budgets and priorities. Engineers should explain problems in clear language. It is not enough to say that equipment is old or damaged. The manager needs to understand the risk, the consequence, the available options and the recommended action. This makes engineering part of hospital strategy.

Connected hospitals create new dependencies. A device may be linked to the network, a patient record, a cloud platform and a remote service provider. A



building management system may collect data from ventilation, energy, temperature and alarms. These links can improve control, but they can also create failure paths. Engineers need to coordinate with cybersecurity and data protection specialists.

Standardization supports trust. Hospitals often contain equipment from many suppliers and systems installed in different periods. Clear procedures make maintenance easier and training more consistent. This includes naming systems, labeling pipes and rooms, storing manuals, recording maintenance, using checklists and defining responsibilities. Trust is built through competence, communication and evidence, not through technology alone.

Table 1.2. Main roles of engineers in modern hospitals

Role	Examples of activities	Expected benefit
Planning and design	Define technical requirements, review layouts, verify capacity and maintenance access	Fewer design mistakes and better long-term usability
Procurement	Prepare specifications, compare offers, estimate life cycle costs	Appropriate technology and better value for money
Commissioning	Test installation, verify safety, train users and accept systems	Safe transition from project to clinical use
Maintenance	Plan preventive maintenance, repair failures and monitor performance	Reduced downtime and controlled risk
Healthcare technology management	Maintain inventory, classify criticality, plan	More organized and safer medical equipment use

	replacement and report incidents	
Utility management	Monitor power, water, medical gases, HVAC, steam and backup systems	Continuity of essential services
Infection prevention support	Control air, water, surfaces, maintenance procedures and technical flows	Lower technical contribution to infection risk
Digital systems	Support IoT, AI, cybersecurity, data quality and interoperability	Safer digital transformation
Sustainability	Reduce energy, water and waste while keeping safety	Lower costs and lower environmental impact
Training and communication	Train users, explain risks and connect departments	Better cooperation and fewer user-related incidents

1.5 OBJECTIVES OF THE SMART HEALTHCARE ENGINEERING PROJECT

The Smart healthcare engineering project was created in response to a practical educational need. Engineering students are usually trained in strong technical subjects, but many have limited contact with hospitals. Hospitals, at the same time, need engineers who understand infrastructure, maintenance, medical technology, digital transformation and safety. The project reduces this gap by connecting engineering education with real hospital practice [10]. The project is an Erasmus+ cooperation project in higher education that brings together



universities and hospitals from Romania, Spain and Türkiye. This cooperation is important. Students learn from teachers, hospital engineers, clinicians, technical staff and real hospital environments. They see that the same engineering subject can look different from one country to another and from one hospital to another.

The project introduces healthcare engineering as an educational direction for engineering students. Many students already know something about biomedical engineering. Fewer students understand the engineering behind hospital buildings, technical systems, water, air, energy, materials, maintenance, logistics and digital infrastructure. The project gives this area a clear teaching frame.

Theory is linked with practice. Corrosion becomes easier to understand when it is connected with hospital water systems, stainless steel surfaces or cleaning agents. Electrical safety becomes clearer when it is connected with operating rooms and emergency power. Automation becomes practical when it is connected with HVAC monitoring or medical gas alarms. Students understand engineering better when they see its effect on healthcare.

International intensive training programmes are a central activity. They expose students to different hospitals, different technical systems and different ways of organizing healthcare. Students do not learn only from lectures. They observe, ask questions, compare practices and discuss with people working in the field. This type of learning is difficult to replace with a normal classroom activity.

This handbook gives continuity to the training. A training programme has a limited duration. A handbook remains available for students, teachers and hospital staff. It collects key topics from the project, including medical devices, hospital systems, materials, water safety, energy, digital technologies,

diagnostics, advanced technologies and case studies. It can be used in courses, seminars, workshops and self-study.

E-learning resources extend access. Digital materials, presentations, quizzes and self-assessment tools allow students to repeat concepts and teachers to reuse content. This is useful in an international project because partners have different timetables and teaching formats. E-learning does not replace practical training. It supports it. Responsible innovation is part of the project message. AI, IoT, robotics, additive manufacturing and smart monitoring can support healthcare. They need safety, maintenance, cybersecurity, training and ethical use. The project encourages students to see innovation as a responsibility, not as a slogan. Sustainability and resilience are also included. Hospitals must reduce energy use, manage water responsibly, control waste and prepare for climate-related disruptions. These topics belong in engineering education. They are no longer optional additions to hospital operation.

The European value of the project comes from cooperation. Students see different hospital systems and different technical cultures. Teachers exchange methods. Hospitals share experience. This helps create a common language around healthcare engineering while respecting local needs.

The project does not claim that every student will become a hospital engineer. Its aim is broader. It gives engineering students a new way to use their knowledge. A graduate may later work in a hospital, a medical device company, a maintenance organization, a public authority, a research group or a design office. In all these places, understanding healthcare needs can improve decisions. The message is also human. Hospitals are places where people are vulnerable. Technical competence must be combined with responsibility, empathy and respect for clinical work. Healthcare engineering gives students a professional identity built around service to safe and sustainable care.



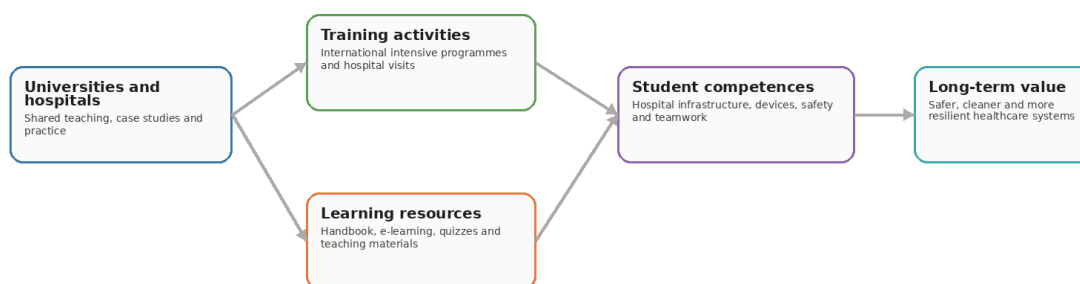


Figure 1.5. Smart healthcare engineering

Table 1.3. Main objectives of the Smart healthcare engineering project

Objective	Meaning	Expected result
Create a healthcare engineering educational direction	Introduce students to the technical systems of hospitals	Students understand healthcare as an engineering field
Connect theory with practice	Use hospital examples to explain engineering subjects	Learning becomes practical and meaningful
Organize international intensive training	Train students in Romania, Spain and Türkiye through practical activities	Students learn from different hospitals and cultures
Develop a handbook	Collect project knowledge in a structured teaching resource	Teachers and students can reuse the material after the project
Develop e-learning resources	Provide digital access to presentations, quizzes and self-assessment	Learning becomes more flexible and accessible
Improve technical competences	Teach infrastructure, medical devices, materials, energy and digital systems	Graduates are better prepared for healthcare-related jobs
Improve transversal skills	Develop teamwork, communication and problem solving	Students can work in interdisciplinary environments

Support hospital-university cooperation	Bring teachers, students and hospital specialists together	Education becomes more connected to real needs
Promote responsible innovation	Discuss AI, IoT, robotics and smart systems with attention to safety	Technology is introduced with a realistic view
Support sustainability and resilience	Include energy, water, waste and climate resilience in training	Future engineers can improve hospital operation responsibly

Healthcare engineering is needed because hospitals have become complex technical systems. Patient safety and quality of care depend on infrastructure, medical devices, materials, energy, digital systems and maintenance.

The healthcare engineer connects engineering with healthcare practice. This role supports safe, reliable, efficient and sustainable care. It requires technical knowledge, clinical awareness, risk thinking, communication and ethical responsibility.

Modern hospitals need engineers in planning, procurement, commissioning, operation, maintenance, infection prevention support, digital transformation, sustainability and emergency preparedness. Much of this work is invisible, but care depends on it.

The Smart Healthcare Engineering project supports this educational direction by bringing universities and hospitals closer together. It connects theory with practice and prepares students to see healthcare as a field where engineering can serve people directly.

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CHAPTER 2

ELECTRICAL AND ELECTRONIC EQUIPMENT IN MEDICAL DEVICES AND IOT-BASED APPLICATIONS

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This section explains the electrical and electronic hardware of medical devices and their functions, as well as the integration of Internet of Things (IoT)-based applications with these devices. It covers the electronic components used in these processes and their operating principles.

2.1. INTRODUCTION

A medical device can be defined as any instrument, tool, or gadget that is used to protect human and animal lives and health, diagnose diseases, conduct treatment, monitor results of treatment, improve the quality of people's lives,



and perform other activities through mechanical and technical means but not by using pharmaceutical properties [1]. A path from a primitive wooden stethoscope, which was used in the nineteenth century for treatment and monitoring purposes, to contemporary medicine industry, which is based on quantum physics and artificial intelligence, has been a great distance. The purpose of this research is to analyze the issue of medical devices, focusing on their technical, scientific, economic, and ethical aspects.

Development and evolution of medical devices represent the interaction of human ingenuity and interest in biology of a living body. Besides, there is an evolution in understanding of diseases, ethics and engineering perspectives.

Creation of medical devices has been driven by the need for pain relief and restoration. Devices of those times were simple from the technical side. Instruments mentioned in ancient Egyptian papyrus including scalpels, forceps, and surgical sutures were made from metal materials. The basic principle of design was that a medical device included either a metal tool designed for surgery or a metal element for grasping or cutting things. There were also various bone drills and speculums invented by Hippocrates and Galen. Development of medical devices went along with discovery of anatomy of human bodies. During the Renaissance period there was no further development of medical devices. However, creation of lenses and eyeglasses led to appearance of a concept of "repairing visual impairment" within the framework of medical devices.

The lack of cooperation and discussion between two important communities – medical specialists and engineers – was preventing further progress in creation of innovative devices. Still there were some prestigious schools and universities, which had initiated programs promoting innovation [2].

The first real turning point is associated with the period of the 19th century, also known as the Industrial Revolution. First discoveries in physics and chemistry started being applied in hospitals. The invention of the stethoscope by René Laennec in 1816 allowed listening to the beating of a patient's heart through a rolled-up piece of paper rather than pressing one's ear against the chest. Thus, in the history of medicine, it became possible to make one's senses amplified with the help of a medical device for the first time. Measuring body temperature and blood pressure meant that illnesses turned from a 'subjective complaint' into an 'objective number.' Hence, the medical device became an instrument of measuring. Wilhelm Röntgen's invention of X-ray radiation led to a complete revision of the notion of a medical device. The non-invasive examination of bones and internal organs became possible for the first time. Hence, a new direction, called radiology, appeared together with new imaging devices.

The second turning point refers to the period in the middle of the 20th century, when electronics made their appearance in medicine. Besides being used in diagnostic procedures, medical devices were introduced in 'life support' procedures, including breathing and other body functions. Willem Einthoven's invention of the first electrocardiograph in 1903 allowed recording the electric signals of the body. The enormous size of these devices, which initially took up almost a whole room, became smaller owing to the creation of transistors and could later be carried in one's pocket. Pressure chambers used for curing people with polio, called 'the iron lung,' became the first massive medical devices fully taking on the function of breathing. An artificial kidney, created by Willem Kolff and named dialysis, was invented, becoming another milestone and turning the idea of a medical device into that of a complex mechanism resembling the functions of an organ. First implantable pacemakers introduced people to the 'cybernetic' stage of medical technology.



The growing power of processors resulted in creating the next generation of devices, making them both data acquisition and processing systems. Medical devices, such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) created in the 70s and improved in the following decade, started building three-dimensional pictures of the organism with the help of mathematical algorithms. Endoscopic and laparoscopic devices helped in substituting large operations for minor incisions. Devices got smaller, more flexible, and more intelligent [3]. With the use of embedded software, infusion pumps, smart ventilators, and defibrillators started minimizing the room for error [4].

Today, the medical device concept moved beyond its initial physical limitations. Besides its data acquisition precision, the add-value of a device lies in its ability to interpret data. Advanced radiology systems incorporating Artificial Intelligence (AI) are able to scan thousands of images within minutes in order to detect even microscopic deviations invisible to humans. With the help of Internet of Things (IoT) applications, we moved to a healthcare system operating synchronously, where all devices continuously send their data to cloud architectures. In this case, the medical device is no longer an autonomous physical device. It becomes a part of the massive healthcare information network. One example of advanced medical devices that can interact bidirectionally with the peripheral nerves to give users a sense of touch in bionic prostheses and a precise device for modifying genes within laboratory conditions (gene editing platform) are among prominent samples of that type.

The revolutionary vision of the evolution of medical technology required a breakthrough in bioethics and regulations as well. Unlike today, there was no specific control over the medical device market until the 20th century. The process of getting marketing clearance according to present-day health safety requirements implies conducting multicenter clinical trials and tests on

biocompatibility throughout several years. In addition, unlike the previous model of medical devices where software functioned as an inseparable part of hardware, software became an independent entity in the digital revolution and was categorized as Software as a Medical Device (SaMD).

Ultimately, the development of medical technology moved beyond mere quantitative prolongation of human life span to become a true revolution which transformed the borders of human physiology. Currently, the trend moves from the reactive use of "conventional therapeutic devices" towards proactive "preventative bionic systems" capable of predicting and intercepting pathologies at the cellular level. In this context, the macro-evolution can be traced historically with the help of major achievements and categorized chronologically in 5 eras.

- **Mechanical & Craftsman Era (Antiquity – 1800):** Scalpels, forceps, basic surgical tools. At this stage, the medical device was used exclusively for improving sharpness and grip of the surgeon's hand.
- **Diagnostic Breakthrough Era (1800 – 1900):** Stethoscope, thermometer, sphygmomanometer. Diseases started being quantified, while the human body could be assessed using instruments that enhanced the physician's ability to hear and see. With the advent of X-ray imaging, it became possible to peer into the interior of the human body.
- **Electro-Mechanical/Life Support Era (1900 – 1980):** ECG, dialysis, pacemaker, ventilator. Instruments no longer only diagnosed pathologies but took over the functions of vital organs on a temporary or permanent basis.
- **Digitization/Advanced Imaging Era (1980 – 2010):** MRI, CT, laparoscopy. Computing technologies helped create 3D images of the human body



while making surgical operations less invasive (minimally invasive procedures).

- **Smart Systems/Centralization Era (2010 – Now):** Artificial Intelligence, wearables, robotics. Devices transform into "information terminals" with autonomous decision-making capability.

Throughout history, the notion of a medical device developed around the following five vectors:

1. **Sensory** (Instrument enhancing the abilities of the physician's hand/eye, for instance, Stethoscope).
2. **Metric** (Quantification of the disease, for example, Thermometer, Sphygmomanometer).
3. **Functional** (Ability to temporarily or permanently take over an organ function, for example, Dialysis, Ventilator).
4. **Digital** (Computational system processing complex data, for instance, MRI, CT).
5. **Autonomous** (Decision making capability, for example, Artificial Intelligence, Wearable Sensors).

2.2 CLASSIFICATION OF MEDICAL DEVICES

The recent advancements in the technology have brought forth numerous innovations in the medical field as well. Devices which were once limited to simple diagnostic equipment and instruments of surgery have grown into highly complex implantable electronics, advanced imaging techniques powered by artificial intelligence, and wireless wearable sensors. Such a wide spectrum of medical devices requires, therefore, a common regulatory language not just

convenient but necessary for ensuring all devices comply with the proper standards in terms of safety.

Classification can be used here as a means of dealing with such a requirement through categorizing devices based on certain attributes, while linking these categories to a specific set of requirements.

For example, according to European Union Medical Device Regulation (EU MDR 2017/745) adopted by Turkey as well, as the basic principle of their regulatory regime, medical devices fall into risk classes that require increasingly higher levels of evidence [5]. However, the risk class is far from being the only factor to consider when it comes to regulation of the medical devices: the purpose of the device, its dependence on an external energy source, and the conditions under which it would be utilized – each of them has a separate impact.

In this part, four distinct yet interconnected approaches to the classification of medical devices will be analysed: (1) functional purpose, (2) risk, (3) technological/physical characteristics, and (4) environmental conditions of use. The key categories in each classification scheme are identified, explained using the clinical examples, and discussed regarding regulatory/engineering aspects. Finally, an analysis of the interaction between these classifications' schemes will be provided.

2.2.1 Classification by Functional Purpose

Functional classification asks a deceptively simple question: what is this device for?

The answer organizes the entire ecosystem of medical devices into four broad categories (diagnostic, therapeutic, life-supporting, and monitoring) each of which carries distinct clinical implications. Unlike risk-based classification, which is inherently regulatory in character, functional classification is descriptive.



Diagnostic Devices

Diagnostic systems are intended for detecting diseases or measuring some physiological quantities. The most well-known examples are derived from radiological and nuclear imaging: radiographic examinations, CT, and MRI allow the acquisition of non-invasive anatomical details almost instantaneously [6]. When paired with CT scans, PET becomes especially useful for staging cancer owing to the inclusion of metabolic features of tissues that are sometimes as critical as their structure. Lab equipment plays no less important roles in the realm of medical devices. Automatic blood analysers, haematology machines, and sequencers form a cornerstone of the current clinical diagnostics practice, supplying numerical information that is essential for decision-making in today's medicine. On the other hand, simple measurement devices like sphygmomanometers, stethoscopes, thermometers, and ECG machines become indispensable in primary care due to their portability and affordability.

Therapeutic Devices

The devices used in therapy are directly involved in therapeutic and surgical procedures. Surgical equipment covers a broad range of sophistication, from the simplest instruments, such as scalpels and forceps, to advanced robotic systems. For instance, the da Vinci Surgical System allows physicians to perform surgeries using minimal invasiveness with tremor reduction and improved accuracy beyond the level possible using hands only [7]. This development has made it possible to use laparoscopy in complex procedures like prostatectomy and mitral valve repair, which was not considered viable due to the technical difficulties involved before.

The radiation oncology field includes the usage of linear accelerators (LINACs), producing high-energy rays in form of X-rays directed towards a tumor. Infusion

pumps provide the administration of drugs via a vein in an extremely precise manner. This equipment is of great importance in ICU, as a mistake in drug administration may lead to life-threatening outcomes among critical patients.

Life-Support Devices

The machines used to help sustain life act as a substitute for body processes that the patient is unable to do by themselves. Mechanical ventilators replace the natural process of pulmonary ventilation in those suffering from respiratory failure; the worldwide COVID-19 crisis has made the general population aware of these machines and how the supply chains of such machines that have never been considered before having become very vulnerable. Machines like dialysis carry out the job of the kidney when it malfunctions in such a way that the patient will be able to lead a meaningful and productive life for many years. The heart-lung machine helps in open-heart surgery and enables the surgeon to operate on a still and bloodless heart [8].

Monitoring Devices

The monitoring devices continuously watch over the physiological state of the patient either on an ongoing basis or at set time periods but do not provide any treatment themselves.

ICU bedside monitors can show at the same time the heart rate, SpO₂, blood pressure, and breathing rate, giving out alarms when the value of one of these parameters becomes unsafe. Wearable technology took the field a long way from the ICUs. One of such examples is CGM that continuously measures the level of interstitial glucose every several minutes and sends its data to a smartphone or insulin pump of the patient, thus enabling managing diabetes with unprecedented precision [9].



Table 2.1. Summary of medical device categories and representative examples under the functional classification framework.

Category	Sub-Group	Example Devices
Diagnostic	Imaging devices	X-ray, CT scan, MRI, PET-CT, ultrasound
Diagnostic	Laboratory equipment	Blood analyzers, microscope, gene sequencer
Diagnostic	Measuring instruments	Sphygmomanometer, stethoscope, ECG
Therapeutic	Surgical equipment	Laser surgery systems, robotic systems (Da Vinci)
Therapeutic	Radiotherapy devices	Linear accelerator (LINAC)
Therapeutic	Infusion pumps	Intravenous drug administration
Life-Supporting	Ventilators	Mechanical breathing support
Life-Supporting	Dialysis machines	Renal function replacement
Life-Supporting	Heart-lung machines	Circulatory support during open-heart surgery
Monitoring	Bedside monitors	Heart rate, SpO ₂ , respiratory rate
Monitoring	Wearable sensors	Continuous glucose monitor (CGM)

2.2.2 Classification by Risk Level (Regulatory Classification)

The most important among the four is the risk-based classification framework because of its significance from a regulatory point of view. The European Union Medical Device Regulation (EU MDR) 2017/745, which is incorporated as the

basis of national medical device regulations by Turkey, classifies the device into four different classes depending upon the extent of danger that can be caused to the patient by that device.

Class I — Low risk

Devices included in Class I are those that either have little or no contact with the body or that do not contact with the body at all. Examples of such devices include wheelchairs, examination gloves, adhesive dressings, and spectacles lenses. The procedure for assessing conformity of these devices is rather simple, and generally the declaration of conformity can be made by the manufacturer independently, without involving any notified body. This is except for Class I sterile and measuring devices [5].

Class IIa — Low to medium risk

In Class IIa medical devices, there will be temporary invasive interaction or only limited interaction with body tissues. The use of hearing aids, fillings for dental purposes, and diagnostic ultrasound machines comes under Class IIa. The technical documentation needs to be reviewed and approved by an accredited third-party agency called the notified body, while the manufacturer must present a Clinical Evaluation Report (CER) that proves that the clinical benefits exceed the remaining risks associated with the use of the device [5].

Class IIb — Medium to high risk

Devices in this class either remain in the body for an extended period or directly influence critical biological functions. Infusion pumps, X-ray machines, and ventilators are typical examples. Notified body involvement is mandatory throughout the conformity assessment process, and the clinical evidence



requirements are considerably more demanding than those for Class IIa. Post-market clinical follow-up is also expected to be more systematic [5].

Class III - High risk

Class III represents the highest risk tier and is reserved for permanent, life-critical devices that come into direct contact with the heart or the central nervous system. Pacemakers, brain stents, and artificial heart valves are the defining examples. Because a single malfunction can prove fatal, these devices must complete a rigorous pathway that includes full clinical investigations, detailed biocompatibility testing [10], sterilisation validation, and ongoing post-market surveillance [11]. These strict requirements exist because failures in such devices can directly affect patient safety and may lead to irreversible harm or death.

Table 2.2 The four risk classes defined in EU MDR 2017/745, with their key characteristics and representative examples.

Class	Risk Level	Characteristics	Example Devices
Class I	Low	Non-invasive, simple	Wheelchairs, exam gloves, bandages, eyeglass lenses
Class IIa	Low–Medium	Short-term invasive	Hearing aids, dental filling materials, ultrasound devices
Class IIb	Medium–High	Long-term invasive or critical function	Infusion pumps, X-ray machines, ventilators
Class III	High	Life-critical, permanent contact	Pacemakers, brain stents, artificial heart valves

2.2.3 Classification by Technological and Physical Structure

This framework shifts the focus from what a device does or how dangerous it might be to how it is built and how it relates to the body physically. Three categories emerge: active devices, passive (non-active) devices, and implantable devices. While these categories overlap with risk classification in important ways, they carry distinct implications for design standards, electromagnetic compatibility testing, and biocompatibility requirements.

Active Medical Devices

Active medical devices refer to medical devices powered externally from sources such as mains electricity, batteries, compressed gas, or any other power supply, and they rely on such an energy source to be able to achieve their desired function. Examples of active medical devices include ECG machines, MRI scanners, pacemakers, and infusion pumps. There is however one key point that needs highlighting here, which is that pacemakers and other similar devices are classified as both active and implantable medical devices at once.

Passive (Non-Active) Devices

Passive devices operate without an inherent energy source. Examples of such devices include scalpels, forceps, bandages, and artificial limbs. However, it should be acknowledged that there is a tendency towards blurring the distinction between active and passive devices since more sophisticated artificial limbs use processors and actuators. Nevertheless, it is still relevant to classify devices according to their main mode of operation.

Implantable Devices

These products are inserted either fully or partly into the human body using a



surgical procedure and are designed to stay in place permanently after the operation is completed. These include hip replacements, breast implants, and brain stents. Biocompatibility is of high importance in this type of implantable devices: all the materials which will have prolonged contact with the living tissue have to be tested in accordance with ISO 10993-1 (2018) to ensure that the product would not cause toxicity, inflammation, allergy, or cancer effects. It should be noted that the periods of exposure to tissue are rather long [10].

Table 2.3. Comparative summary of active, passive, and implantable device categories.

Type	Definition	Examples
Active Devices	Require electrical energy or an external power source to operate	ECG, MRI, pacemaker, infusion pump
Passive (Non-Active) Devices	Operate without an independent power source	Scalpel, bandage, prosthetic leg, surgical instruments
Implantable Devices	Surgically placed inside the body and intended to remain there	Hip prosthesis, breast implant, brain stent

2.2.4 Classification by Environment of Use

The final classification dimension asks not what a device does or how it is built, but where it is used and by whom.

This distinction has direct consequences for user interface design, labelling requirements, and post-market surveillance strategies, since the risk profile of

a device shifts significantly depending on whether it is operated by a trained clinician in a controlled environment or by a patient at home.

Professional and Clinical Use

Equipment designed solely for the use by trained medical professionals in hospital environments is categorized as professional use. Equipment used in surgical procedures such as surgical microscopes, robotic surgery units, and radiotherapy equipment falls within this category. The design interface in such cases can take into account high levels of user expertise as they have the know-how to use the equipment properly. This is because a lot of information can be included in the user guide without the risk of the user misunderstanding or misusing it. On the downside, any mistakes made during operation cannot be blamed on the equipment alone.

Home Care and Personal Use

Home care and personal use devices must be user-friendly in the sense that anyone who doesn't have a medical education should be able to use the device. These devices include smart glucometers, nebulizers, home blood pressure monitors, and wearables for ECGs. In the case of home-use devices, it cannot simply be said that an intuitive design is a matter of usability; a poor design and an unclear alarm may result in a clinical incident. Home-use devices' connection with the cloud computing platform and electronic health record systems makes it possible to conduct remote monitoring, which means that a clinician can monitor a patient's physiological parameters remotely without the need for a trip to the hospital [12].

As we have seen, however, the above classifications are not mutually exclusive and independent. In fact, there is a significant intersection between them. To provide another example, a pacemaker would be a life supporting and



monitoring device according to the functional classification scheme. According to the risk-based classification scheme, it would fall into Class III. According to the technological and physical structure classification scheme, it would be an active implantable device. According to the environment of use classification scheme, it would be implanted in a professional clinical environment but then used all the time in domestic life. Each of these characterizations would require a distinct set of regulations, resulting in the strictest possible pre-market and post-market requirements.

This complexity makes the classification process extremely important as, depending on how it is classified, different devices are subject to different pre-market requirements. First, risk classification will determine whether conformity is declared by the manufacturer itself or a notified body. Also, depending on the risk class, different amounts of clinical evidence will be needed prior to marketing.

Classification as an active device would mean application of certain electromagnetic compatibility standards and electrical safety standards. Being an implantable device would mean undergoing the entire biocompatibility testing programme. Finally, being designed for domestic use would imply certain labelling and usability testing requirements. Failure to correctly classify a device may thus lead to either not testing the product enough to ensure patient safety or wasting effort on unnecessary testing.

In Turkey specifically, the regulatory authority — the Medical Device Directorate of the Ministry of Health — operates within a framework closely aligned with EU MDR. Understanding these classification systems is therefore an academic exercise for biomedical engineering students and a mandatory practical prerequisite for anyone seeking to bring a device to the Turkish or European market.

2.3 IMAGING TECHNOLOGIES AND USED DEVICES

Imaging systems constitute the largest and most widely utilized group of devices within medical instrumentation. Thanks to these technologies, the era of "exploratory surgery" has come to an end, being replaced by pinpoint (localized) diagnosis.

2.3.1 Magnetic Resonance Imaging (MRI)

A Magnetic Resonance Imaging (MRI) device requires a massive electromagnetic and electronic hardware infrastructure to convert a complex physical phenomenon (nuclear magnetic resonance) into an image. The electrical-electronic architecture of an MRI device basically consists of three main subsystems.

Main Magnet (Superconducting magnet) System

As the heart of the MRI machine, this system produces a very strong and stable static magnetic field that aligns the protons in the body.

- **Superconducting Coils:** Generally made of a Niobium-Titanium (NbTi) alloy. Electrical current passes through these coils without any resistance.
- **Cryogenic Cooling:** To maintain superconductivity, the coils must be cooled with liquid helium down to around -269°C (4 Kelvin). The control of this system is electronically monitored using precise temperature and pressure sensors.
- **Shim Coils:** Corrective electronic coils used to ensure the homogeneity of the magnetic field (making it the same strength at every point).



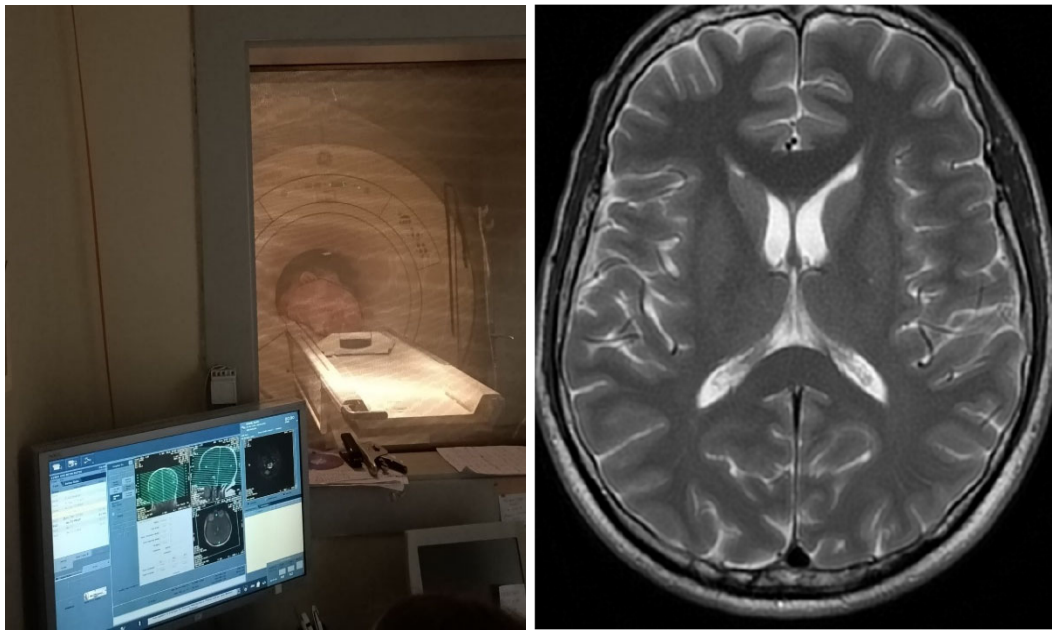


Figure 2.1. MRI device and image

Gradient Subsystem

This is the system that alters the main magnetic field in a controlled manner to determine from which slice the image will be acquired (spatial encoding).

- **Gradient Coils (X, Y, Z):** Positioned inside the main magnet, these coils alter the magnetic field linearly along the respective axes.
- **Gradient Amplifiers (Drivers):** This section is one of the most powerful electronic units of the MRI machine. Generating kilowatts of power (exceeding 1 MW in some systems), they deliver extremely fast and precise current pulses to the gradient coils. These rapid current fluctuations are the source of the loud "knocking" or "clicking" noises heard during an MRI scan.

Radio Frequency (RF) Subsystem

This system is responsible for transmitting energy to excite the protons in the body and collecting the weak signals returning from them.

A. Transmitter Unit

- **RF Synthesizer:** Generates a digital signal matching the Larmor frequency of the protons (e.g., approximately 63.8 MHz for a 1.5 Tesla system).
- **RF Power Amplifier:** Boosts the generated low-power signal up to several kilowatts and delivers it to the RF coils.

B. Receiver Unit

- **RF Receiver Coils (Antennas):** Collect the very weak electromagnetic signals emitted from the body.
- **Low-Noise Amplifier (LNA):** Because the signal is extremely weak, it must be amplified immediately before it gets distorted by background noise.
- **Analog-to-Digital Converter (ADC):** The captured analog signals are converted into digital data at high speeds and sent to the computer for processing.

Control Unit and Data Processing

This is the unit that ensures all these hardware components operate synchronously with millisecond precision.

- **Pulse Sequence Controller:** A microprocessor system that coordinates when, in what order, and at what power the RF pulses and gradient currents are applied.
- **Faraday Cage:** An electronic shield where the entire room is lined with copper or aluminum sheets to prevent external radio waves (from radio stations, mobile phones, etc.) from interfering with the device's sensitive receivers.

2.3.2 Computed Tomography (CT)

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A Computed Tomography (CT) device is an engineering marvel that uses X-rays to create cross-sectional images of the body, combining high-speed data processing with precise electromechanical control. The electrical-electronic hardware of the device is examined under four main groups: power management, X-ray generation, data detection, and mechanical motion control.

Gantry and Mechanical Control System

The gantry is the large circular structure into which the patient enters. It houses the X-ray tube and detectors, which rotate at very high speeds (3–4 full rotations per second).

Slip-Rings: This is the most critical electrical component of a CT scanner. Because the gantry rotates continuously, using cables is impossible. Slip-ring technology continuously transmits electricity and data to the rotating part (rotor) via a brushed system.

Servo Motors and Drivers: These components control the rotation speed of the gantry and the movement of the patient couch with micron-level precision. In modern devices, high-torque brushless DC motors are preferred.

Laser Alignment System: Low-power laser diodes are utilized to ensure the correct positioning of the patient.

X-Ray Generation Hardware (High voltage chain)

To generate X-rays, electrons must be accelerated to extremely high speeds.

High Voltage Generator: A transformer and rectifier system that takes mains electricity and boosts it to a range between 80 kV and 140 kV (kilovolts).

X-Ray Tube: A vacuum tube containing a cathode (electron source) and a rotating anode (target). The anode rotates at high speed to dissipate heat, and this rotation is controlled by an electromagnetic motor.

Thermal Control System: The tube generates a massive amount of heat during operation. To dissipate this heat, an electronic feedback circuit consisting of oil-cooled heat exchangers, pump drivers, and temperature sensors is utilized.

Detector and Data Acquisition System (DAS)

After the X-rays emitted from the tube pass through the patient, they are captured by the detectors on the opposite side.

Scintillator and photodiodes: The scintillator first converts the X-ray energy into light, which the photodiode then converts into a very weak electrical current.

Data Acquisition System (DAS): Collects the nano-ampere level analog signals coming from the photodiodes.

Amplification: Amplifies the weak signals.

ADC (Analog-to-Digital Converter): Converts analog signals into digital data at high resolutions, such as 24-bit.

Optical data transmission: Due to the high rotation speed, gigabytes of data collected by the DAS are wirelessly transmitted from the gantry to the main computer via laser/optical transmitters.

Power Supply and Filtering

CT devices draw very high instantaneous power (50 kW–100 kW+).



Uninterruptible Power Supply (UPS) and regulators: Protect the sensitive electronics of the device (especially computers and detectors) from fluctuations in the mains grid.

DC Power supplies: Provide the stable, low-voltage (5V, 12V, 24V) energy required for the internal control boards, FPGAs, and processors.

Computer and Image Reconstruction Unit

Image reconstruction engine: Applies complex mathematical algorithms (Filtered Back Projection or Iterative Reconstruction) to the raw data (sinograms) received from the DAS. This unit generally consists of numerous high-performance GPUs (graphics processing units) working in parallel.

Main console: The main computer unit that manages the user interface and synchronizes all system components.

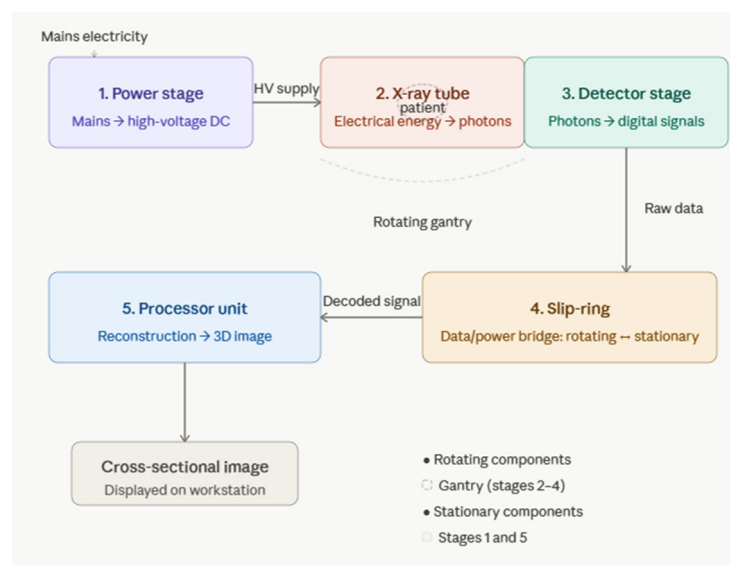


Figure 2.2. Hardware workflow and sequential signal processing in a computed tomography (CT) scanner.

Computed tomography (CT) and magnetic resonance imaging (MRI) are different methods since both have unique techniques to visualize the body. CT uses X-

rays to create a series of cross-sectional images in a very short time, and it is the most useful method for assessing bone tissue and trauma cases. On the other hand, MRI creates images by using the interaction between a strong magnetic field and radiofrequency waves which produces high-quality images of soft tissues, nerves, and blood vessels.

CT scan: Cross-sectional images based on variations in tissue density, achieved by rotating X-rays in the area to be visualized. Radiation exposure is an essential aspect that needs to be considered since ionizing radiation is applied during CT imaging. It is recommended to exercise caution when scanning children and pregnant women due to possible harm from radiation. Moreover, the use of contrast medium containing iodine carries the risk of nephrotoxicity; therefore, urinalysis before the procedure should be performed. Possible adverse events include allergies and toxicity of the contrast media.

MRI scan: An imaging technique based on the influence of a strong magnetic field on protons in the body which become aligned in relation to the field direction and can transmit signals when exposed to the radiofrequency wave. An advantage of MRI is that no ionizing radiation is used; therefore, there are fewer contraindications. Gadolinium contrast agents used in MRI rarely cause hypersensitivity reactions.

Which method is appropriate is determined by the physician, taking into factor elements such as the patient's medical condition, scanning requirements, urgency, and patient comfort.

2.3.3 Ultrasonography

Ultrasound devices are radiation-free systems that operate on the principle of sound wave reflection (echo). They do not require massive magnets or high-voltage generators like MRI or CT; however, they are highly complex in terms of



high-speed signal processing and precise analog-to-digital conversion capabilities.

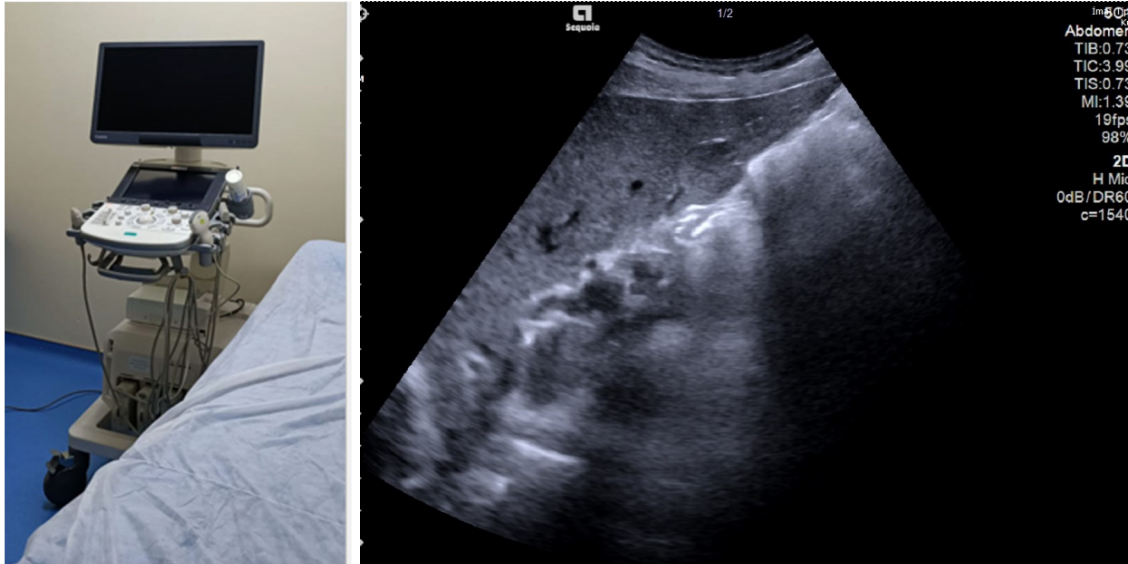


Figure 2.3. USG device and image

The electrical-electronic hardware of an ultrasound device consists of the following main sections:

Probe (Transducer) unit: The piezoelectric heart

The probe acts as both the "speaker" and the "microphone" of the device.

Piezoelectric Crystals: Quartz or PZT (Lead Zirconate Titanate) ceramics that convert electrical energy into mechanical sound waves (and vice versa).

Acoustic Matching Layer: An electronic and material layer that optimizes sound transmission between the crystal and the skin.

Beamformer: The circuit that controls at which exact millisecond the electrical current is sent to each individual crystal element. This allows the sound wave to be focused in a specific direction.

Transmitter and Receiver Stage

This section is responsible for generating sound waves and capturing the weak returning echoes.

High-Voltage Pulse Generator: Generates short-duration but high-voltage (usually between 10V and 200V) electrical pulses to vibrate the piezoelectric crystals.

TGC (Time Gain Compensation): Sound waves returning from deep within the body lose more energy and come back weaker. The TGC circuit automatically amplifies these weak signals returning from deeper tissues, ensuring uniform brightness across the entire image on the screen.

LNA (Low-Noise Amplifier): Returning signals are at the microvolt level. These circuits amplify these signals before they are overwhelmed by background noise.

Signal processing and image reconstruction hardware

This is the stage where the captured ultrasound data is converted into an image that a physician can interpret.

ADC (Analog-to-Digital Converter): Converts the received analog echo signals into digital data at high speeds.

Digital Signal Processor (DSP) or FPGA:

B-Mode Processing: Generates brightness (grayscale) data.

Doppler Processing: Analyzes frequency shifts to calculate blood flow velocity (phase shift measurement).

Scan Converter: Converts data from polar coordinates (the fan-shaped data structure originating from the probe) into Cartesian coordinates (the square pixel grid layout of a display monitor).



User Interface and Control Panel

Control Unit (CPU): The main computer layer that manages the entire system.

TGC Sliders: An array of potentiometers that allows the user to manually adjust image brightness relative to tissue depth.

Rotary Encoders and Trackball: Precision input devices used for taking measurements and navigating through the image.

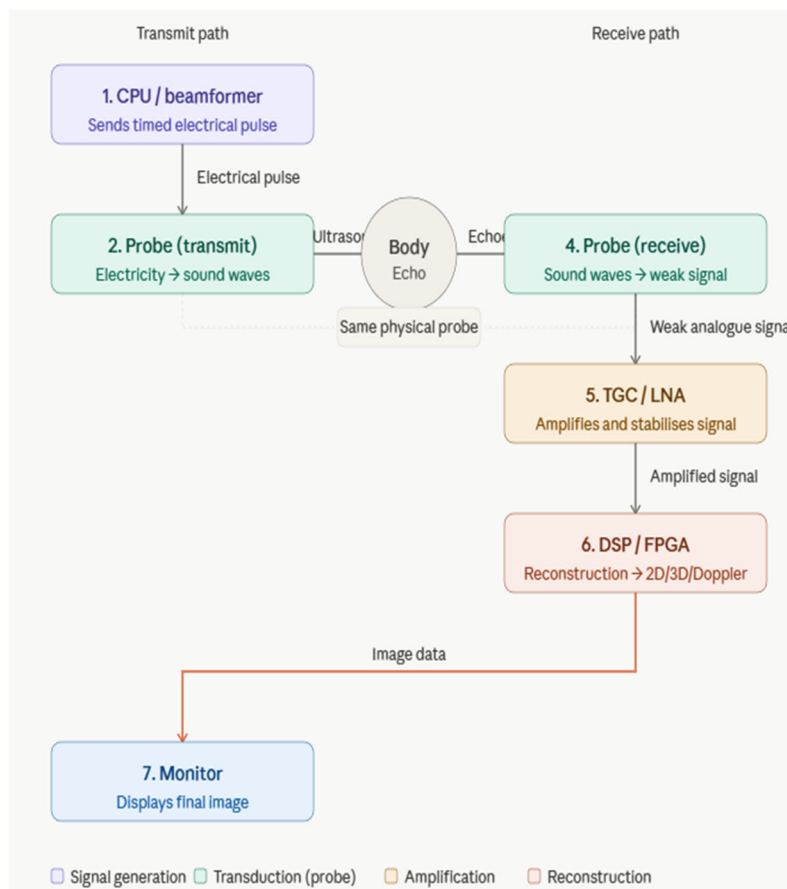


Figure 2.4. Hardware workflow and sequential signal processing in an ultrasound scanner.

Power Supply and Isolation

Since ultrasound devices come into direct contact with the patient, electrical safety is kept at the highest possible level.

Medical-Grade Power Supply: Power units featuring very low leakage current values and specialized isolation transformers.

Battery Management System: Includes lithium-ion battery packs and their dedicated charge control circuits to provide uninterrupted power for portable ultrasound devices.

Doppler and ultrasound are two modalities that fundamentally utilize the same sound wave technology. The primary difference between them lies in their intended purpose for measurement and focusing.

Standard Ultrasound: Visualizes the size, shape, and structure of organs and soft tissues. It functions similarly to a static, motionless photograph.

Doppler Ultrasound: Evaluates moving structures, specifically blood flow within blood vessels. It analyzes the velocity and direction of blood flow, as well as vascular obstructions (blockages). It is also commonly referred to as "Color Doppler" or "Color Ultrasound."

Both modalities are completely harmless to the body and contain no radiation. In most modern medical imaging systems, these two features are integrated and available together.

2.4 LIFE SUPPORT AND THERAPEUTIC DEVICES

These devices play a life-saving role by stepping in when vital body functions become insufficient.

2.4.1 Ventilators

This is a mechanical breathing system used for patients who have experienced respiratory failure and it helps the breathing system do its work effectively. The ventilator is defined as equipment used to help or substitute the breathing system through provision of air or oxygen to the patient's lungs. In simple terms, the machine helps the patient breathe if his lungs are not functioning properly by providing the necessary oxygen and exhaling the excess carbon dioxide [13].



Figure 2. 5. Ventilator user interface

The ventilators mainly work using the positive pressure mechanism. Air is pushed into the lungs and after which the air is naturally exhaled due to the natural elasticity of the chest wall. Delivery of the air to the lungs can be done either by use of mask or the airway tube (invasive/non-invasive respectively). There are some factors that are controlled by doctors according to the clinical condition of the patient.

Ventilators usually must be attached when a patient experiences breathing difficulties. They are often used for patients undergoing surgery, as well as for those who suffer from respiratory conditions, injuries, and illnesses.

2.4.2 Dialysis Systems

Dialysis machine refers to a biomedical device used for removing the toxins from the blood of people having problems with their kidneys. Physiologically, under normal circumstances, the filtering system in the body (kidneys) filters out the toxins, excess water, and electrolytes from the bloodstream. With malfunctioning of the kidneys, it is a matter of life and death with the buildup of such elements in the body. The dialysis machine at this point comes into play and facilitates the process of extracorporeal blood purification.

■ **Blood Withdrawal:** Blood is removed from the patient's vein, usually the one in the arm through either a fistula or a catheter.

■ **Filtering (Dialyzer):** The blood enters the machine through a system of tubing and is filtered using a device known as a dialyzer (also referred to as artificial kidney). It is the main part of the machine consisting of thousands of tubes.

■ **Dialysis Fluid:** Within the filter is special fluid (dialysate) where the waste products of the blood get into.

■ **Return of Clean Blood:** The purified blood returns to the patient.

There are two main forms of dialysis depending on the mode of application:

■ **Haemodialysis** – purification of blood outside the body via a machine. It is conducted three times a week in a hospital setting.

■ **Peritoneal Dialysis** – a procedure which utilizes peritoneal membrane of the body for filtration with the help of a catheter introduced in the abdominal cavity. It involves less use of machines and can be performed at home.

Dialysis machine purifies the blood and preserves balance of the body functions by means of the following actions:

■ **Filtration of Wastes** – urea, creatinine and other toxic elements from blood stream.



- Preservation of Fluid Balance – ensuring that any extra water (edema) in the body is eliminated.
- Maintenance of Electrolyte Balance – preserving safe levels of mineral electrolytes in the blood (potassium, sodium and bicarbonate).
- Blood Pressure Control – ensuring safe blood pressure due to reduced fluid volume load.

2.4.3 Defibrillators

The defibrillator is employed to supply electrical stimulation to the heart in case of heart muscles fibrillation, causing them to contract irregularly, thus preventing the heart from pumping blood. The machine also includes a built-in ECG monitor to monitor the heart muscle electrical activity.



Figure 2.6. An example for Defibrillator [14]

2.5 INTERNET OF THINGS AND REMOTE MONITORING

The internet, which lies at the center of modern life, has opened a new era in digital health applications by making devices remotely manageable through the Internet of Things (IoT). The Internet of Things (IoT) is an innovative technology featuring billions of sensors across various IoT applications. Crucial elements utilized in IoT are sensors that harvest data for the required analyses. IoT and sensors are highly critical in smart cities, smart agriculture, smart education, healthcare systems, and other applications [15,21-23].

Piezoresistive, optical, and biosensors designed to perform various functions are widely utilized microchips. In recent studies, Internet of Things-based applications are frequently encountered [16–17].

Patients' vital parameters, such as Pulse/Heart Rate (HR), Heart Rate Variability (HRV), and Core Body Temperature (CT), can be monitored in real-time via an Android-based application. Wearable sensors attached to the patient transmit the measured signals directly to the mobile application via a wireless connection. If these values drift outside safe physiological limits, the system automatically intervenes to report the patient's data and real-time location to the physician and family members via email and Twitter. This technology enables patients in critical conditions to sustain their social lives safely, even while under medical surveillance. In these and similar systems, sensor data are integrated with appropriate interfaces to perform the necessary notifications and interventions [18–19].

The architecture of an Internet of Things-based application system is schematically illustrated in Figure 2.7. Internet of Things-based applications provide numerous contributions to the healthcare sector through processes such as Remote Patient Monitoring and Early Disease Detection, Personalized Treatment and Chronic Disease Management, Enhanced Elderly Care and



Patient Autonomy, Preventive Healthcare Services and Early Intervention, Support for Caregivers and Family Members, and Global Health Monitoring and Data Collection.

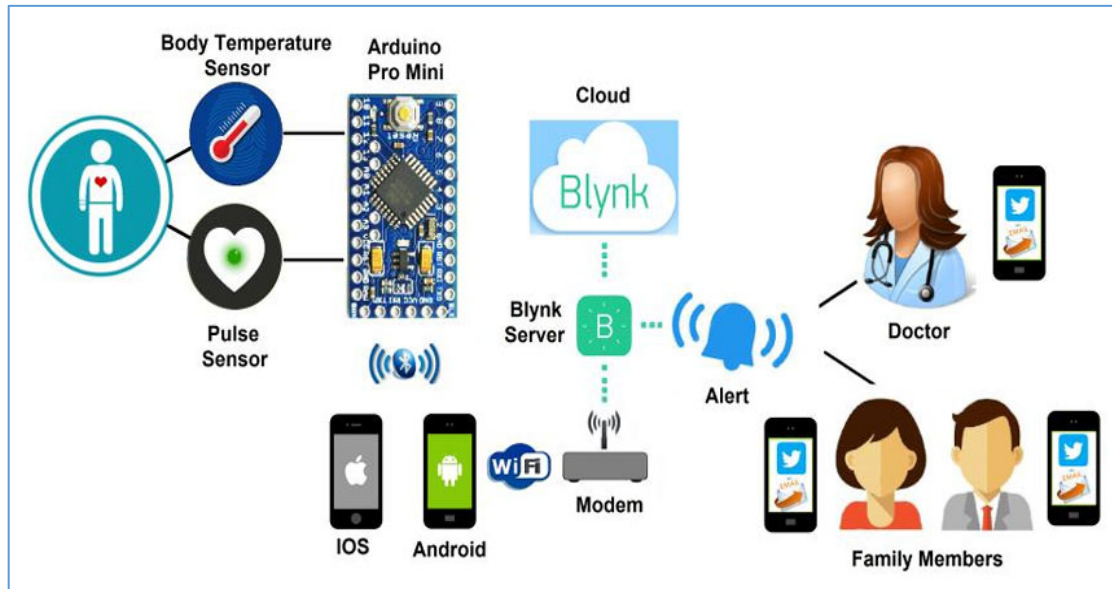


Figure 2.7. Architecture of an Internet of Things-based application system [16].

Patient management and monitoring have become significantly easier through modalities such as smartwatches capable of recording ECGs, measuring blood oxygen saturation (SpO₂), and performing fall detection, as well as telemetry systems that transmit the real-time rhythm data of cardiac patients directly to a centralized hospital facility.

2.6 ROBOTIC SURGERY AND ARTIFICIAL INTELLIGENCE

The medicine of the future is now focused on minimizing human error. Robotic arms, controlled by a surgeon from a console, operate with a level of precision and tremor-free movement that the human hand cannot replicate. This translates into smaller incisions, reduced blood loss, and accelerated patient recovery [20].

The benefits of robotic surgery include:

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■ **Haptic Feedback:** Can the surgeon sense the tissues while manipulating the robotic arms? Nowadays, there is much attention paid to tactile feedback technologies, which help the surgeon feel "resistance."

■ **Telesurgery:** The advent of 5G allows the surgeon to operate a robot thousands of miles away from the patient without it being a fiction.

Medical devices embody one of humanity's oldest ambitions: to compensate for the fragility of our biology through engineering. What began as simple instruments placed in the hands of physicians has, over the course of a few decades, grown into a vast ecosystem woven into everyday life. As a result, healthcare itself is shifting in character — moving away from a model built around managing disease after it appears, and toward one centred on personalised, preventive care. Artificial intelligence has accelerated this shift considerably. Algorithms can now scan thousands of radiological images within seconds, flagging micro-tumours so small that even an experienced radiologist might miss them on a first pass. Taken together, these developments mark a quiet but profound transformation: devices that once simply repaired the body are increasingly becoming systems that monitor it continuously, anticipate problems before they escalate, and operate almost as an extension of human biology itself.

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CHAPTER 3

MATERIALS AND INFRASTRUCTURE IN HEALTHCARE FACILITIES

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This chapter explains why stainless steel is one of the most important engineering materials used in hospital infrastructure. It discusses grades used in healthcare facilities, the comparison with copper, medical gas standards, welding, quality assurance and maintenance.

3.1 STAINLESS STEELS IN HEALTHCARE FACILITIES

Hospitals are among the most demanding engineered buildings. A modern hospital depends on a dense network of technical systems that must work continuously, safely and with very low tolerance for failure. Water, heating, ventilation, vacuum, sterilization steam, drainage, medical gases and digital monitoring infrastructure are not secondary services. They are part of the clinical



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chain, because failure in these systems can affect diagnosis, surgery, intensive care, infection control and patient comfort.

For this reason, the choice of materials in hospital infrastructure is not only a construction issue. It is also a safety issue, a maintenance issue and in many cases, a public health issue. Materials used in hospitals are exposed to cleaning agents, repeated disinfection, high humidity, temperature changes, aggressive local chemistries and strict hygiene routines. At the same time, these materials must remain easy to inspect, easy to clean and stable over long service periods.

Among the metallic materials used in healthcare facilities, **stainless steel** has a special place. It is widely used in pipework, sterilization systems, utility rooms, tanks, sinks, furniture, service panels, process equipment and many hygienic surfaces. Its value comes from a combination of corrosion resistance, mechanical strength, good cleanability and compatibility with high quality welding and fabrication methods [1-3].

Another key material is copper. Copper has long been used for medical gas pipelines and remains the reference material in many standards and hospital projects. It offers very good workability, strong tradition in gas installations and important antimicrobial behaviour at the surface [4,5]. The practical question for the healthcare engineer is therefore not whether one material is universally better than the other. The correct question is which material is more appropriate for a specific hospital service, under a specific standard, with a specific maintenance strategy.

This chapter focuses on stainless steel in hospital infrastructure. The focus is placed on building services and utility systems, not on implants or clinical instruments and it is sustained by the PowerPoint presentation (<https://www.smarthealtheng.com/training-documents.html>) [1].

3.1.1 Why Material Selection Matters in Hospital Engineering

A hospital contains multiple fluid and gas systems, but they do not all operate under the same risk profile. Potable cold water, domestic hot water, medical air, oxygen, vacuum, clean steam, condensate lines and process drains each have different demands. Some systems are sensitive mainly to corrosion. Others are sensitive mainly to contamination, leakage, or maintenance accessibility. In practice, material selection is therefore made by balancing several criteria at the same time.

The first criterion is patient safety. A material must not compromise the purity of the transported medium. For medical gases this is an obvious requirement, because the delivered gas reaches the patient directly. For hot water systems, the same principle appears in another form: material choice affects deposits, corrosion products and biofilm behaviour, all of which influence hygienic risk and operational reliability [6-9].

The second criterion is durability. Hospitals are expensive buildings and they are expected to remain in service for decades. Utility systems hidden in shafts, ceilings and plant rooms are difficult to replace once the building is operational. A low initial cost can become a poor decision if the selected material creates recurring shutdowns, leakage events, or premature replacement.

The third criterion is maintainability. Technical staff need systems that can be inspected, isolated, repaired, documented and returned to service without creating unacceptable risk. In some services, the best material is the one that gives the broadest safety margin during maintenance operations. This is particularly true in welded stainless steel process lines and in standardized copper medical gas systems, where installation practice, joint quality and traceability strongly affect life cycle performance [4,6,10-12].



The fourth criterion is hygiene. Stainless steel is not intrinsically antimicrobial in the same way as bare copper, but its smooth, compact and stable surface can be cleaned effectively. Cleanability is not a trivial property. Surface degradation, discoloration, pitting, roughening or poorly finished welds can reduce both aesthetic quality and hygienic performance. Recent work on stainless steel under hospital disinfection conditions shows that surface condition matters, because damage caused by repeated cleaning can change roughness and slow drying even before obvious structural failure occurs [13,14].

The fifth criterion is compatibility with fabrication. A good bulk material can perform poorly if it is joined badly. Stainless steel depends strongly on weld quality, shielding, cleanliness and post weld finishing. Copper depends strongly on correct brazing practice, cleanliness and protection of the internal bore during installation [2,4,15].

In healthcare engineering, the correct decision is therefore rarely based on a single property. It is based on the whole service environment. The engineer must ask: What is flowing in this line? What are the operating temperatures and pressures? What cleaning chemicals will be used nearby? What standard governs this service? How will the line be installed, inspected and repaired? Only after those questions are answered does material selection become technically correct.

3.1.2 Basic Metallurgy of Steels and Stainless Steels

Steel is an iron based alloy in which carbon and additional alloying elements are used to modify microstructure and properties. In a simple introductory classification, steels may be divided into low carbon, medium carbon and high carbon grades. As carbon content increases, hardness and strength tend to increase, but ductility and weldability often decrease. Ordinary carbon steel is

common in structural use but often less suitable for hygienic or corrosive services [1].

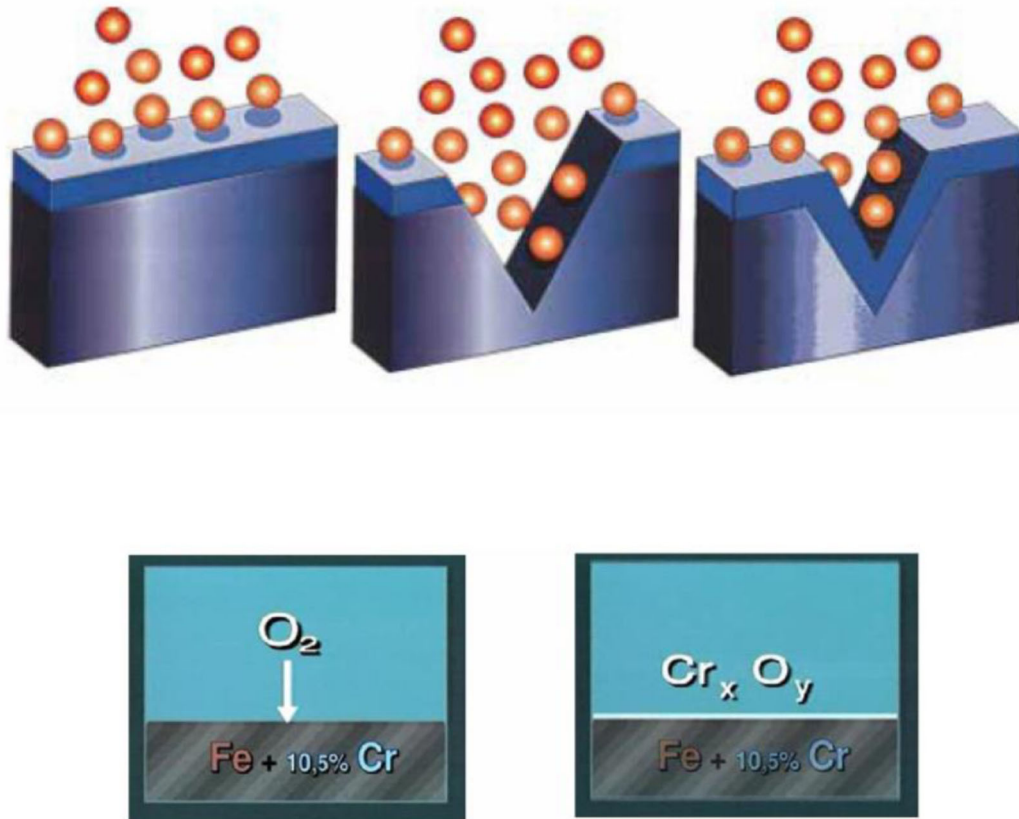


Figure 3.1. Formation of the oxide layer on the surface of stainless steel [3]

Stainless steel is not a single alloy. It is a family of corrosion resistant steels in which chromium is the key element. According to EN 10020 "stainless steels are steels with at least 10.5% of chromium and max. 1.2% of carbon". In practical terms, steels containing equal and more than 10.5% chromium can develop a stable passive oxide film on the surface. This film is thin, adherent and self renewing in the presence of oxygen. It is the reason stainless steel can resist many environments that would rapidly attack ordinary carbon steel (Figure 3.1) [1,2].

The passive behavior of stainless steel is very important for hospital applications. If a material is used around moisture, chlorinated cleaning agents,



disinfectants or hot water, the surface must remain stable enough for the system to keep its integrity and cleanable character. The passive layer does not make stainless steel immune to all damage, but it creates a much wider window of safe use.

Alloying additions further refine performance. Nickel stabilizes the austenitic structure and improves toughness and formability. Molybdenum increases resistance to localized attack, especially in chloride containing environments. Carbon strengthens the alloy but can create welding problems if present in excessive amount, because chromium carbides may form at grain boundaries during thermal cycles. This is why low carbon variants such as 316L are widely preferred when welding quality and corrosion resistance must be maintained after fabrication [2,3].

IMPORTANT: stainless steel performance is not determined only by the word "stainless". It is determined by composition, microstructure, surface condition, fabrication route and service environment. A poor choice of grade or a poor welding practice can reduce the advantage that the material would otherwise provide.

3.1.3 Stainless Steels Classification

Solid solutions α , having Body-Centered Cubic (BCC) structure, and γ , having Face-Centered Cubic (FCC) structure, comprising alloying elements in interstitial position (C and N) or substitution position (Cr, Ni, Ti) are the matrix of stainless steels. Interstitial and intermetallic phases and inclusions comprise minor constituents:

- interstitial phases:
 - the most common types of carbides are $M_{23}C_6$,

- $\text{Cr}_{23}(\text{B,C})_6$, Cr_{23}C_6 and Cr_{23}C_6 that can dissolve elements like Mo, Ni, V, W,
 - other chromium carbides (Cr_7C_3 , Cr_6C) and nitrides (CrN , Cr_2N),
 - the presence of Ti, Nb or Zr generates the formation of MX-type carbides, nitrides, or carbonitrides with FCC structure,
- intermetallic phases:
- the sigma phase (σ) having complex crystal network with chemical composition B_4A or BA_4 ,
 - the AB_2 type phase and the Laves (n) phase, when molybdenum (Fe_2Mo), niobium, titanium, tungsten etc. are present,
 - the intermetallic phase having electronic character (Hume-Rothery type) such as the χ phase, with an isomorphous crystallographic network.

According to EN 10088 the symbolization of stainless steels in Europe is: X + %C x 100 + AE (alloying elements) + % AE in order of symbols. Examples:

- X2CrNiMo17-12-2 SR EN 10088-2:2015 means stainless steel with chemical composition: C = 0.02 %, Cr = 17 %, Ni = 12%, Mo = 2 %.
- X8CrNi25-21 SR EN 10088-2:2015 means stainless steel with chemical composition: C = 0.08 %, Cr = 25 %, Ni = 21 %.

Stainless steel can be classified based on their chemical composition or crystal structure (Figure 3.2).

Ferritic stainless steels (400 series according to AISI) are usually chromium-containing alloys with BCC crystal structures. They have a Cr content of 13...17% and a C percentage of < 0.07%. Some grades may contain aluminum, molybdenum, niobium, silicon and titanium to obtain specific characteristics. Selenium or sulfur can be added to improve machinability.



The ferritic stainless steels are ferromagnetic. Because of BCC structure they have good ductility and formability, and their high-temperature strengths are not as good as those of the austenitic grades. In heavy sections and at low temperatures, toughness may be somewhat restricted. These steels are neither heat treatable, nor hardenable since their structure cannot be changed by heat treatment. They have a propensity for grain growth during heat treatment and welding, which causes cold brittleness in large cross-sections.

Stainless steels are usually grouped by their metallurgical structure. This structure controls many practical properties, such as corrosion behaviour, weldability, formability, magnetic response, thermal expansion and mechanical strength. In hospital infrastructure and technical equipment, this distinction is useful because the same name, stainless steel, can describe materials with very different behaviour.

A grade selected for a hygienic surface may not be suitable for a cutting tool. A steel used for a welded tank may not be the best choice for a spring, a surgical blade or a chloride-rich environment.

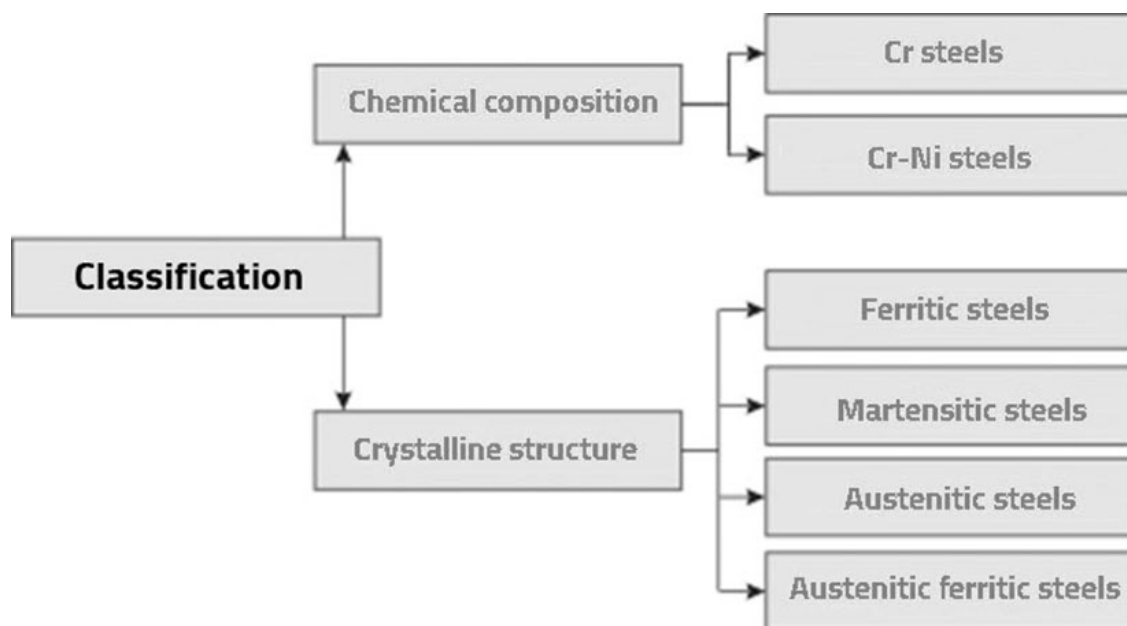


Figure 3.2. Classification of stainless steel

Ferritic stainless steels

Ferritic stainless steels are chromium-rich steels with a body-centered cubic structure. They contain little or no nickel, which makes them more economical than many austenitic grades. Their corrosion resistance is generally good, especially in mild atmospheric or indoor environments. For this reason, they are often considered for equipment, panels, covers, sinks, non-critical surfaces and other components where cost and corrosion resistance must be balanced.

A useful feature of ferritic stainless steels is their resistance to stress corrosion cracking. This is important in environments where austenitic steels may suffer cracking under the combined action of tensile stress and corrosive media. Ferritic grades are also magnetic. This property is sometimes useful for identification, although magnetic response alone should never be used as the only method for selecting a material.

Their thermal behaviour is also different from austenitic steels. Ferritic grades have a lower coefficient of thermal expansion and a higher thermal conductivity. In practical terms, they deform less during heating and cooling and can transfer heat more easily. These aspects can be useful in components exposed to temperature changes. At the same time, their welding behaviour needs attention. Thin sections can usually be welded with acceptable results, but thicker sections may become more difficult because of grain growth and reduced toughness in the heat affected zone.

Ferritic stainless steels cannot be strengthened by heat treatment. Their mechanical properties are mainly adjusted through composition, processing and cold work. They generally show good cold and warm formability, which helps in bending, drawing and shaping operations. Still, the final choice must consider the exact grade, thickness, service temperature and welding conditions.



Table 3.1 Practical property profile

Property	Practical meaning
Corrosion behaviour	Good corrosion resistance in many normal service conditions.
Stress corrosion cracking	Generally resistant, which is an advantage over several austenitic grades in specific environments.
Welding	Best suited for thin sections. Welding of thicker parts needs careful procedure control.
Formability	Good cold and warm formability for many sheet and light structural applications.
Magnetism	Magnetic because of the ferritic structure.
Heat treatment	Cannot be hardened by conventional heat treatment.
Thermal behaviour	Low thermal expansion and high thermal conductivity.
Cost	Usually more economical than austenitic stainless steels because of the low nickel content.

Martensitic Stainless Steel

Martensitic stainless steels are iron-chromium-carbon alloys. In the AISI system, they are mainly included in the 400 series. After hardening, their structure becomes body-centered tetragonal. This structure appears when carbon-containing ferritic steel is rapidly cooled from the austenitizing temperature. The result is a hard material. If it is left directly after quenching, it is also brittle.

Tempering is therefore necessary. It reduces brittleness, improves stability and makes the steel easier to machine and use. Without this step, martensitic stainless steels can be sensitive to cracking, especially when internal stresses

remain after heat treatment. Their main advantage is the possibility of obtaining high hardness and good wear resistance while keeping a useful level of corrosion resistance. Their weakness is toughness, especially at low temperature, where they perform less well than austenitic steels.

These steels are ferromagnetic. Their chromium content is commonly between 10.5 and 18 percent. Carbon may exceed 1.2 % in some grades, especially when high hardness and wear resistance are required. Carbon and chromium must be balanced carefully.

The composition must allow martensite to form after hardening, while still keeping enough chromium in solid solution for corrosion resistance. In grades used for cutting edges, extra carbides may be intentionally present. They help maintain sharp edges and increase resistance to wear. Other elements can be added to control the response after hardening and tempering. Niobium, silicon, tungsten and vanadium are examples. Small nickel additions may improve toughness and corrosion resistance in selected environments. Sulfur or selenium can be added in some grades when easier machining is required, although this may influence corrosion behaviour and toughness.

Table 3.2 Practical property profile

Property	Practical meaning
Corrosion behaviour	Good corrosion resistance, but usually lower than highly alloyed austenitic or duplex grades.
Stress corrosion cracking	Normally not considered highly susceptible.
Welding	Weldable only with care. Preheating, controlled cooling and post-weld heat treatment may be needed.



Formability	Moderate hot and cold formability compared with ferritic and austenitic grades.
Magnetism	Magnetic.
Heat treatment	Can be hardened by heat treatment, followed by tempering.
Thermal behaviour	Low thermal expansion and high thermal conductivity.
Cost	Usually more economical than austenitic stainless steels.
Machining	Many grades can be machined well, especially when modified with sulfur or selenium.

Austenitic Stainless Steels

Austenitic stainless steels have a face-centered cubic structure. This structure is stabilized by alloying elements such as nickel, manganese and nitrogen. According to the AISI designation, chromium-manganese austenitic steels belong mainly to the 200 series, while chromium-nickel austenitic steels belong to the 300 series.

These steels are widely used because they combine high corrosion resistance, good forming behaviour and excellent toughness.

Austenitic grades cannot be hardened by heat treatment. Their strength can be increased by cold working. In the annealed condition they are usually almost non-magnetic, although some grades may become slightly magnetic after cold deformation. They also keep good toughness at very low temperatures, which makes them useful in cryogenic service. At the other end of the temperature

range, several grades also show good resistance to elevated temperature and oxidation when the composition is suitable.

The typical chromium content is about 16 to 26 percent. Nickel may reach approximately 35 percent in highly alloyed grades, while manganese can reach about 15 percent in some compositions. Steels from the 200 series usually contain lower nickel, often up to about 7 percent, with manganese in the range of 4 to 15.5 percent and additions of nitrogen. The 300 series usually contains up to about 2 percent manganese and higher nickel contents, which help maintain the austenitic structure and improve corrosion resistance.

Additional alloying elements are used when special properties are needed. Molybdenum improves resistance in chloride-containing environments. Titanium and niobium can be used to stabilize the steel against sensitization in specific conditions. Copper, aluminum and silicon may be added for selected corrosion or oxidation requirements. Sulfur or selenium may be added when better machinability is needed, but this choice must be made carefully because it can reduce some corrosion and toughness properties.

Table 3.3 Practical property profile

Property	Practical meaning
Corrosion behavior	Very good corrosion resistance in many environments, depending on grade and alloying level.
Stress corrosion cracking	Can be susceptible, especially in chloride-containing environments and at elevated temperature.
Welding	Generally easy to weld, with suitable filler metal and control of sensitization risk where needed.
Formability	Very good hot and cold formability.
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Magnetism	Usually non-magnetic in the annealed state. Cold work may produce some magnetic response.
Heat treatment	Cannot be hardened by heat treatment. Strength increases through cold working.
Thermal behaviour	Higher thermal expansion and lower thermal conductivity compared with ferritic steels.
Toughness	Excellent toughness, including at low and cryogenic temperatures.

Duplex Stainless Steels

Duplex stainless steels contain two phases: austenite with a face-centered cubic structure and ferrite with a body-centered cubic structure. Their properties come from the balance between these two phases. The exact proportion depends on the chemical composition and on the heat treatment. Many commercial duplex grades are designed to contain approximately equal amounts of ferrite and austenite after annealing.

Chromium and nickel are the main alloying elements, but the composition is adjusted with other additions. Molybdenum and nitrogen are often used to increase resistance to localized corrosion, especially in chloride-containing environments. Copper, silicon and tungsten may also be added in selected grades to adjust structure or improve corrosion performance. The balance must be controlled carefully because too much ferrite or too much austenite can reduce the expected combination of properties.

Duplex steels can offer corrosion resistance similar to austenitic grades with comparable alloying levels. Their major advantage is mechanical strength. They

usually have higher yield strength and tensile strength than austenitic stainless steels. They also show better resistance to stress corrosion cracking, especially in chloride environments. This makes them attractive for water systems, chemical equipment, heat exchangers and other installations where strength and corrosion resistance are both needed.

Their toughness is generally between that of austenitic and ferritic stainless steels. They can be welded, but welding must preserve the correct phase balance. Heat input, cooling rate and filler metal selection are important. If the procedure is not controlled, the weld and heat affected zone may lose part of the duplex advantage. Duplex steels are magnetic because of their ferrite content and they cannot be hardened by heat treatment.

Table 3.4 Practical property profile

Property	Practical meaning
Corrosion behaviour	Very good corrosion resistance, often close to austenitic grades with similar alloying content.
Stress corrosion cracking	Good resistance, especially compared with many austenitic steels.
Welding	Generally weldable, but phase balance must be controlled.
Formability	Moderate hot and cold formability.
Structure	Mixed ferrite and austenite structure, often close to a 50:50 balance after annealing.
Heat treatment	Cannot be hardened by heat treatment.
Thermal behaviour	Moderate thermal expansion and moderate thermal conductivity.
Magnetism	Magnetic because of the ferrite phase.



Chloride resistance

Good resistance to chloride-induced corrosion and stress corrosion cracking when the grade is correctly selected.

Ferritic steels are useful when good corrosion resistance, magnetic behaviour, low thermal expansion and moderate cost are required. Martensitic steels are selected when hardness, wear resistance and heat treatability are important. Austenitic steels remain the common choice for many hygienic and corrosion-resistant applications because they form and weld well and keep excellent toughness. Duplex steels are chosen when higher strength and chloride resistance are needed. The best choice is always linked to the exact environment, fabrication route, cleaning procedure, welding requirements and expected service life.

3.1.4 Main Steel Grades and Their Relevance to Hospitals

The most important stainless steel grades are ferritic, martensitic, austenitic and duplex grades. For hospital infrastructure, austenitic stainless steels are the most relevant because they combine good corrosion resistance, good toughness and good weldability [1,2,3].

Ferritic stainless steels contain chromium but little or no nickel. They are often less expensive and may be satisfactory in moderately corrosive indoor environments, for example decorative panels or some kitchen related components. However, they are generally not the first choice for critical hygienic pipelines.

Martensitic grades contain more carbon and can be hardened. They are useful where higher hardness is needed, but they are less central to building utility

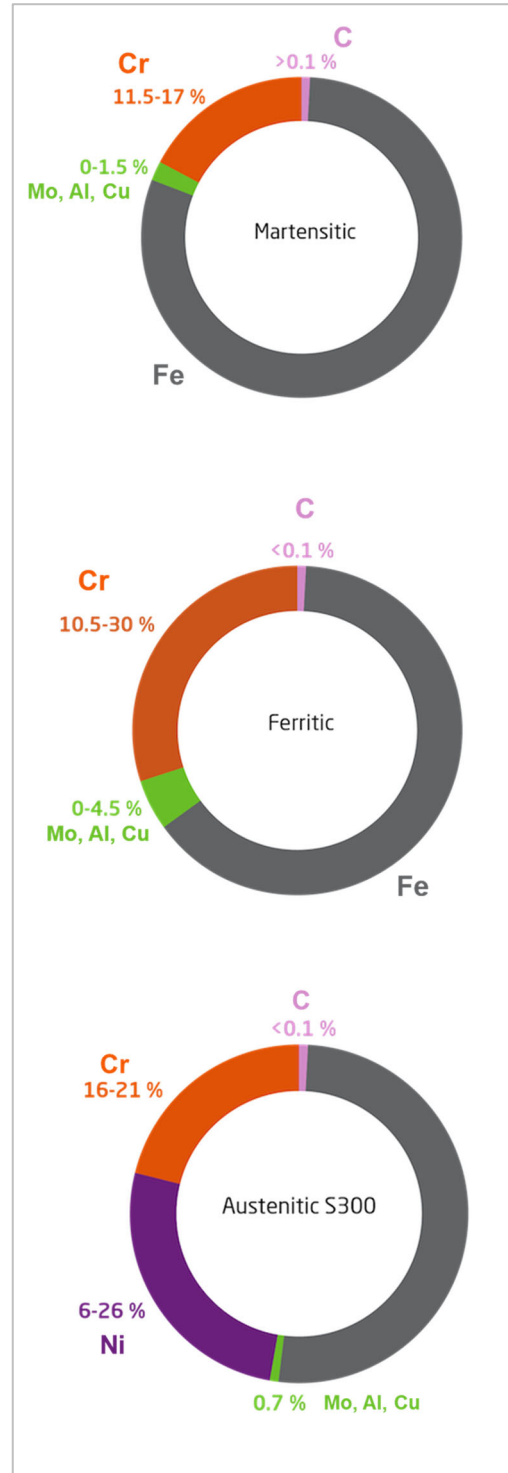
systems and are more commonly associated with tools and components requiring wear resistance.

Austenitic grades, especially 304, 316 and 316L, dominate in healthcare utilities. They remain ductile, are easy to form and support high quality welded joints when good practice is followed. Duplex grades offer high strength and good corrosion resistance, but in hospital infrastructure they are used less often than in highly aggressive industrial sectors. Their use may still be justified in special water systems or plant areas, but they are not the standard educational starting point for healthcare engineers [2,16].

In practice, four grades are especially useful to be recognized. AISI 304 is a common all purpose austenitic grade with good corrosion resistance and excellent fabricability. AISI 316 contains molybdenum and is therefore more resistant in chloride bearing environments.

AISI 316L is the low carbon version of 316 and is particularly attractive when welded hygienic systems are required. AISI 430 is

a ferritic grade that may be used in less severe indoor applications where cost must be controlled [1].



Element	S355 (%)	AISI 304 (%)	AISI 316 (%)	AISI 316L (%)	AISI 430 (%)
Carbon (C)	≤ 0.23	≤ 0.08	≤ 0.08	≤ 0.03	≤ 0.12
Chromium (Cr)	0.3 max	18.0 - 20.0	16.0 - 18.0	16.0 - 18.0	16.0 - 18.0
Nickel (Ni)	-	8.0 - 10.5	10.0 - 14.0	10.0 - 14.0	≤ 0.75
Manganese (Mn)	≤ 1.6	≤ 2.0	≤ 2.0	≤ 2.0	≤ 1.0
Silicon (Si)	≤ 0.55	≤ 0.75	≤ 0.75	≤ 0.75	≤ 1.0
Phosphorus (P)	≤ 0.045	≤ 0.045	≤ 0.045	≤ 0.045	≤ 0.04
Sulfur (S)	≤ 0.045	≤ 0.030	≤ 0.030	≤ 0.030	≤ 0.03
Molybdenum (Mo)	-	-	2.0 - 3.0	2.0 - 3.0	-
Nitrogen (N)	-	≤ 0.10	≤ 0.10	≤ 0.10	-
Copper (Cu)	≤ 0.55	-	-	-	-
Iron (Fe)	Balance	Balance	Balance	Balance	Balance

Figure 3.3 Chemical composition overview of common stainless steel compared with S235 carbon steel

Table 3.5. Role of common stainless steel grades in hospital infrastructure

Grade	Main alloy idea	Typical hospital use	Comment
AISI 304	Cr-Ni austenitic	general water lines, furniture, sinks, counters	good general purpose grade
AISI 316	Cr-Ni-Mo austenitic	hot water plant, aggressive cleaning environments, some process services	better chloride resistance
AISI 316L	Low carbon 316	welded hygienic systems, sterile services, equipment interfaces	better after welding
AISI 430	ferritic Cr steel	panels, kitchen components, less severe indoor locations	Cost effective but less versatile

3.1.5 Applications of Stainless Steel in Modern Hospital Facilities

Stainless steel is one of the most used engineering materials in modern hospitals. Its value comes from a combination of corrosion resistance, mechanical strength, cleanability, formability and long service life. The material is present in visible elements, such as instruments, trolleys, tables and

handrails, but also in technical systems that patients rarely see. These include sterilization units, laboratory benches, duct components, support structures, cabinets, drains and parts of diagnostic equipment [17-21].

The use of stainless steel in hospitals should not be treated as a general choice of a single material. Different applications require different grades and surface conditions. Surgical cutting instruments need hardness and edge retention.

Implantable devices

need high purity, corrosion resistance and biological evaluation. Hospital furniture and fixed infrastructure need smooth surfaces, good weld quality and resistance to cleaning products. In many cases, the same hospital contains martensitic, austenitic, ferritic and precipitation-hardening stainless steels, each selected for a specific role. Standards for surgical instruments and metallic materials define this approach and show that the selection must be linked to the final use [22, 23].

In a practical hospital environment, the material is also part of infection prevention. A surface that is smooth, intact and compatible with repeated cleaning is easier to manage. However, stainless steel is not automatically safe

Stainless steel in hospitals

- 1. Corrosion Resistance:** Exceptional resistance to corrosion.
- 2. Mechanical strength and durability:** Stainless steel exhibits high tensile strength and can endure the wear and tear of daily use in a hospital setting,.
- 3. Hygienic properties:** Smooth and non-porous surface of stainless steel prevents the accumulation of dirt, bacteria, and other pathogens.
- 4. Biocompatibility:** Stainless steel, particularly certain grades like 316L, is biocompatible, meaning it is not harmful or toxic to living tissue.
- 5. Thermal conductivity and stability:** Stainless steel is capable to distribute heat evenly.



only because it is stainless. It can be scratched, contaminated, corroded by aggressive chemicals or damaged by poor design. The engineering task is therefore to select the correct grade, finish, joining method and maintenance route for each application. This subchapter presents the main categories of stainless-steel use in hospitals and connects them with technical and clinical requirements.

Surgical instruments and reusable devices

The most classical hospital application of stainless steel is the surgical instrument. Scalpels, forceps, clamps, retractors, scissors, needle holders, dental instruments and many reusable accessories must combine precision with mechanical durability. Instruments with cutting edges usually require martensitic stainless steels, because they can be heat treated to reach high hardness.

Handles, non-cutting components and some complex instruments may use austenitic grades when corrosion resistance and toughness are more important than edge retention. The standardization of metallic materials for surgical instruments is important because the word surgical steel alone does not define a safe material [22, 23].

The design of a surgical instrument must take into account repeated use. During its life cycle, the instrument is exposed to blood, saline, alkaline detergents, water, steam sterilization, mechanical handling and sometimes disinfectants. A good alloy cannot compensate for poor geometry. Hinges, serrations, box joints and narrow gaps can retain residues and moisture. These areas are difficult to inspect and can become the starting point for corrosion or contamination. For this reason, the instrument has to be evaluated as a complete system: alloy, heat treatment, surface finish, geometry and cleaning procedure.

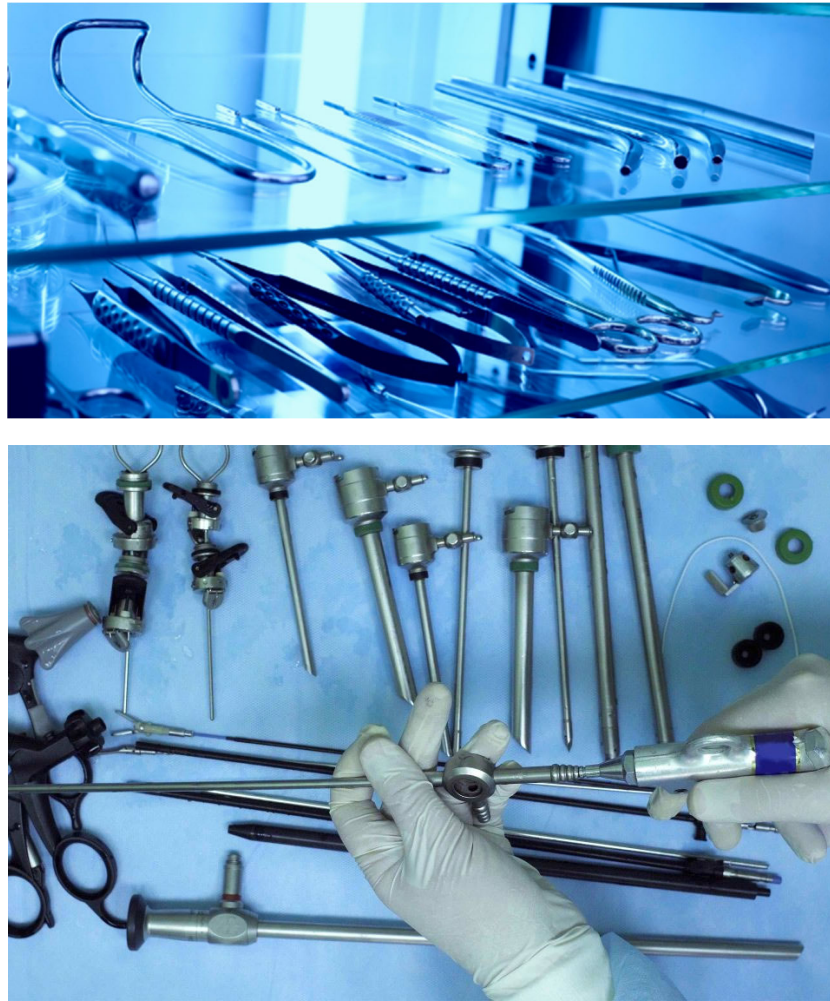


Figure 3.4 Stainless steel reusable devices [24, 25]

Reprocessing is a central part of the material selection problem. World Health Organization [WHO] guidance on decontamination and reprocessing shows that safe reuse of medical devices depends on correct cleaning, disinfection, sterilization, storage and transport [26]. Center for Disease Control [CDC] guidance also separates critical, semi-critical and non-critical devices and links the required level of processing to patient-contact risk [27]. Surgical instruments normally belong to the critical group, because they enter sterile tissue or the vascular system. For these devices, steam sterilization is common, but cleaning before sterilization is equally important. Organic residues can protect microorganisms and may also accelerate local corrosion.



From an engineering point of view, instrument maintenance should include visual inspection, functional testing and corrosion control. Brown or black spots on stainless steel instruments are often interpreted by users as rust, but the cause can be more complex. It may involve residues, water quality, chloride contamination, inappropriate detergents, damaged passivation or contact with carbon steel. The correct response is not the replacement. The technical team must identify the mechanism, verify the washing and sterilization route and check whether similar instruments show the same damage. This is a practical example where materials knowledge directly supports patient safety.

Implants and temporary fixation devices

Stainless steel is also used in surgical implants, but this application needs more caution than external instruments or furniture. Implant-grade stainless steel is a specific material class. It is not equivalent to general 304 or 316 stainless steel used in common equipment. ISO 5832-1 specifies wrought stainless steel for surgical implants and identifies requirements that are linked to composition, mechanical properties and test methods [28]. ASTM F138 and ASTM F139 cover wrought 18Cr-14Ni-2.5Mo stainless steel bar, wire, sheet and strip for surgical implants, corresponding to UNS S31673 [29, 30]. These standards are important because implants remain in contact with tissue and body fluids and may be loaded for long periods.

The most common implant applications include bone plates, screws, intramedullary nails, spinal rods and some cardiovascular components. Stainless steel is especially useful for temporary fixation, where the device is removed after healing. It provides good strength, established processing routes and lower cost compared with some other implant alloys. It is also easier to machine than many cobalt-based alloys. In trauma surgery, these advantages

are important because implants must be available in many sizes and geometries.

The main limitations are linked to corrosion, fatigue and biological response. The chloride-rich environment of the human body can challenge the passive film, especially in crevices, under screw heads or at modular connections. Nickel is part of many austenitic stainless steels and must be considered in biological evaluation. ISO 10993-1 requires the biological safety of medical devices to be evaluated within a risk management process [31]. In the European Union, the Medical Device Regulation also requires a structured approach to safety, performance, risk management and post-market surveillance [32]. This means that implant selection is not a simple material choice. It is part of device design, clinical indication and regulatory control.



Figure 3.5 Stainless steel orthopedic implants [33]

Surface finishing is very important for implant-grade stainless steel. Polishing, electropolishing and passivation reduce roughness and improve the stability of the surface oxide. In small components, such as coronary stent struts, surface defects can influence fatigue behaviour, corrosion and thrombogenic response.



The surface must be smooth and free from embedded contamination. Any manufacturing step that changes the passive layer has to be controlled. Welding, laser cutting, grinding and heat treatment can introduce local changes that require careful post-processing.

Hospital equipment and furniture

Stainless steel is widely used in equipment that supports clinical work but does not always enter the patient directly. Operating tables, instrument trolleys, carts, IV poles, sinks, bed frames, cabinets, autoclave chambers, sterilization baskets and trays are typical examples. In these applications, cleanability is often as important as strength.



Figure 3.6 Various equipment made by stainless steel [34]

A surface that can be cleaned quickly and repeatedly reduces the burden on staff and helps maintain routine hygiene. WHO environmental cleaning guidance

emphasizes that cleaning programmes must be adapted to the risk level of the area, the type of surface and the healthcare activity.

Equipment used in operating rooms, intensive care units, laboratories and sterilization departments must resist frequent cleaning and disinfection. Stainless steel supports this requirement because it tolerates many detergents and disinfectants better than painted steel, wood or low-grade plastics. It also has good mechanical resistance. Trolleys are pushed, hit, washed and loaded every day. Sinks, scrub stations and benches are exposed to water, disinfectants and mechanical abrasion. If a material fails in these areas, the problem is more than an aesthetic issue. Damaged surfaces become harder to clean and can create maintenance costs.

The selection must still be realistic. Some disinfectants are aggressive to stainless steel, especially when contact times are long, concentrations are excessive or residues are not rinsed. Studies on bleach disinfectant wipes have shown that commonly used hospital products can create corrosive damage on stainless steel surfaces. More recent work on AISI 420 used in medical applications showed that surface finish affects stability under long-term cleaning, disinfection and sterilization [35]. These studies are important for hospital engineers because cleaning policy and material durability are connected. Infection control and corrosion control should not be managed as separate problems.

Good equipment design avoids sharp corners, open threads, deep crevices and inaccessible joints. Welds should be continuous and smooth when they are located in wet or high-risk areas. Bolted connections may be needed for repair, but they should not create dirt traps. For movable equipment, engineers should also consider the compatibility between stainless steel frames, polymer wheels,

rubber seals, bearings and electronic components. The surface that looks easiest to clean may hide mechanical parts that retain moisture or residues.

Diagnostic tools, probes and technical devices

Diagnostic and monitoring equipment also contains stainless steel. The material appears in probe housings, endoscope components, guide tubes, needle electrodes, sensor supports, connectors and protective covers. The role is not always structural. In some devices stainless steel gives dimensional stability, supports sterilization or protects sensitive components from mechanical damage. In others, it provides electrical conductivity or a stable metallic surface for contact with the patient.



Figure 3.7 Technical devices with stainless steel frames [36]

This application group is more diverse than surgical instruments. A diagnostic device may contain stainless steel next to polymers, ceramics, copper alloys, optical fibres, electronic boards and sealing materials. The engineer has to consider the complete device. A stainless-steel housing can resist cleaning, but

the gasket or adhesive may not. A probe may tolerate high-level disinfection, while an internal sensor may be damaged by heat or moisture. This is why the processing instructions from the device manufacturer must be respected. The hospital engineer should not assume that every metallic diagnostic component can be sterilized in the same way as a simple instrument.

Magnetic and imaging compatibility must also be considered. Austenitic stainless steels are usually less magnetic than martensitic grades, but cold work or welding can increase magnetic response. In imaging rooms, the material selection must consider magnetic field safety, X-ray attenuation, electrical noise and the need for cleaning. Stainless steel can be appropriate for many supports and accessories, but it is not the correct answer in every diagnostic environment. For high-field MRI areas, non-magnetic materials and strict safety control are needed.

In smart healthcare systems, stainless steel can also support sensors and monitoring elements. It can be used as a stable substrate, connector, casing or electrode material. The important point is that a smart device still needs a reliable physical surface. Data quality depends on contact stability, cleaning compatibility and mechanical protection. Poor material selection can create signal noise, corrosion, leakage or premature failure. For this reason, digital healthcare must remain connected to materials engineering.

Fixed hospital infrastructure

Beyond devices and equipment, stainless steel forms part of the fixed infrastructure of the hospital. It is used for wall cladding and splashbacks in sterile areas, laboratory benches, scrub stations, sinks, drains, handrails, door furniture, ventilation elements, support frames and technical room components. In these locations, the hospital engineer is usually concerned with hygiene,



chemical resistance, service life and maintenance access. The material has to survive many years of cleaning, moisture, impact and repairs.

The value of stainless steel in infrastructure is strongest in areas where surfaces are wet, frequently touched or repeatedly cleaned. Laboratories, CSSD areas, operating departments, kitchens, laundries, pharmacies and water-treatment rooms are typical examples. A smooth stainless-steel worktop can support routine disinfection and resist splashes better than many painted or laminated materials. Stainless cladding can protect walls near scrub stations, sinks and technical equipment. Handrails and door furniture need enough resistance for continuous contact and cleaning.



Figure 3.8 Stainless steel pipes in the healthcare facilities [37]

Ventilation and air-handling systems also include metallic components exposed to air, condensate and cleaning operations. The detailed requirements for healthcare ventilation are covered by specialist standards and guidelines. ASHRAE/ASHE Standard 170 provides ventilation requirements for healthcare facilities and has been updated in the 2025 edition to include changes related to natural ventilation, imaging rooms, filtration testing and other healthcare space requirements [14]. Stainless steel may be selected for some ductwork, drain pans, supports or components when corrosion risk, cleanability or water exposure justify the cost. In other areas, galvanized steel, coated steel or aluminium may be sufficient. The decision should follow risk, not habit.



Figure 3.9 Stainless steel enclosures for power distribution [38]

Infrastructure details often decide the success of stainless steel. A good grade used with poor detailing can still fail. Water must not remain trapped around welds, brackets or floor transitions. Dissimilar-metal contacts should be controlled, especially in wet environments. Mechanical polishing should avoid



contamination with carbon steel particles. In high-chloride or chemically aggressive areas, grade 316 or more resistant alloys may be needed instead of grade 304. In some technical rooms, stainless steel is selected less for appearance and more for predictable ageing.

Relation with antimicrobial materials and surface engineering

Stainless steel is durable and cleanable, but it is not a strongly antimicrobial material by itself. Microorganisms can survive on stainless-steel surfaces if cleaning is insufficient. For this reason, the material must be part of a wider infection-prevention strategy. This includes correct surface design, cleaning procedures, staff training, monitoring and timely replacement of damaged components. Antimicrobial coatings and surface technologies have been proposed as additional tools for environmental surfaces in hospitals, but their performance depends on durability, cleaning compatibility, safety and real clinical use [39].

Copper alloys are often discussed as an alternative for high-touch surfaces because copper can have direct antimicrobial activity. Reviews in the hospital infection literature note that copper has potential for infection prevention, but also that wider routine implementation requires careful evaluation of evidence, cost, maintenance and compatibility with clinical practice [40]. This does not reduce the value of stainless steel. It shows that material selection in hospitals must be application-specific. Stainless steel remains suitable where mechanical surface resistance, corrosion resistance and cleanability are the main requirements. Copper or coated surfaces may be considered where antimicrobial activity is the main design objective.

Surface engineering can improve some stainless-steel applications. Electropolishing, passivation, mechanical polishing, **laser texturing**, coatings and

antimicrobial layers can modify roughness, corrosion resistance or biological behaviour. These treatments are useful only when they are validated for the intended use. A coating that works in the laboratory may fail after repeated cleaning or mechanical impact. A very smooth surface may be easy to clean but more vulnerable to visible scratching. The engineer must balance hygiene, durability, cost and maintenance.

Practical selection guidance for hospital engineers

The first selection question is the type of contact. A stainless-steel part may contact sterile tissue, intact skin, staff hands, cleaning chemicals, water, air or no clinical environment at all. Each situation has a different risk. Implantable and invasive devices require medical-device standards, traceability and biological evaluation. Reusable surgical instruments require validated reprocessing. Environmental surfaces require cleanability and compatibility with the local cleaning protocol. Fixed infrastructure requires durability and ease of maintenance.

The second question is the environment. Blood, saline, chloride residues, cleaning agents, humidity, steam and mechanical wear can all change the surface condition. Stainless steel relies on a passive chromium-rich oxide layer. If this layer is damaged, contaminated or kept under deposits, local corrosion can start. Good practice therefore includes suitable water quality, correct detergent concentration, rinsing where required, drying, inspection and avoiding contact with carbon steel tools during fabrication or maintenance.

The third question is the surface finish. Rough surfaces retain soil and are more difficult to clean. Mirror-like surfaces look clean but may show scratches and fingerprints. Brushed surfaces are common in hospital furniture, but the direction and roughness must not create cleaning problems. For instruments



and implants, finish requirements are more strict and may include electropolishing or passivation. For infrastructure, the finish should match the cleaning method and expected damage level.

The fourth question is joining. Welded stainless steel must be made with appropriate filler, heat input and shielding. Heat tint, lack of passivation, crevices and poor grinding can reduce corrosion resistance. In hospital applications, the weld is often the weakest visible point. This is important for sinks, tables, handrails, racks, support frames and stainless panels. Engineers should specify continuous welds where hygiene is important and should avoid rough grinding marks in areas that are cleaned every day.

The final question is maintenance. Stainless steel has a long service life, but it is not maintenance-free in the hospital environment. Technical staff should inspect for pits, rust-like staining, broken welds, sharp edges, loose fittings and areas that cannot be cleaned. When a defect appears, the decision should consider the function of the component and the risk level of the area. A stain on a technical-room bracket is not the same as corrosion on a surgical instrument or a scrub station. The engineering response must be proportional to the clinical risk.

Quality control and documentation

The use of stainless steel should be documented in the same way as other technical decisions in a hospital. For critical and semi-critical devices, the grade, manufacturer, processing route and cleaning instructions must be known.

For fixed infrastructure, the documentation should include the specified grade, surface finish, welding requirements and maintenance recommendations. This information is useful when a defect appears after several years, without it, staff

can only guess whether the problem comes from the material, the cleaning product, the water quality or the fabrication route.

A simple inspection sheet can be used during routine technical rounds. It may include visible corrosion, staining, cracks, sharp edges, loose elements, damaged welds, areas with retained water and components that are difficult to clean. The same sheet can also record corrective actions. This type of documentation helps the facility manager to connect material performance with cleaning practice and user feedback. It also gives students a clear example of how materials engineering becomes part of hospital quality management.

3.1.6 Stainless Steel Versus Copper in Hospital Facilities

The comparison between stainless steel and copper is especially important for healthcare engineers because both materials are present in hospital utility systems and both have strong technical arguments in their favor.

Copper has a long history in medical gas pipelines. Standards, installation practices and contractor experience are well developed around copper tube systems [4]. Copper is easy to form, easy to cut and easy to join by brazing. Its thermal conductivity is high and its natural antimicrobial behaviour is a recurring advantage in hospital discussions [5,20,21]. Copper surfaces can reduce microbial burden under certain conditions, which is why copper and copper based materials continue to attract interest for high touch surfaces and some water related applications.

At the same time, copper is a softer metal. It is generally easier to deform mechanically and in some plant applications it may not offer the same structural stiffness as stainless steel. Copper systems also depend on very good brazing practice. A poorly cleaned or poorly protected joint can still become a point of weakness. In addition, material interactions, stagnation and water chemistry

matter. Studies on building water systems show that pipe materials can influence biofilm formation and Legionella behaviour in complex ways, so no simple rule such as "copper always solves the hygiene problem" is technically sound [7,17,41].

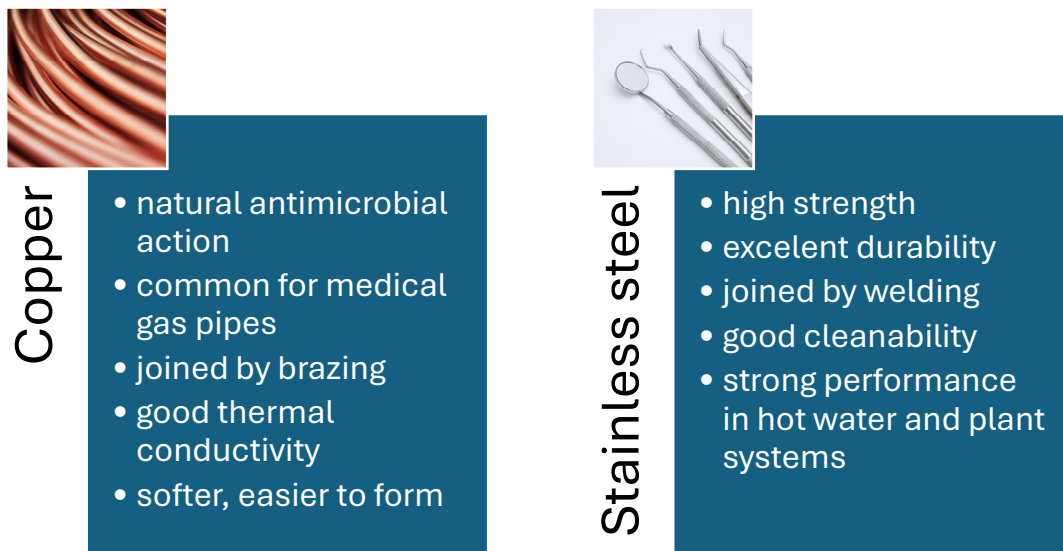


Figure 3.10. Comparison between copper and stainless steel in hospital services.

Stainless steel offers a different performance package. It is stronger, stiffer and often preferred where high durability, stable surface finish and welded hygienic construction are required. It is attractive for process pipework, hot water plant sections, tanks and equipment interfaces. In chlorinated or disinfected environments, the right stainless steel grade may offer very good life cycle performance, although surface finish and maintenance still remain important [13,14].

In medical gas systems, copper remains dominant in many regions because it aligns directly with established standards and industry practice [4,6]. Stainless steel may still be used in selected systems or special applications, but the design team must confirm compliance with local codes, accepted installation procedures, cleaning requirements and commissioning practice.

Table 3.6. Comparison between copper and stainless steel in hospital infrastructure

Criterion	Copper	Stainless steel
Common use	medical gas pipelines, selected high touch surfaces	water plant sections, process pipework, sterile services, hygienic fittings
Joining method	usually brazing	usually welding, often TIG or orbital TIG
Mechanical behaviour	softer, easier to form	stronger and stiffer
Hygiene related aspect	intrinsic antimicrobial behaviour at the surface	good cleanability and stable finish when correctly maintained
Key design note	highly standardized in gas networks	excellent where welded durability and stable plant room performance are needed

Important: Copper is often preferred where medical gas tradition, brazed tubework and antimicrobial arguments are strong. Stainless steel is often preferred where structural rigidity, welded hygienic construction, high durability and broad plant room compatibility are decisive. The best choice depends on the service, not on fashion.

3.1.7 Medical gas pipeline systems and the standards framework

Medical gas systems are critical utility systems. They distribute gases such as oxygen, medical air, nitrous oxide, carbon dioxide and sometimes specific mixtures, as well as vacuum and scavenging services. These systems feed operating theatres, intensive care units, recovery areas and many other clinical spaces. Because the delivered medium is directly linked to patient care, standards are essential [4].

ISO 7396-1 defines requirements for design, installation, function, performance, testing, commissioning and documentation of pipeline systems for compressed medical gases and vacuum in healthcare facilities [4]. The standard does not merely describe materials. It addresses the system as a safety critical whole, including supply sources, distribution lines, monitoring, alarms, shut off devices, identification and commissioning logic.



For copper tube systems, EN 13348 defines the tube requirements for medical gases or vacuum [6]. This standard is important because it supports the traceability and cleanliness expectations needed in medical applications. It reflects the fact that not every copper tube used in construction is suitable for a healthcare gas pipeline.

A key educational point is that standards are not optional references that are checked only at the end of the project. They shape material choice from the beginning. If a hospital plans a new oxygen pipeline, the material, joining process, cleaning protocol, pressure tests, labeling and alarm strategy must all fit the standard framework. The same principle applies during renovation. A shutdown or extension of an existing gas system must be planned carefully to avoid creating clinical risk [10,11].

Published incident reports and safety discussions show why this discipline matters. Medical gas misconnections, supply interruptions and poorly managed shutdowns can become life threatening events [10,11]. In a well managed hospital, pipeline work is therefore treated as a controlled engineering activity with strong documentation, isolation procedures, revalidation and multidisciplinary communication.

Important: medical gas systems are where materials science, welding or brazing technology, standards and clinical safety meet most visibly. The service may look like simple pipework, but in reality it is one of the most tightly controlled technical systems in the hospital.

When stainless steel is selected for hospital pipework, the success of the system depends on more than the alloy grade. Design detail matters. Pipe routing, slope, dead legs, supports, thermal expansion, insulation, accessibility, valve arrangement and drainability all influence performance. The first design principle is service clarity. Engineers should define exactly what the line will carry

and under which operating conditions. A line carrying softened hot water, a line carrying clean steam and a line connected to a sterilizer do not have the same thermal, chemical, or hygienic requirements. Good design begins with correct classification.

The second principle is hygienic geometry. Where cleanliness matters, dead ends should be minimized, internal surfaces should be smooth and areas that trap moisture or deposits should be avoided. Although this is more often emphasized in pharmaceutical design, the same logic is useful in hospital process and utility services.

The third principle is support and expansion control. Stainless steel has a coefficient of thermal expansion that must be considered, especially in hot water and steam related systems. Poorly designed supports can create stress at joints and equipment nozzles. In long runs, expansion loops, flexible sections, or appropriately placed anchors may be necessary.

The fourth principle is material continuity. Mixed material systems can be necessary, but they should be introduced carefully. The engineer must consider differential expansion, galvanic effects where relevant, joint quality and maintenance compatibility. A visually neat installation is not enough. It must also behave well over time.

The fifth principle is inspection access. One of the most common practical mistakes in building services is to hide critical joints in places where they cannot be inspected without removing major building finishes. In hospitals, where downtime is costly, maintainability is a design variable from day one.

IMPORTANT: It does not matter if the pipe material is excellent but the routing creates stagnant pockets, if the welds are good but the supports allow vibration, or if the plant room is durable but inaccessible, the installation is still incomplete from an engineering point of view.

3.1.8 Welding and joining methods

Hospital utility systems use both welding and brazing, but the method depends on the material and service. Stainless steel systems are generally welded. Copper medical gas systems are generally brazed [1,4].

Welding creates a permanent metallurgical joint through local fusion of the base material, often with the aid of filler metal and shielding gas. It is strong and well suited to stainless steel process pipework, especially when tube alignment, purge protection and welder qualification are properly controlled.

Brazing joins metals by melting a filler alloy at a temperature below that of the base materials. The base copper does not melt. Capillary action distributes the filler in the joint gap. Brazing is highly established in copper medical gas systems because it is compatible with copper tube practice and when performed correctly, can provide reliable, leak tight joints [4].

The choice between the two should not be framed in simplistic terms such as "welding is modern, brazing is old". Both are mature technologies. What matters is fitness for service. Stainless steel is best exploited through controlled welding. Copper is best exploited through disciplined brazing. Each method requires trained personnel, procedure control, cleanliness, documentation and appropriate inspection.

IMPORTANT: It is necessary to compare the internal cleanliness challenge in both processes. Stainless steel welding often requires internal purge gas to protect the root side from oxidation.

Copper brazing requires control of internal cleanliness and protection against contamination during installation. In both cases, a technically acceptable joint is more than a visually acceptable joint.

3.1.9 Welding of stainless steels for hospital applications

Among stainless steel welding processes, TIG welding remains one of the most useful reference processes for healthcare engineering education. It offers precise heat control, high weld quality and clean joints when executed correctly. In tube systems, orbital variants of TIG welding are especially attractive because they improve repeatability and documentation [1,2,15].

Laser welding is also important conceptually, especially because it demonstrates the compatibility of stainless steels with high precision and automated joining technologies. In many hospital building services projects, laser welding is less common than TIG, but it is highly relevant for understanding advanced fabrication routes and for selected equipment manufacturing applications [1,42].

The metallurgical challenge in stainless steel welding is that the thermal cycle changes the local microstructure and chemistry. If heat input is poorly controlled, if surface contamination is present, or if an unsuitable filler is selected, the weld region may suffer reduced corrosion resistance, distortion, lack of penetration, or hot cracking susceptibility [2,3,43,44].

The concept of ferrite in austenitic stainless steel weld metal is particularly important. A small amount of delta ferrite in an austenitic weld can improve resistance to solidification cracking. This is why constitution diagrams, including the classical Schaeffler logic and later variants, remain very useful. They help engineers estimate the balance between austenite and ferrite from alloy composition and support informed filler and procedure selection [42-45].

Hot cracking deserves special mention because it is directly relevant to high quality welded tubework. Many research studies shows that austenitic stainless steels may be sensitive to hot cracking if composition and solidification



mode are unfavourable [43,46,47]. Segregating impurities such as sulfur and phosphorus are especially undesirable because they can form low melting films in interdendritic regions. Procedure qualification, filler choice, base metal chemistry and controlled heat input are therefore essential.

It is very relevant for hospital grade tubing: modern low sulfur medical and pharmaceutical grades can change weld behavior and parameter adjustment may be necessary to avoid defects such as incomplete penetration or root over-melting [1]. Better service performance can come with tighter process windows.

Cleanliness before welding is equally important. Stainless steel welds made in hospital or hygienic service should be prepared on clean surfaces, with controlled fit up, proper shielding gas and careful root protection. Post weld finishing, if required, should restore a smooth surface and avoid leaving heat tint or rough contamination zones. Post weld surface treatment remains useful in this regard [15].

Welding of stainless steel

WIG	<i>Wolfram Inert Gas</i>
TIG	<i>Tungsten Inert Gas</i>
GTAW	<i>Gas Tungsten Arc Welding</i>
heliarc	<i>Helium - Arc electric</i>

- Advantages:
 - High quality welds for suitable applications
 - No spatter because no filler metal through arc
 - Little or no post-weld cleaning because no flux
- Disadvantages:
 - Generally slower and more costly than consumable electrode arc welding processes

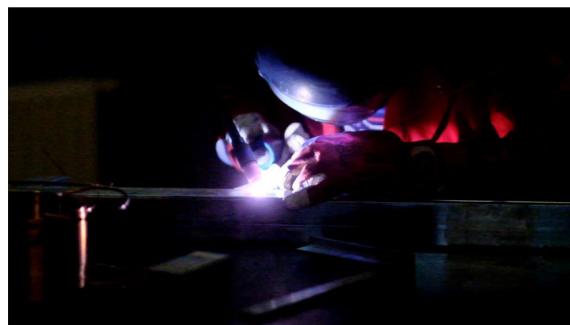


Figure 3.11. TIG welding of stainless steel

In practical healthcare engineering, a welded stainless-steel joint should therefore be judged by five questions. Is the material grade appropriate? Was

the joint prepared and purged correctly? Was the procedure qualified and executed by competent personnel? Does weld geometry support cleanability? And is the documentation sufficient to support future maintenance? If the answer to any of these is uncertain, the joint should not be treated as routine.

Welding of stainless steel

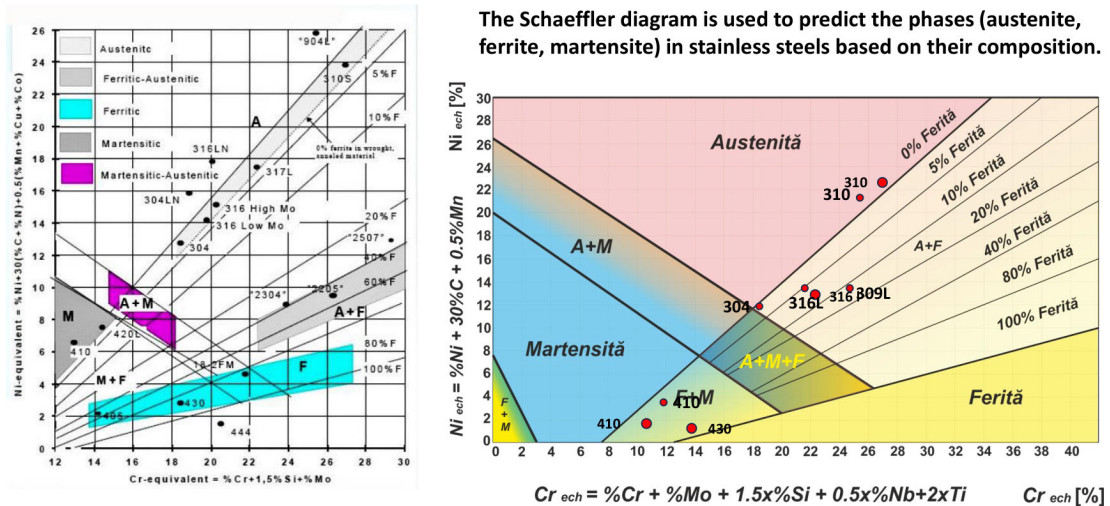


Figure 3.12. Schaeffler diagram

Table 3.7. Welding and joining methods relevant to hospital metallic pipeline systems

Method	Typical material	Main advantage	Main control point
TIG / GTAW	stainless steel	high quality and good control	purge protection, heat input, root condition
Orbital TIG	stainless steel tube	repeatability and documentation	Fit up, machine parameters, cleanliness
Laser welding	selected stainless parts	precision and automation	joint fit up and reflectivity
Brazing	copper tube	mature practice in medical gas systems	cleanliness and correct filler use



3.1.10 Inspection, testing and quality assurance

No hospital pipeline system should be accepted on appearance alone. Quality assurance must confirm that the line is leak tight, correctly identified, compatible with the service and properly documented.

For stainless steel utility systems, inspection usually begins with visual examination of alignment, support spacing, joint appearance, valve access, slope and identification. Visual checks are valuable because they reveal many practical errors quickly. However, they are only the first line of control.

Pressure testing is then used to confirm integrity. The exact method depends on the service and governing code. For medical gas systems, commissioning and verification are tightly connected to the requirements of ISO 7396-1 [6]. The system must be proven safe before being released to clinical use.

Depending on the service, additional non destructive testing may be appropriate **(more details in chapter 3.3)**. Dye penetrant testing, borescope inspection of selected weld roots, radiography, or orbital welding records may be used where quality demands justify them. In hygienic tubing, internal oxidation and root condition are often more important than an untrained observer expects.

Documentation is part of quality assurance, not an administrative afterthought. Hospitals change over time. Renovations, line extensions, equipment replacements and temporary shutdowns are common. Without clear drawings, line labeling, material certificates and commissioning records, future interventions become more dangerous and more expensive [10-12].

IMPORTANT: If a hospital line fails a pressure test, the event is not only a project delay. It is feedback on design, installation discipline and procedure control. Good engineering cultures use such feedback to improve future work.

3.1.11 Maintenance of hospital pipelines

The best material cannot remove the need for maintenance. In hospitals, maintenance has a preventive mission because shutdowns affect care delivery and emergency repairs are usually more risky than planned interventions.

A preventive maintenance strategy for stainless steel and copper systems usually begins with an asset register. Every critical line, valve station, plant room header, alarm point and shut off device should be known, labeled and linked to drawings and service records. This is especially important in hospitals that have been expanded over many years and may contain legacy installations [12,19].

Routine inspections should focus on leaks, support integrity, insulation condition, valve accessibility, unauthorized modifications, unusual vibration and visible surface change. For water systems, maintenance also interacts with infection control practice, especially where *Legionella* prevention is relevant. According to [7-9,48] water system management in hospitals must be systematic, because material choice alone does not control risk. Temperature, flow, stagnation, deposits, disinfection regime and monitoring all play important roles.

For medical gas systems, periodic verification of alarms, shut off valves, outlet identification and pressure performance is essential [6,10,11]. Any planned shutdown should be treated as a controlled operation with clear clinical communication, isolation strategy and recommissioning checks.

Cleaning and flushing should not be improvised. In stainless steel systems, aggressive cleaners may damage the surface if selected or used incorrectly. Work on bleach wipes and repeated hospital disinfection shows that even corrosion resistant materials can suffer surface degradation under unfavourable



cleaning regimes [13,14]. This matters for appearance and for long term cleanability and inspection.

A good maintenance culture also values traceability. After any repair, records should show who performed the work, which materials were used, what test was applied and when the system was returned to service. Such discipline reduces the risk of repeated hidden errors.

IMPORTANT: maintenance is the bridge between design and operation. The long term success of a hospital system depends just as much on inspection frequency, shutdown planning and documentation discipline.

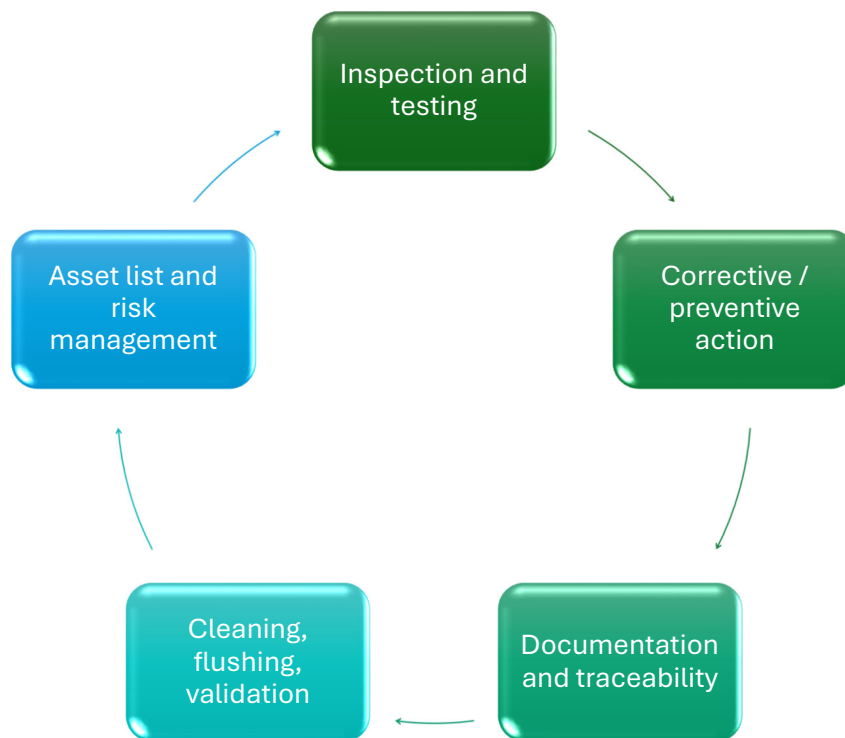


Figure 3.13. Preventive maintenance cycle for hospital pipeline systems.

3.1.12 Health effects of stainless steels

According to Directive 98/79/EC of the European Parliament and of the Council of 27 October 1998 on in vitro diagnostic medical devices "The devices and their

manufacturing processes must be designed in such a way as to eliminate or reduce as far as possible the risk of infection to the user or other persons. The design must allow easy handling and, where necessary, reduce as far as possible contamination of, and leakage from, the device during use and, in the case of specimen receptacles, the risk of contamination of the specimen. The manufacturing processes must be appropriate for these purposes". Let's first analyze the influence of the chemical composition of stainless steels on toxicity.

Chromium toxicity is associated with hexavalent chromium, that easily crosses biological membranes, interacting with protein components and nucleic acids within the cell before being deoxygenated to trivalent chromium. Hexavalent chromium's carcinogenic properties are derived from its reaction with genetic material [47]. Trivalent chromium is the most stable form of Cr found in living organisms. The most significant biological difference between it and hexavalent chromium is its inability to cross cell membranes and low reactivity. Trivalent chromium enters the body through the digestive tract and is necessary for the metabolism of carbohydrates, proteins and lipids [47]. Because chromium in stainless steels is in metallic form (with zero valence), its use in medical devices is not a health hazard.

Nickel plays an important role in human mineral balance, as nickel deficiency leads to reduced intrauterine growth and is also accompanied by reduced iron adsorption, which leads to anemia [48]. Like chromium, nickel enters the body through the digestive tract, as there are a lot of foods that contain Ni: spinach, cabbage, lettuce, peas, lentils, almonds, plums, dates, pineapple, buckwheat, oats, cocoa beans, soybeans, peanuts, walnuts, hazelnuts, dark chocolate, seafood (crab, oysters, shrimp, salmon) [48].

Manganese is a vital nutrient for both animals, humans and plants. Rocks, soil, water, and food all naturally contain manganese, that is involved in the

formation of glycosaminoglycans, bone mineralization, protein and energy metabolism, metabolic regulation, and cellular defense against dangerous free radical species. Manganese functions as an enzyme activator as well as a component of metalloenzymes [49]. Consuming manganese-containing foods or supplements is the primary way that humans are exposed to manganese. Heavy tea drinkers and vegetarians who eat foods high in manganese, like grains, beans, and nuts, may consume more manganese than the average person. Some occupations, where manganese is inhaled in the form of dust or fumes (from welding or machining of steels), may increase the chances of nervous system or respiratory system damages caused by high manganese content. Manganese in solid state stainless steels is non-toxic and safe for everyday use [48].

Like manganese, in both plants and animals, including humans, molybdenum is an essential micronutrient. The dietary requirement for adults is 0.64 µg/kg body weight/day. Although these low levels of molybdenum are essential for human health, excessive exposure to environmental pollution, mainly industrial emissions, mining and steel processing, poses severe risks. Reduced body weight, kidney damage, decreased male fertility, and anemia after oral exposure to molybdenum trioxide appear to be the most sensitive disorders, as do respiratory effects after inhalation exposure. The majority of the general public's exposure to molybdenum comes from food. When compared to foods derived from tubers or animals, foods derived from surface plants, such as cauliflower, leafy vegetables, and legumes, typically have a higher concentration of molybdenum. The most abundant sources of molybdenum in the typical diet are beans, grains, leafy vegetables, legumes, liver, and milk [50]. Molybdenum in stainless steel, in its solid and stable alloy form, poses no health risks and is considered extremely safe for food, medical and everyday contact use.

Essential requirements designed to protect both patients and professional users are standardized in Europe in the Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices. According to this Regulation “medical device means any instrument, apparatus, appliance, software, implant, reagent, material or other article intended by the manufacturer to be used, alone or in combination, for human beings for one or more of the following specific medical purposes:

- diagnosis, prevention, monitoring, prediction, prognosis, treatment or alleviation of disease,
- diagnosis, monitoring, treatment, alleviation of, or compensation for, an injury or disability,
- investigation, replacement or modification of the anatomy or of a physiological or pathological process or state,
- providing information by means of in vitro examination of specimens derived from the human body, including organ, blood and tissue donations

and which does not achieve its principal intended action by pharmacological, immunological or metabolic means, in or on the human body, but which may be assisted in its function by such means.

Also medical devices are considered:

devices for the control or support of conception;

products specifically intended for the cleaning, disinfection or sterilization of medical devices”.

According to this Regulation design and manufacture requirements for medical devices are:



- to select the materials and substances, particularly with respect to toxicity and, when applicable, flammability;
- to guarantee the materials' compatibility with biological tissues, cells, and body fluids, considering the device's intended use as well as, when relevant, metabolism, absorption, distribution and excretion;
- to ensure compatibility among implantable device components;
- to verify that processes do not affect the characteristics of the materials;
- to respect the results of previously proven biophysical or modeling studies, where applicable;
- to consider the mechanical properties of materials used, including strength, ductility, fracture toughness, wear resistance and fatigue resistance;
- to ensure adequate surface properties;
- to confirm that device meets any defined chemical and/or physical specifications.

Despite having adequate mechanical and biocompatibility qualities, stainless steel has some flaws on the implant surface, primarily because of its uneven microstructure.

The bacterial response and cellular integration are greatly influenced by the surface characteristics of implants, including chemical composition, surface roughness, wettability, electrical properties, and protein adhesion. Preventing bacterial adhesion is the primary concern for medical instruments and devices, whereas the surface of cardiovascular implants should prevent bacterial

adhesion and to encourage the growth of endothelial cells, inhibit platelet adhesion and decrease the proliferation of smooth muscle cells.

In the case of stainless steel used in orthopedic surgery, good proliferation of osteoblast cells (bone-forming cells) is very necessary to ensure the desired biocompatibility, even though bacterial adhesion is not desired (Figure 3.14).

As a result, the surfaces need to be appropriately prepared for use in particular applications. Bacterial adhesion should always be stopped without affecting the intended biological reactions with other cells [53].

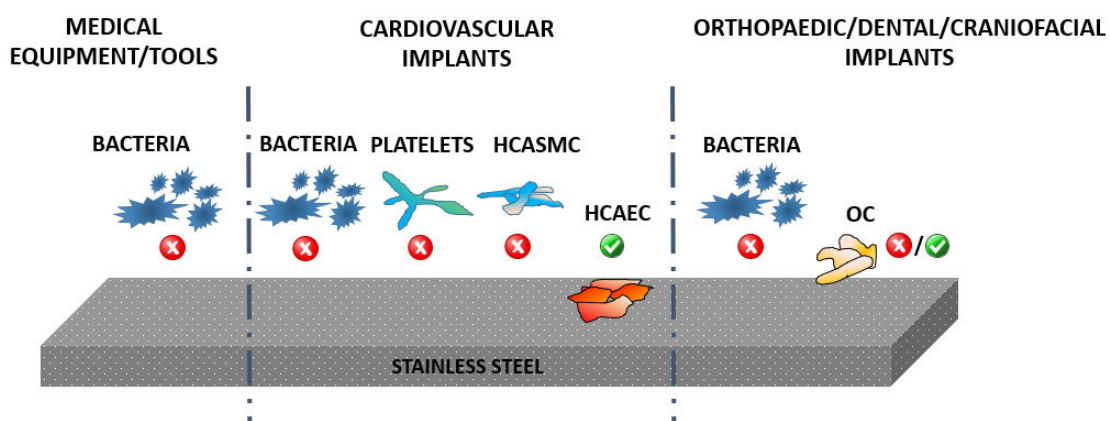


Figure 3.14. Desired events that occur on the surfaces of stainless-steel biomaterials used for medical devices, cardiovascular implants, orthopedic, dental and craniofacial implants (HCAEC—human coronary artery endothelial cells, HCASMC—human coronary artery smooth muscle cells, OC—osteoblast cells) [51].

Compared to other metallic implants, stainless steel implants have been linked to higher infection rates because the material lacks intrinsic antibacterial qualities and frequently forms fluid-filled fibrous capsules at the interface between the implant and surrounding tissue, which provides the perfect conditions for bacterial colonization. In addition to preventing the intimate integration of an implant with the surrounding tissues, this can result in the formation of a biofilm that effectively shields the enclosed microorganisms from immune cells and antibiotics. This can also lead to the development of chronic



infections, which can result in extended hospital stays, postoperative complications such as implant-associated infections, implant rejection, and, in severe cases, death [53].

The antibacterial activity of stainless steel (SS) biomaterials can be enhanced by:

- changing the surface chemistry using antimicrobial substances added to inorganic or organic thin surface layers, coating with biochemical materials (calcium phosphate or hydroxyapatite), application of hardystonite nano-bioceramics using sol-gel and surface platinization;
- nanostructuring for breaking the microbial membrane that ensures cell adhesion through Laser surface texturing (LST), Laser-induced periodic surface structures (LIPSS) and nanocavitation;
- lowering water contact angle, ultrafine granular structure and suitable surface chemical composition;
- superficial microalloying with plasma.

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3.2 COPPER ALLOYS FOR HEALTHCARE APPLICATIONS

3.2.1 Background

Healthcare-associated infections (HAIs) remain among the most significant challenges facing modern healthcare systems. Despite continuous improvements in sterilization procedures, antibiotic therapy, environmental cleaning protocols, and infection prevention strategies, microorganisms continue to spread through contact with contaminated surfaces, medical devices, water distribution systems, and ventilation equipment. The increasing prevalence of multidrug-resistant microorganisms has further intensified the need for complementary infection-control measures that do not rely solely on antibiotics or chemical disinfectants.

Materials engineering smart usage of materials has thus become an essential tool for prevention of infections. Rather than relying only on periodic cleaning protocols, antimicrobial materials provide continuous passive protection against spread of germs, by directly reducing microbial survival on their surfaces. Among antimicrobial materials, copper and its alloys occupy a unique position because they combine excellent engineering properties with intrinsic broad-spectrum antimicrobial activity in exchange for limited rise in costs.

The antimicrobial activity of copper is an inherent property of the material itself, and thus, properly manufactured copper alloys maintain their antimicrobial performance throughout their service life, even after repeated cleaning, mechanical wear, or surface abrasion. This characteristic makes copper alloys particularly attractive for healthcare environments where surfaces are subjected to continuous human contact and frequent cleaning cycles.

Copper has been recognized for its hygienic properties since antiquity, as usage of copper vessels for water storage was observed to keep the water fresh for



longer periods. Although the mechanisms responsible for these observations were unknown at the time, modern microbiology has demonstrated that copper ions released from metallic surfaces exert powerful antimicrobial effects against bacteria, fungi, and many viruses.

Antimicrobial properties of copper have attracted considerable attention in healthcare engineering because environmental contamination plays an important role in pathogen transmission. Numerous studies have demonstrated that microorganisms may survive for several days-or even months-on stainless steel, plastics, and other conventional hospital materials. Frequently touched objects such as door handles, bed rails, intravenous poles, over-bed tables, light switches, faucet handles, and nurse call buttons become reservoirs for microbial transmission. Copper alloy replacements substantially reduce microbial burden on these high-touch surfaces, thereby lowering the probability of indirect pathogen transfer between patients, healthcare personnel, and visitors.

Furhtermore, copper alloys are increasingly investigated for use in hospital plumbing systems, heat exchangers, heating, ventilation, and air conditioning (HVAC) equipment, surgical instruments, implantable devices, wound dressings, and antimicrobial coatings. In each application, the material combines structural performance with continuous antimicrobial activity.

One of the major advantages of copper alloys is the diversity of available compositions. Pure copper provides the highest antimicrobial performance but possesses relatively low mechanical strength. Alloying with zinc, tin, nickel, aluminum, silicon, or manganese enables engineers to tailor mechanical properties, corrosion resistance, hardness, color, machinability, and wear resistance while retaining significant antimicrobial activity. Consequently, different copper alloys can be selected according to the specific functional requirements of healthcare equipment.

It has been demonstrated that replacing selected high-touch surfaces with copper alloys leads not only to lower microbial contamination but also to measurable reductions in healthcare-associated infections in intensive care units and other hospital settings. Such findings have shifted copper from being considered merely an antimicrobial material toward becoming an integral component of infection prevention strategies.



Figure 3.15. Hospital room with sani-station and touch-point hardware: grab bar, faucet, and light switch.

3.2.2 Copper alloys used in healthcare

Numerous commercial copper alloys are commercially available and they comprise of a broad family of engineering materials in which copper is combined with one or more alloying elements to enhance mechanical properties, corrosion resistance, wear behavior, castability, or manufacturability. Selection of an



appropriate copper alloy depends on balancing antimicrobial performance with engineering requirements. Since antimicrobial activity generally increases with copper content, alloys containing a larger percentage of copper are typically preferred in healthcare applications. Lower-copper alloys may be selected when higher strength, improved corrosion resistance, or enhanced wear resistance is required.

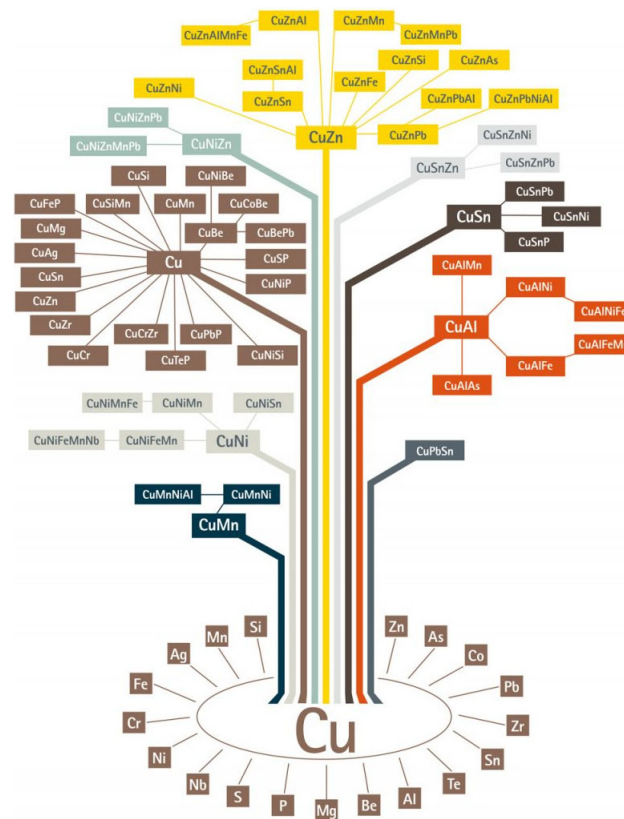


Figure 3.16. The Copper Tree: major classes of copper alloys.

Pure copper

Commercially pure copper exhibits the highest antimicrobial performance because its surface readily releases biologically active Cu^+ and Cu^{2+} ions. It also possesses excellent thermal conductivity, high electrical conductivity, and outstanding corrosion resistance under many environmental conditions. The

primary limitations of pure copper are its relatively low hardness and modest mechanical strength, making it susceptible to scratching, denting, and plastic deformation under repeated mechanical loading. Consequently, pure copper is generally reserved for applications where maximum antimicrobial performance is required and structural demands remain moderate. Typical applications include:

- antimicrobial touch plates;
- decorative architectural components;
- specialized medical equipment surfaces;
- laboratory equipment;
- antimicrobial inserts.

Brasses (Cu–Zn)

Brasses represent the most widely used copper alloys in healthcare environments. Zinc additions up to 40 wt.% significantly improve strength, hardness, and machinability while maintaining high antimicrobial efficacy. Brass components exhibit attractive golden coloration, excellent corrosion resistance in indoor environments, and relatively low manufacturing costs. Consequently, they are commonly selected for architectural hardware, including:

- door handles,
- push plates,
- grab rails,
- handrails,
- faucet handles,
- cabinet pulls,
- nurse station fittings.



Bronzes (Cu–Sn)

Bronzes contain tin as the principal alloying element and generally offer superior wear resistance, fatigue strength, and corrosion resistance compared with brasses. In healthcare engineering, bronze alloys are particularly valuable for moving mechanical components requiring prolonged durability, such as:

- bearing elements,
- pump components,
- valve systems,
- precision mechanical assemblies.

Copper–Nickel alloys

Copper–nickel alloys are widely employed in marine engineering because of their exceptional corrosion resistance. Their resistance to biofouling has also stimulated interest in medical and water-treatment applications, including:

- hospital plumbing,
- heat exchangers,
- HVAC piping,
- water circulation systems,
- cooling equipment.

Aluminum bronzes and silicon bronzes

Aluminum bronzes combine high mechanical strength with outstanding corrosion resistance and wear behavior. Silicon bronzes exhibit excellent formability together with attractive surface appearance. Although these alloys contain lower copper contents than pure copper, they remain sufficiently antimicrobial for many architectural applications while providing improved resistance to scratching and mechanical damage. Uses include:

- door hardware,
- elevator buttons,
- push bars,
- bed-frame fittings,
- wheelchair components,
- hospital furniture.

Table 3.8. Main copper alloys

Alloy family	Cu content	Main advantages	Healthcare applications
Pure copper	>99%	Maximum antimicrobial activity	Touch surfaces, inserts
Brass (Cu-Zn)	60-90%	Strength, machinability, aesthetics	Door handles, rails, faucets
Bronze (Cu-Sn)	80-95%	Wear resistance	Mechanical components
Cu-Ni	70-90%	Corrosion resistance	Water systems, HVAC
Aluminum bronze	75-90%	High strength	Architectural hardware
Silicon bronze	94-96%	Good formability	Furniture fittings

3.2.3 Differences from conventional materials in hospitals

The majority of hospital contact surfaces are currently manufactured from stainless steel, aluminum alloys, painted steel, polymers, laminates, or coated wood products. These materials are selected primarily for their mechanical durability, ease of cleaning, and economic considerations rather than their biological properties.



Importantly, conventional materials are generally microbiologically passive. Stainless steel, for example, neither kills microorganisms nor inhibits their proliferation. Instead, microorganisms deposited on stainless steel surfaces may remain viable for prolonged periods, depending on environmental conditions such as humidity, temperature, and nutrient availability.

Consequently, effective infection control depends almost entirely on regular cleaning and disinfection. Between cleaning cycles, microbial contamination can accumulate and contribute to pathogen transmission through repeated hand contact.

Copper alloys differ fundamentally because they provide continuous antimicrobial activity independent of external intervention. Once microorganisms come into contact with a copper-containing surface, a sequence of physicochemical and biological interactions is initiated that leads to rapid microbial inactivation. This passive yet continuous mode of action complements standard cleaning practices rather than replacing them.

Copper surfaces do not eliminate the need for routine hygiene measures, but they significantly reduce the microbial burden that develops between cleaning events, thereby lowering the likelihood of indirect transmission.

Another distinguishing feature is durability. Because the antimicrobial activity originates from the bulk material rather than from an applied coating, moderate wear or abrasion generally does not diminish performance. Freshly exposed copper surfaces continue to release biologically active ions, allowing antimicrobial functionality to persist throughout the service life of the component. This contrasts with many antimicrobial coatings, whose effectiveness may decline as the coating degrades, delaminates, or becomes mechanically damaged.

The combination of inherent antimicrobial activity, mechanical resistance, and compatibility with conventional manufacturing processes has made copper alloys one of the few antimicrobial material classes to achieve widespread implementation in real healthcare environments rather than remaining confined to laboratory studies.

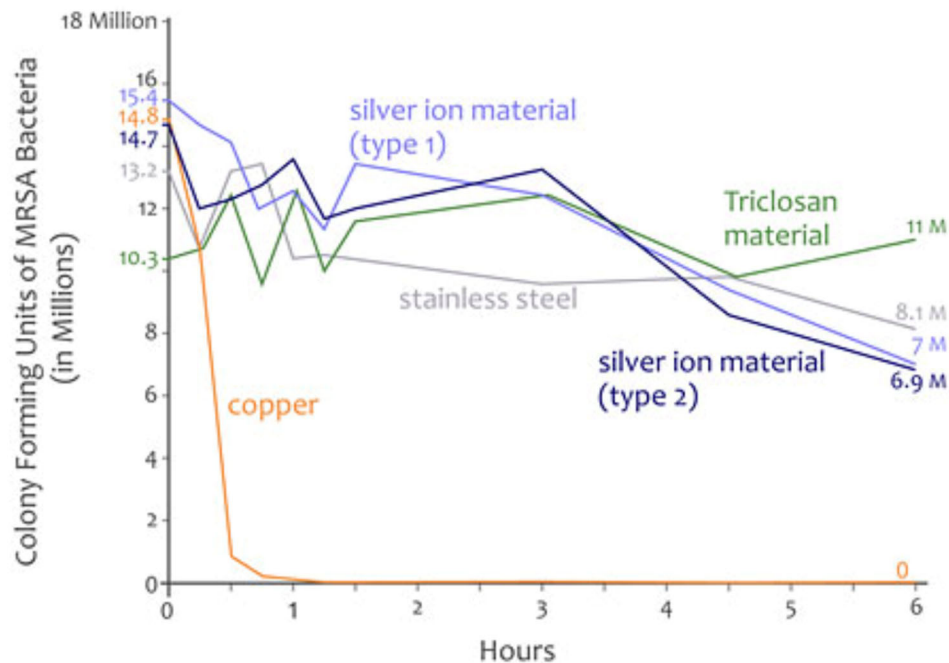


Figure 3.17. Antimicrobial effectiveness: copper vs. other common materials used in healthcare.

3.2.4 Antimicrobial Mechanisms

The antimicrobial performance of copper and its alloys is fundamentally different from that of conventional disinfectants or antibiotic therapies. Rather than relying on a single biochemical target, copper exerts toxicity through several simultaneous mechanisms that collectively overwhelm microbial defense systems. This multi-target mode of action is one of the principal reasons why copper remains effective against a broad spectrum of microorganisms, including antibiotic-resistant bacteria and clinically relevant fungi.

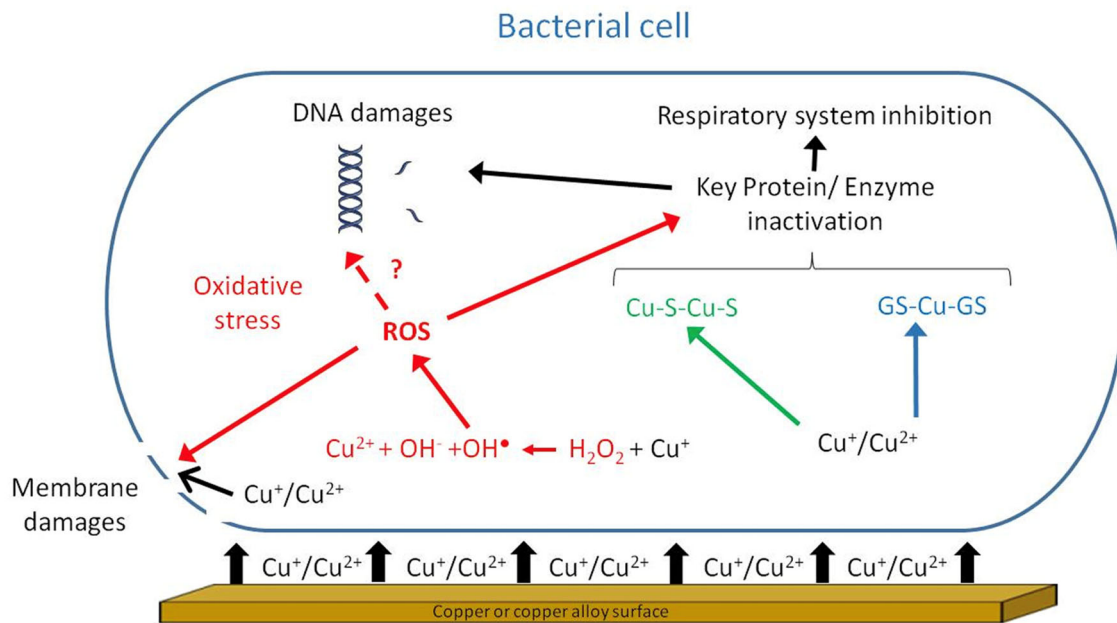


Figure 3.18. Putative mechanisms involved in contact killing: direct destruction of the membrane by cupric and cuprous ions (black pathway); hydrogen peroxide-dependent oxidation of Cu^+ in the cell under aerobic conditions generating reactive oxygen species (ROS) (red pathway); interactions between copper ions and glutathione under anaerobic conditions (blue pathway) and displacement of iron from iron-sulfur clusters (green pathway). The final steps leading to bacterial cell death include inactivation of key proteins/enzymes, among which are those involved in the respiratory system as well as membrane and DNA damages. (Source: Dauvergne, E.; Mullié, C. "Brass Alloys: Copper-Bottomed Solutions against Hospital-Acquired Infections?" *Antibiotics* 2021, 10, 286)

Unlike antimicrobial coatings that release a specific biocide or pharmaceutical agent, metallic copper continuously generates biologically active copper ions at its surface through electrochemical interactions with moisture, oxygen, and organic compounds present in the surrounding environment. These ions participate in a cascade of reactions that progressively damage microbial cells until irreversible loss of viability occurs.

The antimicrobial process begins immediately after microorganisms come into contact with the copper surface and continues until complete cellular destruction has occurred. Although the rate of killing varies depending on

environmental conditions and microbial species, the sequence of events follows a remarkably consistent pattern.

Contact killing

One of the defining characteristics of copper surfaces is their ability to induce contact killing, a phenomenon in which microorganisms are rapidly inactivated after direct contact with metallic copper or copper-rich alloys. Unlike chemical disinfectants that require manual application, contact killing is a passive process continuously occurring at the material surface. Once bacteria adhere to the copper substrate, intimate contact enables electrochemical interactions between the cell envelope and the metal. These interactions promote localized oxidation of the copper surface and release of Cu^+ and Cu^{2+} ions into the thin moisture layer surrounding the microorganism. The concentration of released ions near the cell membrane is considerably higher than would normally occur in surrounding fluids, creating a localized microenvironment with pronounced antimicrobial activity. Because the ions are generated directly at the interface between the cell and the surface, microorganisms are exposed to toxic concentrations before they can establish stable adhesion or initiate biofilm formation. The speed of contact killing depends on several factors, including:

- copper concentration within the alloy;
- surface roughness and oxide composition;
- relative humidity;
- temperature;
- microbial species;
- initial microbial load;
- presence of organic contamination.



Generally, alloys containing higher percentages of copper exhibit faster microbial inactivation because greater amounts of biologically active ions are released from the surface.

Release of copper ions

Copper exists primarily in two biologically relevant oxidation states: cuprous (Cu^+) and cupric (Cu^{2+}). Both species contribute to antimicrobial activity, although they participate in somewhat different biochemical pathways. Under normal environmental conditions, oxidation of metallic copper produces a continuous supply of ionic copper.

Once released, copper ions interact strongly with negatively charged functional groups present on microbial cell surfaces (i.e. phospholipids, lipopolysaccharides, teichoic acids, peptidoglycan, membrane proteins, and extracellular polysaccharides). Accumulation of copper at the cell envelope rapidly exceeds the organism's capacity for metal homeostasis. Although bacteria naturally possess mechanisms for regulating intracellular copper concentrations, these systems evolved to manage trace quantities of copper required for metabolic functions rather than the extremely high local concentrations generated at metallic copper surfaces. As intracellular copper accumulates, numerous biochemical pathways become disrupted simultaneously, resulting in widespread metabolic failure.

Damage to the cell membrane envelope

The bacterial cell envelope represents one of the first targets of copper toxicity. The plasma membrane maintains osmotic balance, nutrient transport, energy production, and communication between the intracellular and extracellular environments. Copper ions interfere directly with membrane integrity through

several mechanisms. Copper binding to phospholipid head groups and membrane proteins, increases the cellular membrane permeability, resulting in intracellular ions leaking into the surrounding medium while unwanted extracellular substances penetrate the cytoplasm. Once extensive membrane damage has occurred, recovery is generally impossible even if microorganisms are subsequently removed from the copper surface.

Oxidative stress

A main pathway for copper toxicity is the generation of oxidative stress. Copper ions participate in redox cycling reactions capable of producing highly reactive oxygen species (ROS), including:

- ❖ hydroxyl radicals ($\cdot\text{OH}$);
- ❖ superoxide radicals ($\text{O}_2^{\cdot-}$);
- ❖ hydrogen peroxide (H_2O_2);
- ❖ singlet oxygen ($^1\text{O}_2$).

These reactive molecules attack virtually every major cellular component: lipids undergo peroxidation, proteins experience oxidation of amino acid side chains, causing enzyme inactivation and structural destabilization, nucleic acids sustain oxidative lesions that interfere with DNA replication and transcription. Because reactive oxygen species attack multiple cellular targets simultaneously, microorganisms rapidly accumulate irreversible molecular damage. Bacteria possess antioxidant defense systems, but exposure to copper surfaces generates ROS at rates far exceeding the capacity of these protective mechanisms. Oxidative stress therefore becomes self-amplifying: membrane damage accelerates copper uptake, increased intracellular copper promotes additional ROS formation, and escalating oxidative damage further

compromises membrane integrity. This positive feedback loop contributes significantly to the rapid antimicrobial performance of copper.

Protein denaturation and enzyme inactivation

Copper ions exhibit high affinity for sulfur-containing amino acids such as cysteine and methionine, as well as histidine residues present in numerous proteins. Binding of copper to these functional groups alters protein conformation, frequently resulting in loss of biological activity. Essential enzymes affected include those involved in: respiration; ATP synthesis; DNA replication; protein synthesis; carbohydrate metabolism; amino acid biosynthesis.

Many bacterial enzymes contain iron-sulfur clusters that are particularly susceptible to copper-mediated displacement reactions. Copper ions can replace iron within these catalytic centers, rendering the enzyme inactive. As metabolic pathways progressively fail, ATP production decreases dramatically. Since ATP supplies energy for nearly every cellular process, depletion rapidly leads to irreversible metabolic collapse. Copper also promotes protein aggregation. Denatured proteins lose their native three-dimensional structures and accumulate within the cytoplasm, overwhelming bacterial protein quality-control systems.

DNA and RNA damage

Although DNA is not the initial target of copper toxicity, extensive nucleic acid damage develops as antimicrobial activity progresses. Copper ions indirectly damage DNA through oxidative stress while also interacting directly with phosphate groups and nitrogen-containing bases. Copper-induced DNA damage occurs only after multiple earlier mechanisms have already

compromised cellular viability. Consequently, microorganisms cannot simply activate alternative metabolic pathways to survive exposure. The cumulative effect of membrane destruction, enzyme inactivation, oxidative stress, and DNA degradation results in complete and irreversible cell death.

Inhibition of Biofilm formation

One of the major challenges in healthcare is the formation of biofilms, microbial communities that adhere to surfaces and exhibit increased resistance to antibiotics, disinfectants, and host immune defenses. Biofilms readily develop on medical devices, implants, catheters, water pipes, and hospital equipment.

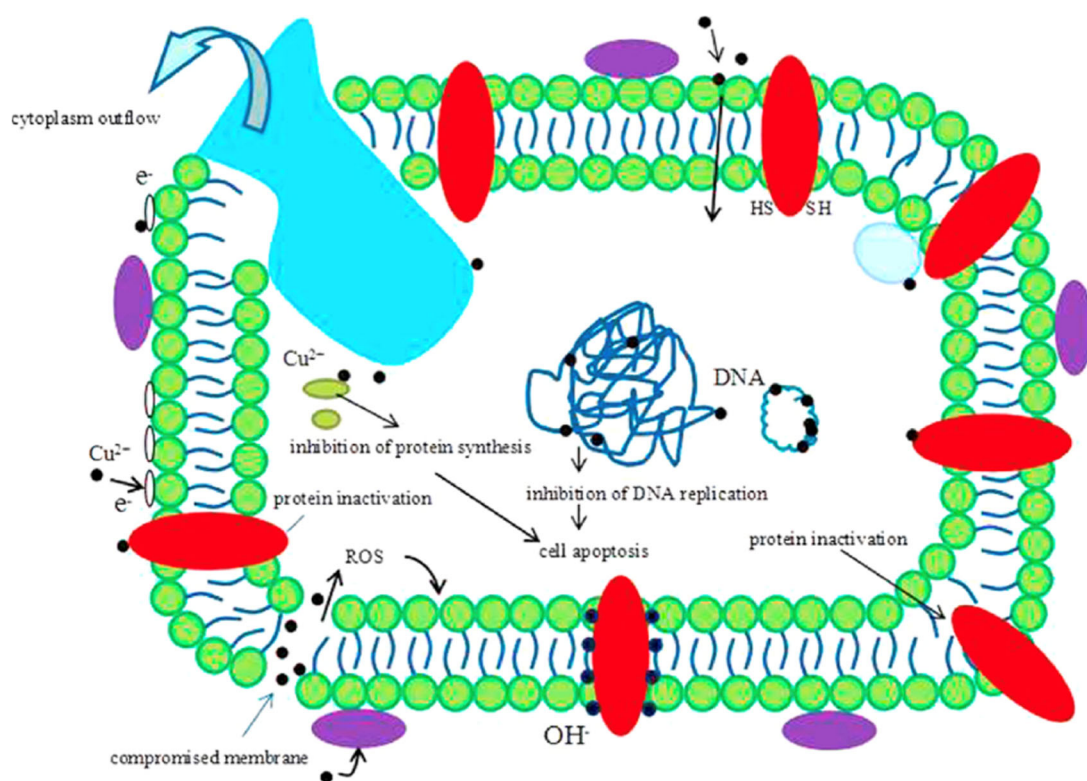


Figure 3.19. The schematic image of hypothesis about the antibacterial mechanism of Cu^{2+} . (reproduced from: R. Liu, et al. "Antibacterial effect of copper-bearing titanium alloy (Ti-Cu) against *Streptococcus mutans* and *Porphyromonas gingivalis*", *Sci. Rep.* 6 (2016) 29985.)



Copper surfaces inhibit biofilm formation by rapidly killing adherent microorganisms, reducing initial surface colonization, and disrupting quorum sensing, which is essential for biofilm maturation. Continuous release of copper ions further limits the growth and viability of developing biofilms. This property is particularly valuable for plumbing systems, HVAC components, and reusable medical devices, where biofilms are difficult to eliminate through conventional cleaning alone.

Antifungal activity of copper

Copper is well known for its antibacterial properties, but its antifungal activity is also highly relevant in healthcare environments. Opportunistic fungal infections remain a significant concern, particularly among immunocompromised patients, transplant recipients, oncology patients, and individuals in intensive care. Pathogenic fungi can colonize medical devices, environmental surfaces, ventilation systems, and water distribution networks, contributing to healthcare-associated infections. Copper exhibits broad-spectrum antifungal activity through mechanisms similar to those responsible for bacterial inactivation. Upon contact with copper surfaces, released copper ions penetrate fungal cells, disrupting membrane integrity, interfering with essential metabolic processes, and promoting the formation of reactive oxygen species (ROS). The resulting oxidative stress damages proteins, lipids, and nucleic acids, ultimately leading to loss of cell viability. Copper also affects fungal cell wall synthesis, weakening structural integrity and further enhancing its antimicrobial action. In addition to inactivating vegetative fungal cells, copper reduces the viability of fungal spores and inhibits their germination, thereby limiting environmental dissemination.

Copper surfaces have also been shown to suppress fungal biofilm formation by reducing initial cell adhesion and impairing the development of mature biofilms.

The antifungal properties of copper have important practical implications for healthcare facilities. Incorporating copper alloys into high-touch surfaces, water distribution systems, HVAC components, and selected medical devices can help reduce fungal persistence between routine cleaning cycles, complementing established infection prevention and environmental hygiene practices.

Antiviral activity

Although this chapter focuses primarily on the antibacterial and antifungal properties of copper, it is worth noting that copper also exhibits significant antiviral activity. Interest in this property has increased following outbreaks of influenza, SARS, MERS, and COVID-19. Unlike bacteria and fungi, viruses lack independent metabolism, so copper acts by damaging their structural components. Copper ions destabilize viral envelopes or capsid proteins and promote oxidative degradation of viral RNA or DNA, preventing subsequent infection and replication. Experimental studies have shown that viruses are inactivated much more rapidly on copper surfaces than on stainless steel or plastics, often within minutes to a few hours.

Although antiviral performance is not the primary reason for implementing copper surfaces in healthcare facilities, it provides an additional benefit by reducing the persistence of infectious viruses on frequently touched surfaces and potentially limiting indirect transmission during viral outbreaks.

Factors influencing antimicrobial performance

The antimicrobial efficacy of copper alloys depends on several material, environmental, and biological factors that influence the release of copper ions and their interaction with microorganisms. Understanding these variables is important for selecting suitable alloys and predicting long-term performance in healthcare environments.



Copper content is the primary material parameter, with antimicrobial activity generally increasing as copper concentration rises due to enhanced release of Cu^+ and Cu^{2+} ions. However, alloying elements also affect surface chemistry, oxide formation, and corrosion behavior, influencing overall performance.

Surface oxidation and **environmental conditions** play important roles. Thin oxide layers generally maintain antimicrobial activity, whereas heavy tarnishing or organic deposits may temporarily reduce ion availability. Moisture promotes electrochemical reactions and ion release, making antimicrobial activity more effective under moderate humidity, while temperature can accelerate microbial inactivation without compromising performance under normal healthcare conditions.

Surface topography also influences efficacy. Moderate roughness may enhance ion release by increasing the available surface area, whereas excessively rough surfaces can retain organic debris that partially shields microorganisms. Consequently, copper components should balance antimicrobial performance with ease of cleaning.

Finally, **organic contamination** and microbial characteristics affect inactivation rates. Blood, proteins, or cleaning residues can temporarily reduce direct contact between microorganisms and the copper surface, emphasizing that copper complements rather than replaces routine cleaning and disinfection. Likewise, susceptibility varies among bacterial, fungal, and viral species depending on factors such as cell envelope structure, metabolic activity, and biofilm-forming ability. Nevertheless, copper remains effective against a broad spectrum of clinically important microorganisms, making it one of the most versatile antimicrobial materials for healthcare applications.

3.2.5 Copper Alloy Applications in Healthcare

The broad antimicrobial spectrum of copper, combined with its favorable engineering properties - including corrosion resistance, thermal conductivity, machinability, and durability - has led to its use in a wide range of healthcare products. Unlike antimicrobial coatings that may wear or degrade, copper alloys provide continuous antimicrobial activity throughout the lifetime of the component, making them attractive for passive infection-control strategies.

Healthcare applications include high-touch architectural surfaces, building infrastructure, medical equipment, reusable instruments, implantable devices, and wound care products. These components share a common objective: reducing microbial contamination between routine cleaning cycles and limiting opportunities for pathogen transmission.

Copper alloys are particularly valuable in healthcare environments, where frequently touched surfaces such as door handles, bed rails, and workstations can act as reservoirs for microorganisms. Replacing conventional materials with copper alloys substantially reduces surface microbial burden without altering clinical workflows or cleaning procedures. Similar benefits have been demonstrated for water distribution systems, HVAC components, reusable medical devices, and selected implantable and therapeutic products, where copper complements the primary engineering function while contributing to infection prevention.

High-Touch surfaces

Environmental contamination plays a significant role in the transmission of healthcare-associated pathogens. Microorganisms deposited on frequently



touched surfaces can survive long enough to be transferred to the hands of healthcare workers and subsequently to susceptible patients. Consequently, reducing microbial contamination on these surfaces has become an important component of modern infection prevention strategies. Copper alloy replacements have been investigated for numerous architectural components, including:

- door handles and knobs;
- push plates and push bars;
- handrails and grab rails;
- bed rails;
- over-bed tables;
- intravenous (IV) poles;
- infusion pump control panels;
- faucet handles;
- sink fixtures;
- toilet flush levers;
- cabinet handles;
- nurse call buttons;
- light switches;
- chair armrests;
- wheelchair handles;
- examination tables.

These components share several characteristics that make them suitable candidates for copper substitution: frequent human contact; simple geometry; long service-life; maintenance; limited influence on medical procedures.

Architectural hardware remains in service for many years, making copper alloys an attractive passive infection-control solution that provides continuous antimicrobial activity without generating additional medical waste.

Field studies have shown that copper alloy touch surfaces typically carry 10-fold lower microbial loads than comparable stainless steel or plastic surfaces under routine hospital conditions. These reductions are maintained despite frequent contact and regular cleaning.

Among the most important applications are bed rails, door handles, and faucet handles, which are repeatedly touched by patients, healthcare workers, and visitors and therefore act as key transmission points for pathogens. By continuously reducing microbial survival between cleaning cycles, copper alloy hardware complements—but does not replace—standard cleaning and hand hygiene practices, providing an additional layer of protection against healthcare-associated infections.



Figure 3.20. A collection of antimicrobial copper door hardware products. Installing copper and copper alloy fixtures, such as light switches and hand rails, can decrease the spreading of infection in healthcare facilities.



Hospital Water Distribution Systems

Hospital water systems constitute another important source of microbial contamination. Although municipal drinking water generally satisfies public health standards, microorganisms may proliferate within complex building plumbing networks, particularly in areas characterized by stagnant flow, elevated temperatures, or extensive biofilm formation.

Traditional hospital plumbing systems frequently employ stainless steel, galvanized steel, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), polyethylene, or polypropylene piping. Although these materials exhibit satisfactory corrosion resistance and mechanical performance, they possess little intrinsic antimicrobial activity and therefore permit biofilm development.

Copper piping offers several advantages in this context. In addition to its excellent corrosion resistance and long service life, copper continuously releases small quantities of antimicrobial ions that inhibit microbial colonization of internal pipe surfaces. Reduced microbial adhesion limits the establishment of mature biofilms, decreasing the persistence of opportunistic pathogens within the distribution system.

Copper also exhibits favorable thermal conductivity, facilitating efficient hot-water distribution and potentially reducing localized temperature gradients that favor microbial growth. Moreover, copper plumbing is compatible with conventional joining methods, including soldering, brazing, and press-fit systems, allowing straightforward integration into healthcare infrastructure.

Investigations have reported lower concentrations of waterborne microorganisms in copper plumbing systems compared with polymeric alternatives, particularly when appropriate water chemistry is maintained. Nevertheless, copper alone should not be regarded as a complete solution for

water hygiene. Effective management continues to require temperature control, regular flushing, disinfection procedures and detailed water safety plans.

The use of copper alloys for valves, fittings, faucets, and mixing devices further extends antimicrobial protection throughout the water distribution network by reducing microbial persistence on wetted surfaces frequently contacted by healthcare personnel.



Figure 3.21 Copper pipes can be used for hospital water distribution systems to reduce biofilm formation and microbial colonization.

HVAC systems

Heating, ventilation, and air conditioning (HVAC) systems play a central role in maintaining indoor environmental quality within healthcare facilities. These systems regulate temperature, humidity, ventilation rates, and airborne particulate concentrations while helping to control the transmission of infectious aerosols. But, HVAC components themselves may become reservoirs for microbial growth. Moisture accumulating on cooling coils, condensate pans, filters, and drainage systems creates favorable conditions for bacteria, fungi,



and algae. Microbial colonization decreases heat transfer efficiency, increases pressure losses, contributes to unpleasant odors, and may release microorganisms or allergens into occupied spaces.

Copper has long been used as the preferred material for heat exchanger tubing because of its exceptional thermal conductivity. More recently, attention has focused on its antimicrobial properties, which provide an additional functional advantage in healthcare environments.



Figure 3.22 Copper coil air handling unit for harnessing the antimicrobial properties of copper in hospital applications, manufactured in Europe by French manufacturer Hydronic.

Copper heat exchanger coils inhibit microbial growth directly on fin and tube surfaces, reducing biofilm accumulation that would otherwise impair thermal performance. Laboratory studies have demonstrated substantially lower bacterial and fungal colonization on copper coils compared with aluminum coils operating under identical environmental conditions. Reduced microbial growth offers several practical benefits:

- improved heat transfer efficiency;
- reduced airflow resistance;
- lower maintenance requirements;
- decreased frequency of chemical cleaning;
- improved indoor air quality;
- reduced dissemination of fungal spores.

The incorporation of copper components into hospital HVAC systems therefore contributes simultaneously to energy efficiency, equipment longevity, indoor environmental quality, and infection prevention.

Surgical instruments and medical devices

Reusable surgical instruments represent another important application of copper-containing materials, although pure copper is rarely used because of its relatively low hardness and susceptibility to deformation. Instead, copper is incorporated into selected alloys or surface treatments designed to combine adequate mechanical performance with antimicrobial functionality.

Conventional surgical instruments are predominantly manufactured from martensitic or austenitic stainless steels because these materials provide excellent strength, corrosion resistance, and sterilization compatibility. However, stainless steel surfaces remain biologically inert, allowing microorganisms to survive until routine sterilization procedures are performed. Copper-containing alloys have been used for surgical instruments that may experience repeated handling between sterilization cycles, including forceps, retractors, clamps, trays, and auxiliary operating room equipment. In these applications, antimicrobial activity reduces the microbial burden during clinical use and transport without replacing established sterilization protocols.





Figure 3.23. Roman copper alloy surgical instruments.

Copper is also incorporated into certain dental instruments, orthodontic devices, and specialized surgical accessories where antimicrobial performance complements existing infection-control measures. Beyond structural medical devices, copper has also been incorporated into wound management products and healthcare textiles. An important consideration is that copper-containing surgical devices must maintain excellent corrosion resistance during repeated exposure to steam sterilization, chemical disinfectants, and mechanical cleaning. Consequently, alloy selection requires careful optimization to balance antimicrobial efficacy with mechanical durability and long-term dimensional stability.

3.2.6 Clinical implementation of copper alloys in healthcare facilities

The practical value of antimicrobial copper alloys lies in their performance under routine healthcare conditions, where surfaces are continuously exposed to

human contact, microbial contamination, and repeated cleaning. Unlike laboratory studies, hospital environments present complex conditions in which materials must maintain their antimicrobial function throughout long-term service while integrating with standard infection-control practices.

In healthcare facilities, surfaces are contacted frequently by patients, healthcare workers, and visitors, making them potential reservoirs for microbial transmission. By continuously reducing the microbial burden between cleaning cycles, copper alloys provide a passive means of limiting environmental contamination without requiring changes to routine maintenance or clinical workflows.

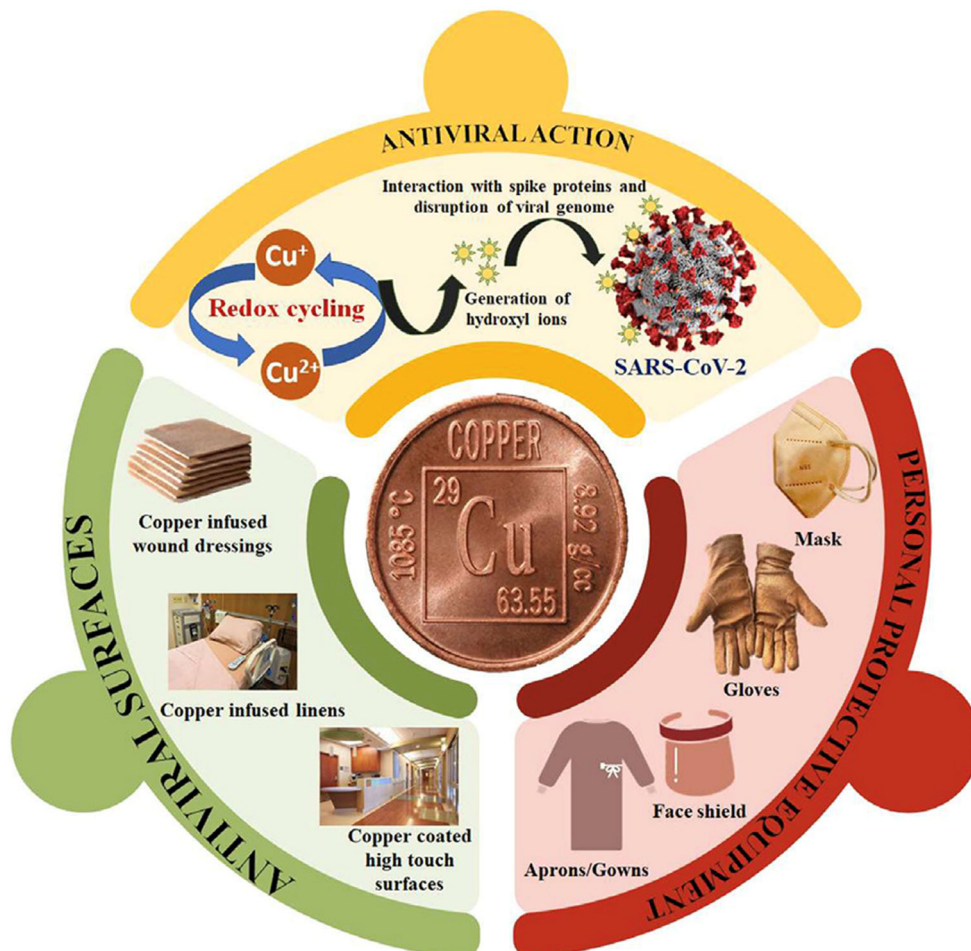


Figure 3.24. Copper's potential as an antiviral tool in emergencies such as the COVID-19 pandemic.

The use of copper has also expanded to other areas of healthcare infrastructure, including plumbing systems, HVAC components, reusable medical equipment, and selected medical devices. In most cases, copper elements are introduced gradually during routine maintenance or refurbishment, allowing existing facilities to incorporate antimicrobial materials without extensive reconstruction. Although copper alloys are not a substitute for established infection-prevention measures such as hand hygiene, environmental cleaning, sterilization, and disinfection, they provide an additional engineering-based strategy for reducing microbial persistence on frequently touched surfaces. Their long-term durability, continuous antimicrobial activity, and compatibility with existing healthcare infrastructure make copper alloys an attractive component of integrated infection-control programs.

3.2.7 Advantages of Copper Alloys in Healthcare

The widespread interest in copper alloys reflects the combination of antimicrobial functionality and well-established engineering performance. Unlike many emerging antimicrobial technologies, copper has been used industrially for centuries, and its manufacturing, processing, and corrosion behavior are thoroughly understood. The principal advantages are discussed below.

Continuous passive antimicrobial activity: copper provides uninterrupted antimicrobial protection throughout the service life of the component. No external power source, chemical replenishment, or user intervention is required.

Broad-spectrum activity: copper is active against a wide range of microorganisms, including: bacteria, antibiotic-resistant pathogens; yeasts; fungi; viruses.

Reduced biofilm formation: continuous ion release suppresses microbial adhesion and biofilm maturation, making copper particularly attractive for plumbing systems, HVAC components, and reusable medical devices.

Mechanical durability: copper alloys exhibit excellent machinability, corrosion resistance, and long-term structural reliability. Appropriate alloy selection allows optimization of hardness, wear resistance, and manufacturability for specific applications.

Compatibility with existing infrastructure: most copper components can directly replace equivalent stainless steel or polymer parts without requiring redesign of hospital equipment or alteration of clinical workflows.

Lifetime antimicrobial function: unlike surface coatings that may wear away, antimicrobial activity originates from the bulk material itself. Moderate abrasion therefore exposes fresh antimicrobial material rather than removing the active layer.

3.2.8 Limitations and challenges

Despite their well-documented antimicrobial properties, copper and copper alloys present several practical limitations that must be considered for successful implementation in healthcare.

Material selection requires balancing antimicrobial efficacy with mechanical performance, durability, cost, maintenance, aesthetics, and regulatory requirements.

Initial cost: it remains the primary barrier to widespread adoption, as copper alloys are generally more expensive than stainless steel or engineering polymers. However, life-cycle analyses suggest that these costs may be offset by reduced infection-related expenses. Consequently, many healthcare facilities



introduce copper components gradually during routine maintenance or renovation.



Figure 3.25. Surface oxidation of copper can lead to surfaces with increased roughness increases, which in turn, can contribute to increased corrosion and scaling. As corrosion and scaling become more pronounced, they lead to more significant biofilm development.

Surface appearance: copper naturally oxidizes, developing a brown patina that may be mistaken for poor cleanliness. This oxidation does not significantly impair antimicrobial performance, provided surfaces are properly maintained and free of heavy organic contamination.

Cleaning and maintenance: copper complements rather than replaces routine hygiene practices, and cleaning agents that leave protective films should be avoided because they can reduce direct contact between microorganisms and the copper surface.

Corrosion resistance: Although copper exhibits excellent corrosion resistance in most indoor healthcare environments, aggressive chemicals and unsuitable water conditions can influence corrosion behavior and ion release. Appropriate alloy selection is therefore important, particularly for plumbing and specialized applications.

Biocompatibility: for implantable devices, copper ion release must be carefully controlled to ensure biocompatibility, while maintaining antimicrobial activity. Modern copper-containing biomaterials achieve this through optimized alloy compositions and surface engineering.

Regulatory standards: implementation of antimicrobial copper products must comply with relevant regulatory standards governing antimicrobial performance, mechanical properties, corrosion resistance, and biocompatibility. Continued standardization and long-term clinical evaluation will support broader adoption of copper-based technologies in healthcare.

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3.3. NON-DESTRUCTIVE TESTING METHODS USED IN HEALTHCARE APPLICATIONS

3.3.1 Introduction

In modern engineering and manufacturing, delivering a product that is safe, reliable and compliant with international standards is not an afterthought, it is the foundation of the entire design and production cycle. Whether fabricating an impressive, welded structure or producing micro-components, engineers must guarantee that every material and joint performs exactly as predicted under load. To achieve this, industries rely on a structured framework of Quality Assurance (QA) and Quality Control (QC). While both terms are used in casual discussions, Quality Assurance and Quality Control are distinct and complementary areas. The first one is focused on the process, while the other is focused on the product [1].

Quality assurance is a proactive, systemic approach and its primary goal is to establish processes, documentation and organizational methodologies that prevent defects before they ever occur. Quality control is reactive and inspection-based discipline. It represents the physical checks where the actual product is compared against the design criteria [1,2].

To evaluate if the material integrity of a component or a structural joint achieves the mechanical requirements defined by the design criteria, engineers must physically test it. These testing methodologies are split into two categories: Destructive testing (DT) and Non-Destructive testing (NDT).

3.3.2 Non-Destructive Evaluation

According to the American Society for Nondestructive Testing, nondestructive evaluation (NDE) comprises inspection methods that assess the condition or



properties of a material or component without altering its structural integrity or compromising its subsequent performance and serviceability.

Several terms are commonly used within the nondestructive inspection community to describe the examination of materials and components without impairing their functionality. Although these terms are closely related and are frequently used interchangeably, they differ in scope and intended meaning:

- Nondestructive Testing (NDT) describes the process of performing an inspection to detect or characterize discontinuities while preserving the integrity of the test object
- Nondestructive Evaluation (NDE) represents a concept that includes both the inspection procedure and the subsequent analysis and interpretation of the acquired data.
- Nondestructive Inspection (NDI) is most frequently used for the evaluation and acceptance of manufactured components or in-service structures, rather than for the continuous monitoring and control of production processes.

The selection of an appropriate nondestructive evaluation (NDE) technique depends largely on the requirements of the intended application and the objectives of the inspection. Factors such as equipment portability, inspection speed, data acquisition and processing capabilities, component accessibility and testing environment all influence the choice of the inspection method. In addition, the motivation for performing the inspection – including quality assurance, safety, reliability, maintenance planning, regulatory compliance or cost reduction – determines both when and where the evaluation should be carried out. Owing to its versatility, NDE has become an indispensable tool in numerous sectors, including manufacturing, aerospace, healthcare and scientific research.

In many engineering systems, the integrity of individual components is critical to the overall safety and reliability of the structure. The failure of a single part may lead to significant financial losses, operational interruptions or even catastrophic accidents. For instance, an undetected defect in an aircraft landing gear component can have serious consequences for flight safety. Likewise, in the medical field, nondestructive evaluation techniques are extensively employed for diagnostic purposes, enabling the assessment of biological tissues and medical devices without invasive intervention.

Once nondestructive evaluation has been identified as the appropriate approach for verifying component quality and structural integrity, the next challenge is selecting the most suitable inspection method. This decision requires balancing the probability of detecting the target discontinuity or material characteristic against practical considerations such as inspection cost, available equipment, accessibility, inspection time, and regulatory requirements. Since no single NDE technique is universally applicable, the selection process should be based on both the characteristics of the component and the expected defect type. An effective selection strategy should therefore consider several key factors:

- The characteristics of both the material and the discontinuity being evaluated, including their physical and geometric properties.
- The fundamental principles governing the selected nondestructive evaluation technique
- The interaction between the inspection medium or probing energy and the material under investigation
- Knowledge of the fundamental physical principles over NDE methods.
- Awareness of the capabilities and limitations of existing NDE technologies.
- Consideration of economic, environmental, regulatory and other relevant factors in selecting the appropriate inspection method

As with most NDE technologies, determining whether to inspect an entire component or only a representative sample is primarily influenced by economic considerations and regulatory requirements. Ideally, only components containing flaws would require inspection.

However, since the presence of defects is unknown beforehand, the extent of inspection must be established as an integral part of the overall nondestructive evaluation strategy. In practice, statistical analyses are employed to estimate the probability of flaw occurrence and compare it against predefined acceptance criteria, such as defect type, size and frequency. The resulting analyses are then used to develop NDE programs that ensure the structural integrity and reliability of the component or system. [3]

A. Liquid penetrant

Penetrant testing (PT) is a rapid, cost effective and high sensitivity nondestructive evaluation technique widely used to detect surface-breaking discontinuities. This technique is suitable for the inspection of a wide range of materials, components, and structural systems, enabling the identification of defects that may originate from the manufacturing process, material imperfections, service conditions or environmental degradation. Owing to its portability and ease of application, PT is particularly well suited for field inspections and evaluations conducted in remote or difficult to access locations.

For penetrant testing to provide reliable results, the discontinuities must be connected to the surface and the test specimen must be thoroughly cleaned before inspection. In addition, accurate interpretation of the indications requires adequate visual capability on the part of the inspector.

The method operates by allowing a low-viscosity penetrant to infiltrate surface-breaking defects through capillary action. After excess penetrant is removed and

the developer is applied, the penetrant trapped within the discontinuities is drawn back to the surface, creating visible indications that facilitate defect detection and evaluation. For a discontinuity to be detected, the penetrant must provide sufficient visual contrast with the test surface and be able to emerge from the defect under suitable inspection conditions. A developer, which acts as a blotting medium, is then applied to draw the penetrant out of the discontinuity, creating a visible indication that outlines the defect. This process represents the fundamental principle of penetrant testing. Compared with many other nondestructive testing methods, penetrant testing requires relatively less operator training and mechanical skill. However, successful inspections depend on strict adherence to cleanliness requirements, proper inspection procedures, appropriate processing times, and a thorough understanding of the types of discontinuities that may be present in the components being examined. Before performing any nondestructive testing procedure, a thorough visual inspection of the component surface should be carried out to identify any surface conditions that could affect the accuracy or reliability of the subsequent examination [3].

Surface preparation is a critical step in penetrant testing, as it ensures that no contaminants interfere with the inspection process. Rust, dirt, paint, protective coatings, oil must be completely removed to ensure that surface breaking discontinuities remain open and accessible to the penetrant. Once the surface has been adequately cleaned, the penetrant is applied and allowed to dwell for a specified period, enabling it to penetrate any surface connected defects. The inspection procedure establishes the appropriate penetrant type and the duration of the dwell period, ensuring sufficient time for the penetrant to enter surface connected discontinuities through capillary action. After the penetration stage, the excess penetrant is removed from the sample surface using a suitable

cleaning method while preserving the penetrant retained within the defects. A thin, uniform layer of developer is subsequently applied to the inspection area. The developer extracts the penetrant trapped inside the discontinuities and simultaneously creates a high-contrast background, thereby improving the clarity and detectability of the resulting indications. Once the indications have been interpreted and, when required, recorded for documentation purposes, the inspected surface undergoes a final cleaning operation to remove any residual developer and penetrant, restoring the component to a clean condition [4].

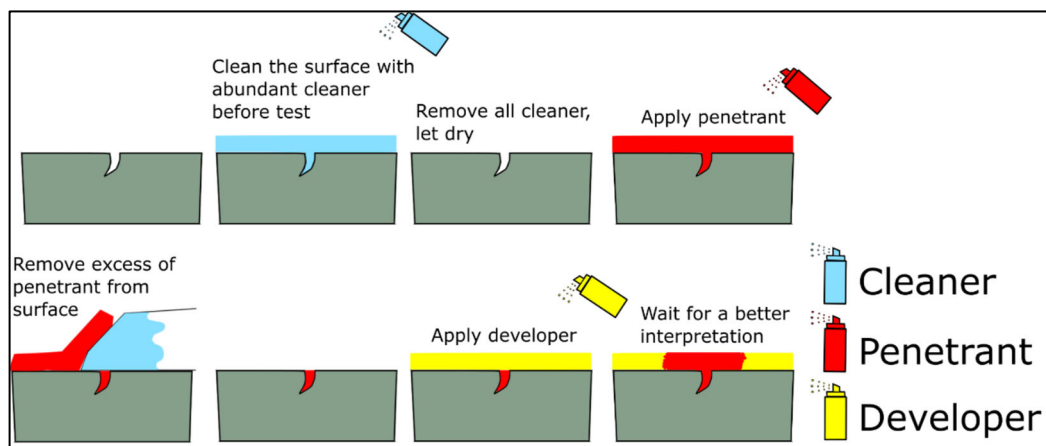


Figure 3.26. Procedure for Penetrant testing [3]

Table 3.9. Advantages and disadvantages of Liquid penetrant

Advantages	Limitations
Low cost and economical inspection method	Detects only surface-breaking discontinuities
Simple and easy to apply with minimal operator training	Performance is reduced on hot, dirty, rough or contaminated surfaces
Applicable to a wide range of materials	Not suitable for porous materials
Rapid inspection process	The inspection process can be messy
Does not require an external power supply	Involves HSE considerations related to penetrant materials and cleaning agents.
Enables 100% surface inspection of a component	Limited by operating temperature range of the penetrant materials

Portable and suitable for field applications	Results can be highly dependent on operator skill and interpretation
Suitable for batch inspections	Requires removal of surface coatings

The principle that “cleanliness is essential” is particularly important in penetrant testing (PT). Proper surface preparation, commonly referred to as precleaning, is a critical step that directly influences the effectiveness and reliability of the inspection. Inadequate or improper cleaning is one of the most common reasons for failing to detect existing discontinuities. For the penetrant to successfully identify defects, it must be able to freely enter surface-breaking discontinuities. Therefore, contaminants, foreign materials and surface irregularities must be removed to prevent them from blocking penetrant entry or producing misleading indications. The cleaning procedure should effectively remove contaminants such as oil films, dirt, grease, rust, paint coatings, slag, welding flux residues and any remaining traces of cleaning agents from the inspection surface. The selected cleaning method must be appropriate for both the type of contaminant being removed and material being inspected while avoiding damage such as corrosion, erosion or chemical attack. Common surface cleaning techniques used in PT include detergent cleaning, solvent cleaning and abrasive cleaning methods.

An effective penetrant must perform two primary functions. First, it must serve as a highly visible indicator capable of revealing surface discontinuities. Second, it must act as a liquid capable of revealing surface discontinuities. Second, it must act as a liquid carrier that transports the indicating material across the test surface and allows it to penetrate the depth of surface breaking defects. Penetrants are generally classified into two main types:

- Type I – fluorescent penetrants – use brightness contrast and are typically viewed under ultraviolet light (UV) to reveal indications.



- Type II – visible (dye) penetrants – use color contrast between the penetrant and the test surface to make discontinuities visible under normal lighting conditions.

Visible dye penetrants are examined under normal white light conditions. The most used colorant is a bright red dye, which provides a strong contrast against the white background produced by most developer materials. Other colors may be selected when they offer improved contrast or specific advantages for a particular application. Red dyes are widely used because of their suitable particle size, high solubility in the penetrating oils, and excellent visibility against the developer background. However, red dye penetrants are generally avoided for components requiring repeated in-service inspections, as residual dye can be difficult to completely remove from surface discontinuities and may interfere with future examinations.

Fluorescent penetrants require inspection under UV light radiation, commonly referred to as black light, with wavelengths typically ranging from 320 to 400 nm. To achieve maximum sensitivity, inspections are often performed under reduced lighting conditions or in a darkened environment. The fluorescent dyes within the penetrant absorb UV radiation and emit visible light at longer wavelengths, primarily under low-light conditions, allowing very small discontinuities to be detected with high contrast. [3]. Any type of penetrant may be applied by immersion, spraying or brushing with the selection of the application method depending on the size, geometry, quantity and accessibility of the components being inspected. Brushing and spraying are widely used methods for penetrant application, particularly during field inspections. Soft bristle brushes, like those used for painting, are commonly used. However, brushes should be reserved exclusively for penetrant application to avoid contamination. Spray application may be carried out using either a conventional

spray gun or aerosol containers containing the penetrant. When applying penetrant with an aerosol can, maintaining approximately 6-8 inches from the test surface helps achieve even coverage while reducing excessive overspray.

Adequate ventilation should always be provided during spraying operations to ensure a safe working environment. Dwell time, also known as penetration time, refers to the duration between the application of the penetrant and the removal of excess penetrant from the surface. This period allows the penetrant to sufficiently wet the surface and flow into any surface connected discontinuities. The required dwell time is influenced by several factors, including the inspection temperature, material type, surface condition, characteristics of the discontinuity, and the properties of the penetrant being used. Temperature plays an important role in determining penetration time. At higher temperatures, penetrants generally enter discontinuities more quickly, resulting in shorter required dwell times. Conversely, colder conditions require longer dwell periods. Most commercial penetrants systems are intended for use at temperatures between 10°C and 49°C. When inspections are performed outside this range, especially at lower temperatures, additional qualification testing or procedure verification may be required to confirm that the desired level of sensitivity can be achieved. In some situations, heating the test component or penetrant may be necessary. Longer dwell times may also be required when the surface has not been properly cleaned or when surface conditions reduce penetrant accessibility. However, excessive dwell times or elevated temperatures can cause the penetrant to dry, which may reduce inspection effectiveness and require the penetrant to be reapplied.

The material being inspected also affects dwell time requirements. High strength and high-temperature alloys, such as stainless steel, titanium and tungsten alloys, typically require longer penetration times than conventional



ferrous materials. According to ASTM E1417, a minimum dwell time of approximately 10 minutes is recommended for common alloys under normal ambient conditions, while specialized alloys may require substantially longer periods. Certain difficult to detect discontinuities, including intergranular stress corrosion cracking and fatigue cracks subjected to compressive stresses, may require extended dwell times, sometimes exceeding 24 hours, to achieve reliable detection.

The removal of excess penetrant using solvents is one of the most widely used techniques, particularly for field inspections conducted with portable penetrant testing equipment. In this process, most of the excess penetrant is initially removed from the test surface using clean, dry cloths. The remaining surface penetrant is then carefully removed by wiping with fresh cloths lightly moistened with a suitable solvent compatible with the penetrant system. The cloths should be damp rather than heavily saturated to avoid unintentionally removing penetrant from within the discontinuities. Effective excess penetrant removal requires proper technique and operator experience. The inspector must ensure that all unwanted penetrant is eliminated from the surface while preserving the penetrant trapped inside the surface breaking defects. Maintaining this balance is essential for producing clear and accurate indications during the inspection process.

Once the excess penetrant has been removed, the inspected surface is coated with a thin layer of developer. This material extracts penetrant retained within surface discontinuities through capillary action, producing well-defined indications that facilitate accurate defect detection and interpretation. The developer serves two important purposes: first, it draws the penetrant retained within discontinuities back to the surface, acting as a blotting agent; second, it helps spread the extracted penetrant to produce clearer and more easily

detectable indications. The primary component of most developers is a fine powder that enhances flaw visibility by removing penetrant from defect cavities through two mechanisms: absorption, which transfers the penetrant into the developer particles, and adsorption, which causes the penetrant to adhere to the outer surface of those particles. In addition to extracting penetrant from discontinuities, the developer creates a contrasting background that improves typically appears dark blue or black under ultraviolet light, providing contrast with the yellow-green fluorescence emitted by the penetrant. In visible dye penetrant testing, the developer forms a white background that enhances the contrast with the colored penetrant indications, allowing defects to be more easily observed and evaluated.

Accurate evaluation of penetrant testing (PT) results relies on the inspector's knowledge, experience, and understanding of the inspection process. Inspectors must be capable of identifying various types of discontinuities while distinguishing true defect indications from false or irrelevant ones. Reliable interpretation also depends on adequate lighting conditions and the inspector's visual capabilities, including satisfactory near vision acuity and color discrimination. The progression of penetrant indications over time can provide useful information about the characteristics of a defect. Surface breaking discontinuities located close to the surface typically produce indications quickly, whereas deeper defects require more time for the penetrant to emerge, resulting in indications that develop more gradually.

In general, defects with a greater volume retain more penetrant, producing larger and more visible indications after the developer has been applied. To ensure traceability and facilitate subsequent evaluation, penetrant testing results are commonly documented using photographic techniques. For temporary documentation, the developed indications may be preserved by

applying a transparent plastic coating, which maintains the image after it has been removed from the component. Alternatively, transparent adhesive tape can be used to lift the developed indication from the surface, providing a practical and reliable method for retaining inspection records.

B. Ultrasonic testing (UT)

Despite the complexity of ultrasonic testing (UT) theory and instrumentation, its fundamental operating principle is relatively simple. The technique is based on the propagation of high frequency sound waves, whose frequencies exceed the upper limit of human hearing, through test material. Although ultrasonic waves can travel through solids, liquids and gases, nondestructive evaluation primarily relies on their propagation through solid materials. As these waves travel, they interact with internal features such as boundaries, discontinuities, and changes in material properties in predictable ways that can be described using the principles of wave mechanics. Ultrasonic waves are generated and detected by a transducer, allowing information about the internal condition of a material to be obtained without causing damage.

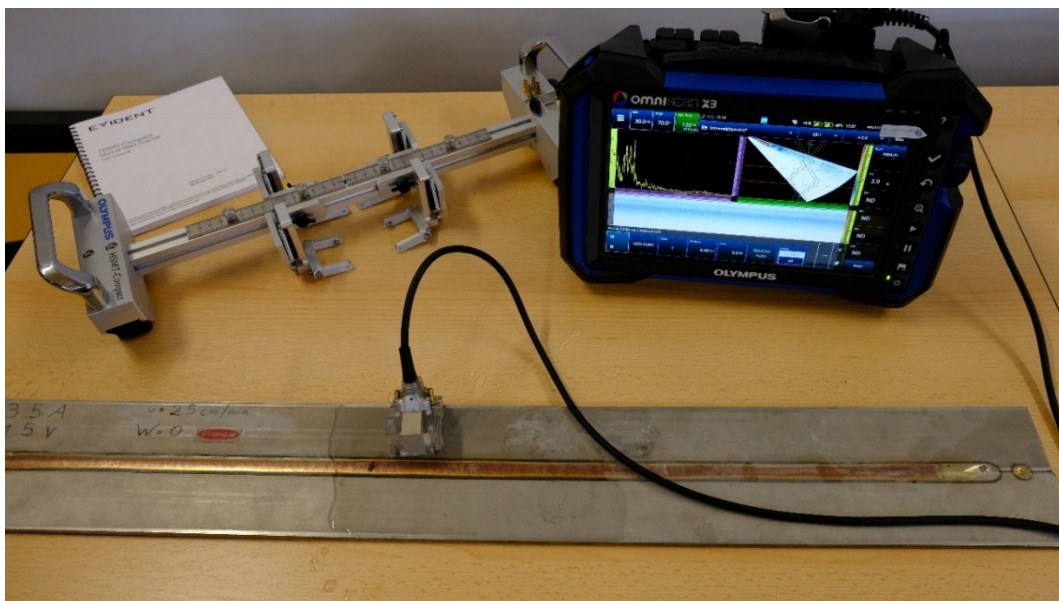


Figure 3.27. Ultrasound testing equipment [7]

By analyzing the reflected or transmitted waves, it is possible to determine material thickness, detect and characterize internal flaws and evaluate mechanical properties such as elasticity. Owing to its high sensitivity, accuracy and versatility, ultrasonic testing has become one of the most widely employed nondestructive testing techniques in industries including aerospace, pipeline inspection, metal fabrication, semiconductor manufacturing and power generation. Ultrasonic testing operates by generating and transmitting high frequency sound waves into a material to evaluate its internal condition [4].

The process begins when a transducer converts electrical excitation into an ultrasonic pulse which propagates through the test specimen. As the wave travels it interacts with the material's internal features, geometric boundaries and physical properties. The transmitted energy is then detected either by a second transducer positioned on the opposite side of the specimen (through-transmission or pitch-catch technique) or by the same transducer after reflection from internal interfaces or discontinuities (pulse-echo technique). The received acoustic signal is converted back into an electrical signal and displayed for analysis by the inspection instrument. The characteristics of the received signal provide detailed information about the inspected component. By evaluating parameters such as signal amplitude, propagation time and waveform characteristics, ultrasonic testing can be used to determine the thickness of a component or the velocity of sound within the material. In addition, the technique enables the detection and characterization of internal discontinuities, including their location, dimensions, orientation and in some cases, their likely nature. Ultrasonic measurements can also be employed to assess material properties, including density and elastic parameters such as Young's modulus and Poisson's ratio, as well as the characterization of complex geometries and multilayered structures.

Modern ultrasonic systems further enhance inspection capabilities by scanning the transducer across the sample surface. This approach allows multiple measurements to be combined into 2D or 3D images, providing a detailed visualization of the internal structure and improving the identification and characterization of defects. Ultrasonic testing (UT) is recognized as one of the most effective and adaptable nondestructive evaluation techniques for assessing the integrity of engineering materials and structures. Its ability to detect internal discontinuities with high accuracy has led to widespread adoption in sectors such as aerospace, energy, manufacturing, transportation and civil infrastructure. Together with radiographic testing, ultrasonic testing is among the few NDT methods capable of reliably identifying defects located deep beneath the material surface.

A major advantage of UT over radiographic methods is the absence of ionizing radiation which makes the inspection safer for personnel and reducing environmental and regulatory constraints. In addition, UT offers considerable flexibility in inspection techniques. Measurements can be performed using conventional contact transducers or advanced non-contact systems, including laser-based ultrasonic methods that allow remote inspection over distances of several meters. Furthermore, the wide variety of probe designs available enables the examination of components with simple or highly complex geometries. The technique is also suitable for a broad range of materials, including metals, composites, ceramics, polymers and certain biological materials. Despite its many advantages, ultrasonic testing also presents several challenges. The reliability of an inspection depends heavily on the knowledge and experience of the operator, particularly during probe positioning, signal interpretation, and defect characterization [5]. Although non-contact approaches continue to evolve, most industrial inspections still require the use

of a liquid or gel couplant to ensure efficient transmission of ultrasonic energy into the test specimen. Additionally, defects whose principal surface is oriented parallel to the direction of wave propagation may generate weak or no reflections, reducing the probability of detection. Finally, the cost associated with specialized equipment, calibration procedures, and personnel training can make ultrasonic testing more expensive than several other conventional nondestructive testing methods.

Ultrasonic transducers may also be classified according to the direction in which ultrasonic energy is introduced into the test material. Based on this criterion, they are divided into straight beam (normal) and angle beam transducers. Straight beam transducers generate ultrasonic waves that enter the specimen perpendicular to the inspection surface and are commonly employed for thickness measurements and the detection of defects oriented normal to the direction of wave propagation. In contrast, angle beam transducers direct the ultrasonic beam into the material at a predefined angle, making them particularly suitable for inspecting welds and detecting discontinuities with orientations that are difficult to evaluate using normal-beam techniques. Angle beam probes are generally constructed by coupling a conventional longitudinal wave transducer to an acoustic wedge, which is typically fabricated from a polymeric material. The wedge alters the propagation direction of the ultrasonic wave before it enters the specimen. According to Snell's law, the refracted angle within the test material depends on the acoustic velocities of both the wedge and the specimen. Therefore, it differs from the physical angle of the wedge [4].

Commercial angle beam transducers are usually calibrated and designated according to the refracted beam angle obtained in steel. Consequently, when inspecting materials with different acoustic properties, the refracted angle must be recalculated to ensure accurate positioning of the ultrasonic beam. At the

interface between the wedge and the test material, the incident longitudinal wave may undergo mode conversion, producing longitudinal waves, shear waves and under certain conditions surface waves. Because these wave modes propagate at different velocities, echoes originating from the same reflector may reach the transducer at different times, increasing the complexity of signal interpretation. To simplify the inspection process and enhance defect characterization, most industrial angle beam probes are designed so that the incident angle lies between the first and second critical angles. Under these conditions, the transmitted energy is converted predominantly into a shear wave, minimizing the generation of additional wave modes and improving inspection reliability [5].

Ultrasonic probes can be differentiated by the direction of wave propagation and by the number of piezoelectric elements incorporated into their design. Although single element transducers are widely used in conventional ultrasonic inspections, many applications benefit from the enhanced performance offered by dual element and multi element transducers. A dual element transducer integrates two independent piezoelectric crystals within a common probe housing, with one element dedicated to transmitting ultrasonic energy and the other to receiving the reflected signals. This arrangement reduces the influence of the transducers near field region and dead zone, resulting in improved sensitivity and resolution for defects located close to the inspection surface. Consequently, dual element probes are frequently employed for corrosion monitoring, thickness measurements and the detection of shallow discontinuities. An extension of this concept is the transducer array, which consists of numerous miniature piezoelectric elements arranged in a linear or two-dimensional configuration. Unlike conventional probes, the individual elements of an array can be activated independently according to precisely

controlled time delays. By adjusting the excitation sequence, the emitted ultrasonic waves interfere constructively in the desired direction while destructive interference suppresses unwanted wave propagation. This principle enables electronic steering, focusing and scanning of the ultrasonic beam without requiring mechanical movement of the probe.

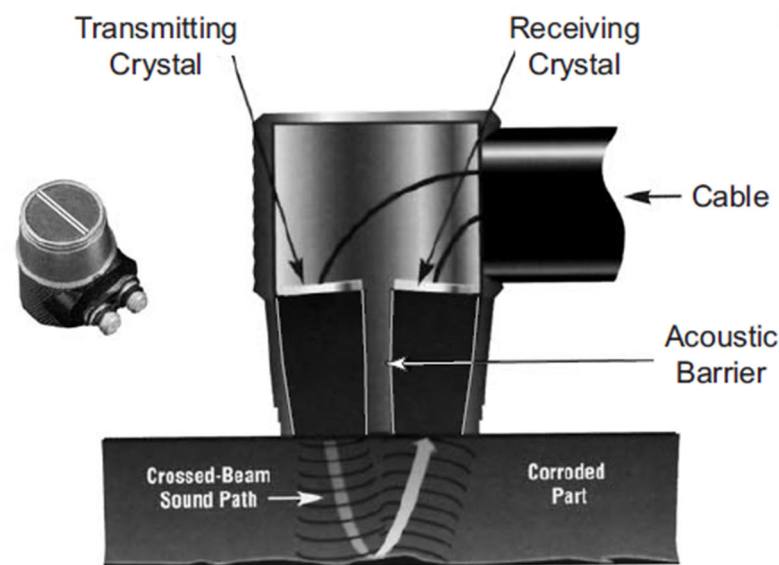


Figure 3.28. Double element transducer [4].

Such systems are referred to as phased-array ultrasonic transducers and represent one of the most advanced developments in ultrasonic nondestructive testing. Because each element is designed to be very small, it behaves approximately as a point source of ultrasonic energy, allowing precise control of the acoustic field. This capability provides superior inspection flexibility, faster data acquisition and improved defect detection and characterization compared with conventional single element transducers. [4]. The transducers can also be categorized according to the geometry of their active surface, with the two principal configurations being flat face and focused transducers. Flat face transducers, which possess a planar emitting surface, are the most widely used because they are suitable for a broad range of conventional ultrasonic



inspections. Nevertheless, specialized applications often require transducers with modified surface geometries to improve acoustic performance or adapt to the characteristics of the test component. Focused transducers are designed either to conform to the profile of the inspected surface or to concentrate ultrasonic energy within a defined region of the material. Transducers with contoured contact surfaces provide improved acoustic coupling when examining curved or irregular components, thereby reducing energy losses at the interface.

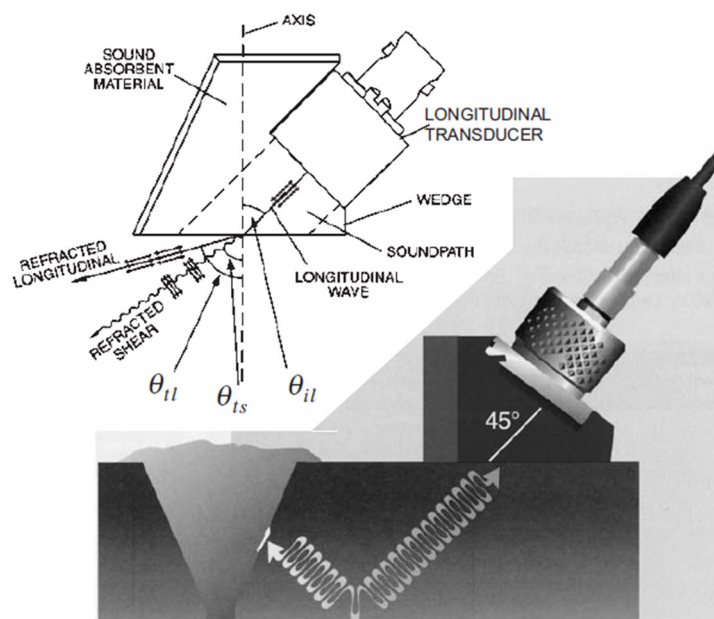


Figure 3.28. Angled beam transducer [4].

Alternatively, transducers with acoustically focused beams concentrate the ultrasonic energy at a predetermined focal distance, increasing signal intensity and enhancing the detectability of small discontinuities. Depending on the application, the ultrasonic beam may be focused into either a line or a point, allowing higher spatial resolution than can be achieved with conventional flat probes. However, beam focusing is subject to inherent physical limitations. The focal region has a finite size rather than forming an ideal point and the beam remains effectively focused only within a limited depth of field. Outside this region, beam divergence increases, reducing both sensitivity and lateral

resolution. Consequently, the focal characteristics of the transducer must be selected according to the geometry of the component and the expected location of defects to achieve optimum inspection performance [4].

The effectiveness of an ultrasonic inspection depends on the appropriate selection of several key parameters before testing begins. The inspection objective must first be clearly defined by determining the material characteristic or discontinuity to be evaluated. Based on this objective, a suitable transducer should be chosen to generate the required ultrasonic wave mode, such as longitudinal, shear, surface or focused waves, each of which is optimized for specific inspection conditions. The inspection technique must then be selected according to the component geometry and the desired information. Depending on the application, ultrasonic measurements may be performed using either the pulse-echo configuration, in which a single transducer transmits and receives the ultrasonic signal, or the pitch-catch configuration, where separate transducers are used for transmission and reception. Another important consideration is the excitation method used to generate the ultrasonic waves. Common excitation techniques include spike pulses, tone-burst signals and continuous-wave excitation, each offering specific advantages in terms of penetration depth, signal resolution and frequency characteristics. Finally, an appropriate signal acquisition and analysis strategy must be established. The received ultrasonic data may be processed and displayed in different formats, such as echo amplitude as a function of time, signal attenuation relative to probe position or other imaging representations. Depending on the inspection requirements, the evaluation may consist of localized measurements at selected points or systematic scanning of the entire inspection area to obtain a complete assessment of the components condition [5].

These methods differ considerably in terms of their inspection principles, defect detection capabilities, sensitivity and practical limitations. Consequently, the



selection of an appropriate NDT technique should be based on the material characteristics, manufacturing process, expected defect morphology and inspection objectives. Penetrant testing represents another widely used surface inspection technique; however, its effectiveness for as built additively manufactured metallic components is often limited by the high surface roughness produced during the manufacturing process. Surface finishing operations, including machining and polishing, can significantly improve inspection performance by producing smoother surfaces and facilitating defect identification. Ultrasonic testing has become an increasingly important inspection method owing to its ability to detect internal discontinuities without exposing operators to ionizing radiation.

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CHAPTER 4

HAZARDOUS WASTE DISPOSAL AND TREATMENT IN HOSPITALS

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This chapter presents the main categories of hazardous healthcare waste and explains how hospitals can collect, separate, treat and dispose of them safely, in order to protect patients, staff, waste handlers and the environment.

4.1 HAZARDOUS WASTE DEFINITION AND REGULATIONS

As in any activity in which many people are involved, the functioning of hospitals results in a lot of garbage, but in addition to the waste we are daily used, there is also waste that can have dangerous effects. The term “**healthcare waste**” is used by European Union (EU) and World Health Organization (WHO) while “**medical waste**” is used in many countries (US, China and South Korea). In Japan is used the term “**infectious waste**” [1]. Administrative, kitchen, housekeeping



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and maintenance functions of healthcare facilities produce between 75% and 90% of the total waste generated by healthcare providers [2], which is comparable to household waste and is usually referred to as “non-hazardous” or “general medical waste.”

According to World Health Organization (WHO) [2] “The term **healthcare waste** includes all the waste generated within healthcare facilities, research centres and laboratories related to medical procedures. In addition, it includes the same types of waste originating from minor and scattered sources, including waste produced in the course of healthcare undertaken in the home (e.g. home dialysis, self-administration of insulin, recuperative care)”.

“**Medical waste** is a subset of waste generated at health care facilities, such as hospitals, physicians' offices, dental practices, blood banks, and veterinary hospitals/clinics, as well as medical research facilities and laboratories. Generally, medical waste is healthcare waste that may be contaminated by blood, body fluids or other potentially infectious materials and is often referred to as regulated medical waste” [3].

According to the Waste Management and Public Cleansing Act [4], “the **infectious wastes** are defined as waste materials generated in medical institutions as a result of medical care or research which contain pathogens that have the potential to transmit infectious diseases”.

International regulations on hazardous waste:

- Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (UNEP, 1992) [5].
- Bamako Convention (1991) [6].
- Stockholm Convention on Persistent Organic Pollutants (UNEP, 2004) [7].

- Agenda 21 (plan of action for the 21st century adopted by 173 heads of State at the Earth Summit held in Rio in 1992) [8].
- United Nations Recommendations on the transport of dangerous goods, ST-SG-AC10/1/Rev.21, 2019 [9]
- Safe health-care waste management, WHO, 2004 [10].
- WHO core principles for achieving safe and sustainable management of health-care waste, 2007 [11].

European regulations on hazardous waste:

- Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives [12].
- Commission Regulation (EU) No 1357/2014 of 18 December 2014 replacing Annex III to Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directive [13].
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- 2014/955/EU: Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council [17].



USA regulations on hazardous waste:

- Guidelines for Environmental Infection Control in Health-Care Facilities, U.S. Department of Health and Human Services, 2003 [18].

Japanese regulations on hazardous waste:

- Waste management and public cleansing law [19].

4.2 Hazardous waste classification

Hospital waste can be categorized based on the type of waste, the location of the waste, and the type of infectious disease [4]. Classification according to the **waste type** is presented in Table 4.1.

Table 4.1. Classification of hospital waste according to form of waste [1, 20-22]

Category	EU/code*	WHO	USA
Terminology	Healthcare waste	Healthcare waste	Medical Waste
Sharps	Sharps Code 18 01 01	Sharps	Contaminated sharps/Unused sharps
Body parts and organic including blood bags and blood preserves	Body parts and organs including blood bags and blood preserves Code 18 01 02	Pathological	Bulk human blood/Pathological wastes
Waste whose collection and disposal is subject to special requirements to prevent infections	Human and Animal Infectious Code 18 01 03	Infectious	Isolation/Cultures and stocks of infectious agents and associated biologicals/animal wastes
Waste whose collection and disposal are not	Infectious Code 18 01 04	Infectious	-

subject to special requirements to prevent infection (e.g., dressings, plaster casts, linen, etc.)			
Chemicals consisting of or containing dangerous substances	Chemical Code 18 01 06	Chemical	-
Chemicals other than those mentioned in 18 01 06	Chemical/ Unused hazardous medicines Code 18 01 07	Chemical	Small volumes of chemical hazardous waste
Cytotoxic and cytostatic medicines	Unused hazardous medicines Code 18 01 08	Cytotoxic	Antineoplastic drug
Chemicals other than those mentioned in 18 01 08	Unused non-hazardous medicines Code 18 01 09	Pharmaceutical	Small volumes of chemical hazardous waste
Amalgam waste from dental care	Amalgam waste from dental care Code 18 01 10	Amalgam waste from dental care	-
Radioactive waste		Waste containing radioactive substances	
Non-hazardous or general healthcare waste		Waste that does not pose any particular biological, chemical, radioactive or physical hazard	



Healthcare waste includes a broad group of materials produced during medical care, laboratory work, diagnosis, treatment, research and related support activities. Some of these materials are similar to normal municipal waste. Others require strict control because they can injure people, transmit infection, contain dangerous chemicals or include radioactive substances. Correct classification is therefore the starting point for safe collection, storage, transport, treatment and final disposal.

Sharps waste

Sharps waste includes objects that can cut, pierce or scratch the skin. Typical examples are scalpels, surgical blades, knives, hypodermic needles, infusion sets, saws, broken glass, pipettes and other small pointed instruments used in medical or laboratory work. These items are dangerous even when there is no visible blood. A needle or a broken ampoule can create a wound in a second, and the wound can become an entry point for infectious agents.

For this reason, sharps are usually treated as highly hazardous healthcare waste. The safe rule is simple. Every sharp object used in a healthcare environment should be handled as potentially contaminated. This approach protects medical staff, cleaning personnel, waste handlers and anyone who may come into contact with the waste after it leaves the clinical area.

Pathological and anatomical waste

Pathological waste is often close to infectious waste, but it is normally kept as a separate category because the handling, treatment and final disposal may require specific procedures. This group includes tissues, organs, body parts, blood, body fluids and other materials removed during surgery, autopsy or medical investigation, especially when they come from patients with infectious

diseases. Human fetuses and carcasses of infected animals are also included in this category.

Anatomical waste refers more specifically to recognizable body parts from humans or animals. These materials may come from surgery, medical research, teaching activities or diagnostic procedures. Some removed body parts may not be infected. Even so, they can still be classified as pathological waste because of ethical, legal, cultural and safety considerations. Respectful handling is needed, together with secure packaging and clear routing inside the healthcare facility.

Infectious waste

Infectious waste contains, or is suspected to contain, microorganisms in quantities that may cause disease in people who are exposed. The pathogens may be bacteria, viruses, fungi or parasites. The risk depends on the type of pathogen, the quantity present, the survival of the organism in the environment and the susceptibility of the exposed person.

This category usually includes materials contaminated with blood or other body fluids, waste from isolation rooms and laboratory materials that contain cultures or stocks of infectious agents. It may also include dressings, swabs, disposable instruments, tubing, personal protective equipment and other items used during care of infected patients. The classification must be made carefully because poor separation increases the risk for staff and also increases the volume of waste that needs special treatment.

Common examples of infectious waste

- Materials contaminated with blood or other body fluids.
- Cultures, stocks and residues of infectious agents from laboratory activities.

- Waste generated during the care of infected patients, including waste from isolation wards.

Pharmaceutical waste

Pharmaceutical waste consists of medicines and pharmaceutical products that can no longer be used safely or legally. This includes expired products, unused medicines, spilled products, contaminated pharmaceuticals, vaccines, sera and prescription or proprietary medicines that are no longer needed. These materials cannot be treated like general waste because their chemical or biological activity may remain even after disposal.

Items contaminated with pharmaceutical residues also belong in this group. Examples include gloves, masks, connecting tubes, bottles, vials, boxes and other materials used during preparation, administration or handling of medicines. The problem is not limited to the drug itself. Packaging and accessories can carry residues and must be managed with the same care when contamination is present.

Genotoxic waste

Genotoxic waste is one of the most dangerous fractions of healthcare waste. It can damage genetic material and may be mutagenic, teratogenic or carcinogenic. In practical terms, this means that it may cause genetic mutations, affect embryos or fetuses, or contribute to cancer. Because of these risks, genotoxic waste needs strict separation, trained personnel and controlled disposal methods.

Examples include some cytostatic medicines, certain chemicals, radioactive substances and contaminated patient excreta such as vomit, urine or feces from patients treated with cytostatic drugs. The term genotoxic means toxic to



deoxyribonucleic acid, or DNA. This explains why exposure must be kept as low as possible, inside and outside the hospital.

Cytotoxic and cytostatic waste

Cytotoxic and cytostatic waste is closely linked with cancer therapy, but its use is not limited to oncology. Cytotoxic means harmful to cells. Cytostatic means that cell growth and multiplication are restricted. Antineoplastic substances are used to stop abnormal tissue growth, while chemotherapeutic substances are used in treatment, especially cancer treatment. Many medicines from this group can kill or inhibit selected living cells. That makes them useful in therapy and dangerous when they are handled as waste.

These medicines have an important role in treating many neoplastic diseases. They are also used more often as immunosuppressive agents in organ transplantation and in some immune-related diseases. In hospitals, they are commonly used in oncology and radiotherapy units. Their use has also expanded to other departments, outpatient clinics and care settings outside large hospitals. Waste management must therefore follow the drug, not only the department.

Main groups of cytostatic drugs

- Alkylating agents. These substances alkylate DNA nucleotides and may produce cross-linking and miscoding of genetic material.
- Antimetabolites. These interfere with the biosynthesis of nucleic acids inside the cell.
- Mitotic inhibitors. These prevent or disturb cell replication.

Typical sources of cytotoxic waste

- Materials contaminated during preparation or administration, such as syringes, needles, gauze, vials and packaging.



- Expired medicines, remaining solutions and drugs returned from wards or treatment areas.
- Urine, feces and vomit from treated patients, because these may contain dangerous quantities of cytostatic drugs or their metabolites. These excreta should normally be considered genotoxic for at least 48 hours after administration, and in some cases for up to one week.

Chemical waste

Chemical waste includes discarded solids, liquids and gases used in healthcare facilities. These substances may come from cleaning, disinfection, diagnostic work, laboratory analysis, maintenance or experimental activities. Some chemicals are used every day and may seem familiar. That does not make them harmless. Their risk depends on concentration, reactivity, exposure route and the quantity stored or discarded.

A chemical waste stream is considered hazardous when it has one or more dangerous properties. It may be toxic, corrosive, flammable, reactive or oxidizing. Acids with pH below 2 and bases with pH above 12 are typical examples of corrosive waste. Reactive substances may explode, react with water or respond dangerously to shock. Because of these properties, chemical waste must be labeled, stored and transported with attention to compatibility.

Hazardous properties of chemical waste

- Toxic or harmful to people, animals or the environment.
- Corrosive, for example strong acids or strong bases.
- Flammable and able to ignite under normal or foreseeable conditions.
- Reactive, including explosive, water-reactive or shock-sensitive materials.
- Oxidizing, with the ability to intensify combustion or react strongly with other substances.



Radioactive waste

Radioactive waste contains materials contaminated with radionuclides. In healthcare, these materials are generated during diagnostic, therapeutic and research activities. Examples include in vitro analysis of tissues and fluids, in vivo imaging of organs, tumor localization and different investigative or treatment procedures. Radioactive sources used in medicine may be sealed or unsealed.

Unsealed sources are often liquids or other substances administered directly to the patient or used in laboratory procedures. Sealed sources are radioactive materials enclosed in equipment components or in resistant objects, such as needles, pins or seeds. The type of source influences the waste generated, the exposure route and the control measures needed. Radioactive waste also appears during storage, maintenance and decontamination of equipment or areas used for radionuclide work.

Examples of radioactive waste from medical and research activities

- Sealed sources that are no longer used.
- Spent radionuclide generators.
- Low-level solid waste, such as absorbent paper, swabs, glassware, syringes and vials.
- Residues from shipments of radioactive material and unwanted radionuclide solutions prepared for diagnosis or therapy.
- Water-immiscible liquids, including liquids used in scintillation counting.
- Residues used in radioimmunoassay and contaminated pump oil.
- Waste from spills and from decontamination after radioactive spills.
- Excreta from patients treated or tested with unsealed radionuclides.
- Low-level liquid waste, such as liquid from washing apparatus.
- Gases and exhausts from storage areas and fume cupboards.



Non-hazardous general waste

Non-hazardous or general healthcare waste is material that has not been in contact with infectious agents, dangerous chemicals or radioactive substances. It also does not create a sharps risk. In many healthcare facilities this is the largest waste fraction. It can represent about 85% of the total waste generated, and its characteristics are often close to those of municipal solid waste.

Paper, cardboard and plastics usually form a large part of general hospital waste. Food residues, metals, glass, textiles, wood and other packaging materials are also common. Because this waste is not hazardous when correctly separated, it offers an important opportunity for recycling, composting or other recovery methods. Good separation at the point of generation is essential. Once general waste is mixed with infectious or hazardous waste, the whole quantity may need special treatment.

In the past, general waste was often sent to landfill or burned in municipal incinerators. This approach has changed in many places because of environmental concerns and because a significant part of non-hazardous healthcare waste can be reused, recycled or composted. Local rules and available infrastructure will decide what is possible, but the principle remains useful.

Hospitals should not treat recyclable material as hazardous waste when it has not been contaminated.

Common recyclable materials from healthcare facilities:

- Corrugated cardboard boxes.
- Newspapers and magazines.
- Polyethylene terephthalate, known as PET or PETE, such as plastic water bottles and soft-drink bottles.

- Polystyrene packaging.
- Wood, including shipping pallets.
- Office paper, computer printer paper and colored ledger paper.
- Metals, such as aluminum beverage cans, food tins and other metal containers.
- High-density polyethylene, known as HDPE, including plastic milk containers, food containers, plastic bottles for saline solutions and bottles for sterile irrigation fluids.
- Clear, colored or mixed glass.
- Construction and demolition debris, when it is not contaminated with hazardous materials.

Factors that influence the quantity and type of waste

The amount and composition of healthcare waste vary from one facility to another. A large university hospital will not generate the same waste as a small outpatient clinic. A dialysis center, an operating theatre, a laboratory and a dental office also produce different waste streams. Waste generation changes with activity level, medical specialties, infrastructure and local regulations.

Internal procedures have a strong influence. If segregation is weak, hazardous waste volumes increase because clean material becomes contaminated by poor practice. If staff are trained and containers are placed correctly, separation is easier and safer. Seasonal variation, weekend schedules, availability of materials and the general level of infrastructure in the country can also influence the waste profile. Main factors that affect healthcare waste generation:

- Activity level, including the number of occupied beds, daily patient flow and staff number.

- Type and size of the health facility, such as a medical clinic, county hospital or university hospital.
- Medical specialties and departments, including operating rooms, laboratories and offices.
- Location, including rural or urban setting.
- Legal and policy rules related to waste classification.
- Internal waste management procedures and staff training.
- Time variation, such as weekdays, weekends and seasonal changes.
- Availability of material resources and disposable products.
- Level of infrastructure development in the country or region.

Major and minor sources of healthcare waste

Healthcare waste is produced in many places where medical care, diagnosis, treatment, research or support activities are carried out. Hospitals are usually the largest and most visible source, because they work continuously and include many departments with different risks. A university hospital, a general hospital or a district hospital can generate infectious waste, sharps, pathological waste, pharmaceutical residues, chemical waste and large quantities of general waste every day. The volume is high, and the composition is mixed. For this reason, hospitals need a clear internal system for sorting, collection, storage, transport, treatment and final disposal.

Other healthcare facilities also generate important quantities of waste, even if they are smaller than hospitals. Emergency medical services produce waste during rapid interventions, transport and first aid. Healthcare centers, dispensaries, obstetric and maternity clinics, outpatient clinics and dialysis centers also generate waste that may contain blood, body fluids, sharps, used

medical materials or pharmaceutical residues. Long term care establishments and hospices produce waste through daily patient care, wound treatment, medication use and hygiene activities. Transfusion centers, military medical services and prison hospitals or clinics must also be included in the same waste management planning, because their activities can create regular and sometimes high risk waste streams.

Laboratories and research centers represent another important group. Medical and biomedical laboratories, biotechnology institutions and medical research centers may generate cultures, samples, contaminated materials, chemical residues and biological waste. Their waste can be more concentrated or more specific than waste from normal patient care. It may also require special packaging, labeling and treatment. In these facilities, the risk is not always linked to quantity. Sometimes a small volume can be dangerous because of the biological or chemical agents involved. Several other activities are also considered major sources. Mortuary and autopsy centers can generate pathological and anatomical waste. Animal research and testing facilities may produce contaminated animal carcasses, tissues, bedding and laboratory materials. Blood banks and blood collection services generate blood-contaminated materials, sharps, bags, tubing and testing residues. Nursing homes for older people may also produce healthcare waste regularly, especially when they provide wound care, injections, medication management or support for patients with chronic diseases. These sources must not be ignored only because they are outside the classic hospital structure.

There are also **minor sources of healthcare waste**. They usually produce smaller quantities, but small does not mean harmless. A single needle, a contaminated dressing or a small amount of chemical residue can create risk if it is placed in normal waste or handled without protection. Small healthcare establishments



such as first-aid posts, sick bays, physicians' offices, dental clinics, acupuncture practices and chiropractic clinics need simple but strict procedures. They may not need complex treatment systems on site, but they still need correct segregation, safe containers, temporary storage and authorized collection.

Specialized establishments with lower waste generation also require attention. Convalescent nursing homes, psychiatric hospitals and institutions for persons with disabilities can produce healthcare waste through medication, minor procedures, hygiene care and occasional medical interventions. The waste quantity may vary from one day to another. This makes training and routine procedures even more important, because staff may treat healthcare waste as an exception rather than as a daily responsibility.

Some activities outside conventional healthcare facilities also create medical waste. Cosmetic ear-piercing and tattoo parlors use needles or sharp instruments and can generate blood-contaminated materials. Needle exchange services and places linked to illicit drug use may also generate sharps and infectious risk. These sources are often difficult to control, but they are important for public health. Safe collection and disposal reduce the risk for workers, users, cleaning staff and the wider community.

Funeral services, ambulance services and home treatment are also part of the waste chain. Ambulances produce waste during transport and emergency care. Funeral services may handle materials contaminated during body preparation.

Home treatment is becoming more common, especially for chronic patients, elderly people and patients using injections, dressings, dialysis-related materials or other medical supplies. Waste produced at home can easily enter municipal waste if patients and families are not informed. Clear instructions, safe containers and collection routes are needed.

The classification of waste sources helps to organize responsibility. Large institutions need detailed management plans, trained personnel and continuous monitoring. Smaller sources need simpler procedures, but the same attention to safety. The basic principle is the same in all cases. Healthcare waste must be identified where it is produced, separated correctly, handled safely and transferred only through controlled routes. This protects patients, staff, waste workers and the environment.

Hazardous waste linked with infectious diseases

The treatment and examination of patients with infectious diseases can generate several types of hazardous waste. The exact classification depends on the disease, the procedure, the materials used and the risk of pathogen transmission. In this context, infectious waste includes materials used during treatment and investigation of patients with infectious diseases [4, 23]. Clear separation at the source is important because these materials can expose staff during collection, transport and treatment.

Health risks associated with hazardous medical waste

Hazardous medical waste can create different types of risk. Some risks are immediate, such as cuts from sharps or burns from chemicals. Others may appear after exposure to infectious agents, toxic substances or radiation. A complete waste management system must therefore consider several risk categories at the same time [23].

Main health risk categories

- Trauma risk, mainly from sharps and broken objects.
- Infection risk, from materials contaminated with pathogens.



- Chemical risk, from toxic, corrosive, flammable, reactive or oxidizing substances.
- Fire or explosion risk, especially when incompatible chemicals or pressurized materials are poorly handled.
- Radioactivity risk, from sealed or unsealed radioactive sources and contaminated materials.

Safe healthcare waste management depends on simple actions repeated correctly: classification at the place where waste is produced, suitable containers, clear labeling, trained staff, controlled storage, safe transport and appropriate treatment. When these steps are respected, the hospital protects patients, staff, waste workers and the environment.

4.3 HAZARDOUS WASTE DISPOSAL

To avoid the accumulation of waste and the increase in the number of associated infections, the frequency of medical waste (MW) collection should be as high as once per day. Is important that general waste not to be collected at the same time or in the same carriage as hazardous medical wastes. Waste bags should be filled three quarters full [2].

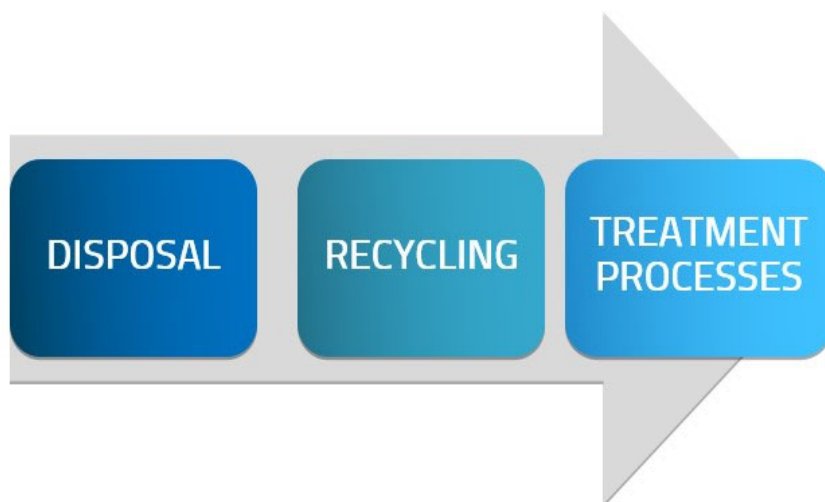


Figure 4.1. Waste treatment facilities [2]

The waste is collected from the health care entity and transported to the treatment facility for one of the 3 situations (figure 4.1).

Treatment facilities can be located:

- within the health care facility or
- off-site, in a special separate location, away from patients and public access depending on the entity possibilities.

Many countries have their national legislation concerning the waste and a colour coding system, that make easier to put the waste in the proper container. Labelling the waste containers is useful to identify the source. There are unanimously accepted few steps that must be strictly followed regarding waste collection before it is handed over for the next stages [24].

4.3.1 Choosing the right container

It is necessary to know exactly which storage container is for a particular medical waste, to ensure that the waste ends up in the correct category and that it will be collected by the designated company. The containers are built to be puncture-resistant and leak-proof to avoid leaks during transport and handling. For example, if a cardboard box is used, it must be assembled so that the joints are sealed with adhesive tape wide enough to ensure the parts are joined together.

4.3.2 Lining the container with a biohazardous waste sealer bag

To protect personnel and the environment, it is recommended that a dedicated hazardous/biological waste bag, which is generally red or orange in colour, be placed in the box/container first. These bags are thick and leak-proof. Medical waste is separated into categories and then placed in special containers. For any separation and collection of medical waste you must consider the legislation of



the respective country. But what is unanimously accepted is that you never throw recyclable waste together with regular garbage and, for example, with sharp objects. Last listed (needles, syringes, scalpels, etc.) are not thrown directly into the bag, but into puncture-resistant and sealable containers. These can then be placed in a larger bin for biologically hazardous waste. Overfilling a container in volume and weight can lead to injuries and leaks during handling (figure 4.2).



Figure 4.2. Level of filling in a box [25]

Closing and sealing the red or orange bag

For this step you need to wear protective equipment (gloves, mask, etc.). It is necessary to remove the air from the top of the bag, so twist and tie with a strong knot to avoid leaks. Then the container/box containing the bag is sealed, taking care not to get any parts of the bag caught between the adhesive tape and the box or between the lid and the box. A correct closure protects any worker who will handle the waste later.

Labelling the container and preparing it for collection

Depending on national regulations and the type of medical waste, it is labelled differently. Generally, most containers are pre-labelled, but if not, it must be

labelled with useful information, namely the name, address of the hospital unit, collection start date, waste category, etc. The area where medical waste is stored and from where it is to be collected must be secured and not accessible to the public [26].

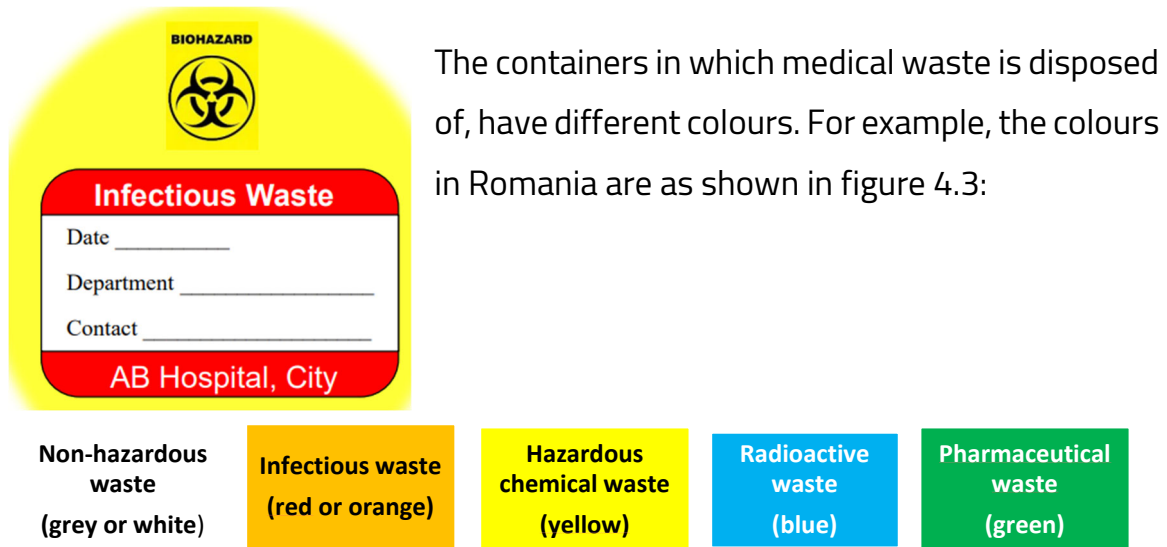


Figure 4.3. Medical waste color code in Romania [27]

In UK hospitals, within the health care facility, the colour code is as below (figure 4.4):



Figure 4.4. Medical waste colour code in United Kingdom [28]

It is necessary to treat this type of waste before the disposal of medical waste, to avoid the negative impact on the environment and health (figure 4.5).

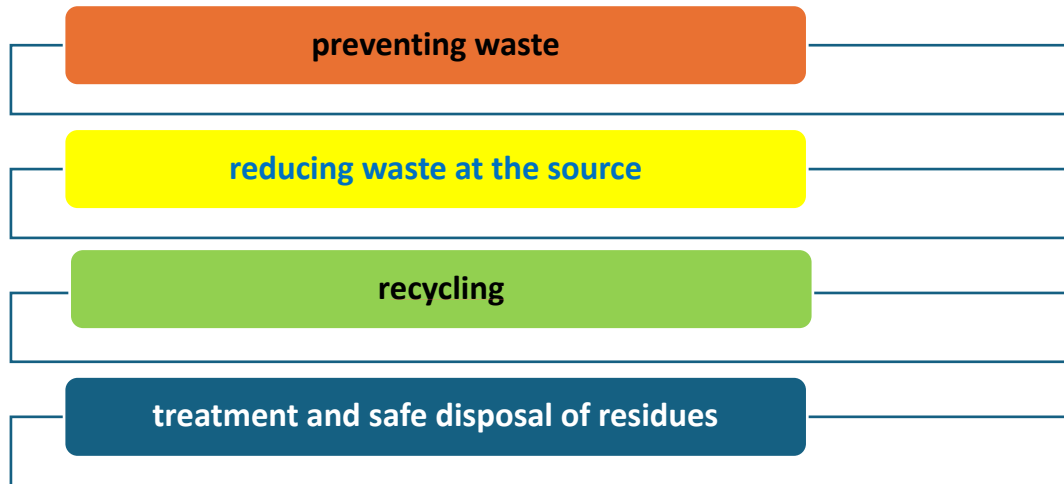


Figure 4.5. Stages of medical waste

Proper training and adherence to guidelines are crucial for the safety of healthcare workers, the public, and the environment.

Some examples of reuse the non-hazardous waste are presented in figure 4.6.



Figure 4.6. The power of 4 R

The impact on the environment and health of medical waste is very dangerous and can be as (figure 4.7):

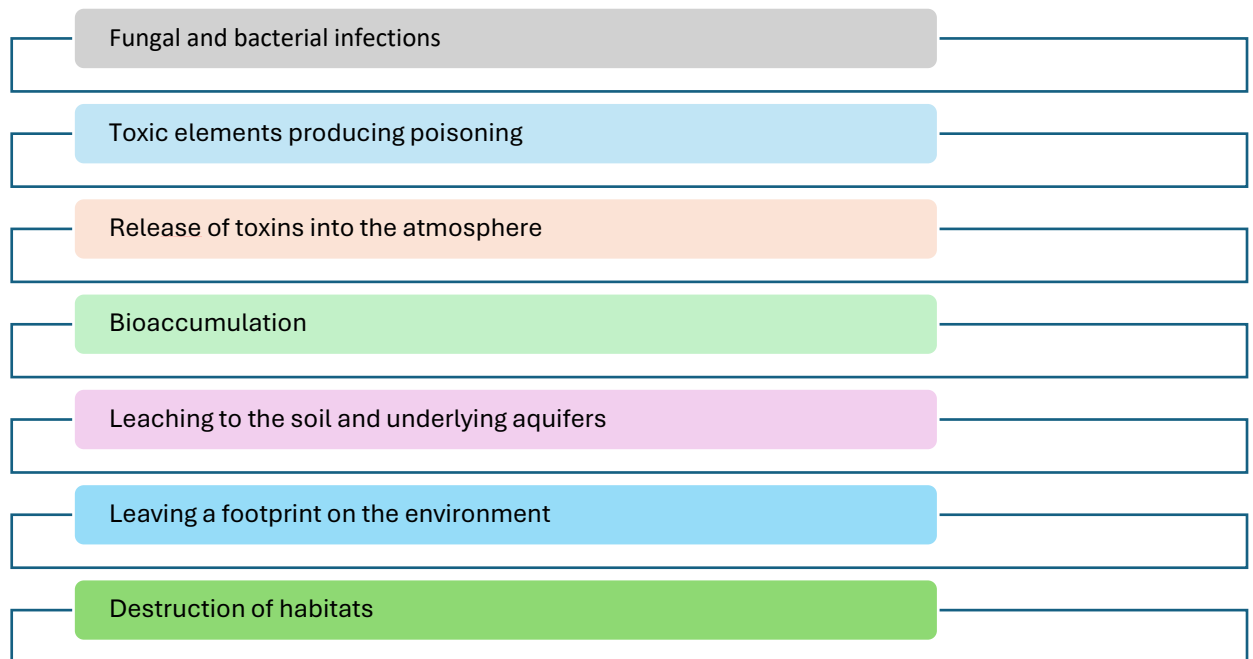
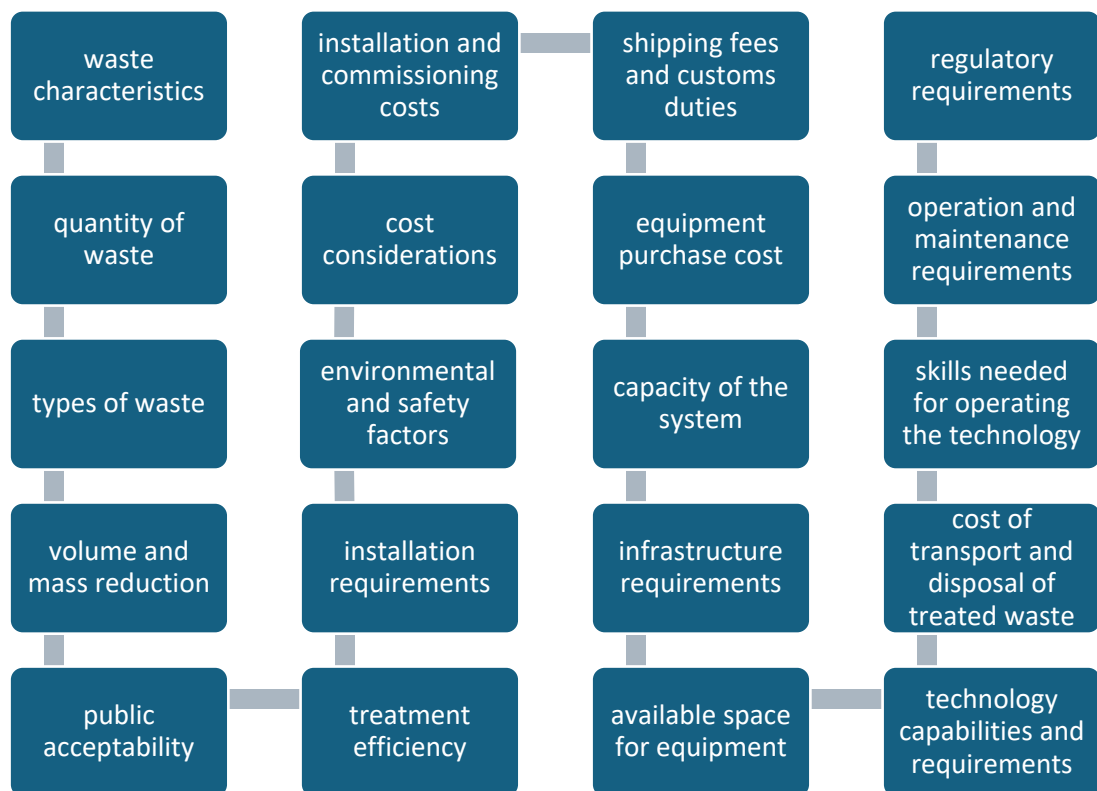


Figure 4.7. Impact on the environment and health [29]

4.4 Hazardous waste treatment



The choice of treatment and disposal system involves some factors [2]:



There are several types of processes that define the treatment of medical waste, the last is a supplement for the others:

- Thermal
- Chemical
- Irradiative
- Biological
- Mechanical

A brief classification regarding the treatment and disposal of medical waste is found below.

A. Thermal processes [2, 23, 30]

- at low temperatures
 - steam (autoclave, microwaves)
 - hot air (convection, combustion, infrared heat)
- at high temperatures
 - incineration (combustion, pyrolysis and/or gasification)

B. Chemical processes

- addition of disinfectants (chlorine dioxide, sodium hypochlorite, ozone, alkaline hydrolysis, peracetic acid)
- encapsulation or solidification

C. Irradiative processes

- UV rays, electron beams

D. Biological processes

- enzymes

E. Mechanical processes

- shredding

F. Burial

- sanitary landfills, trenches, pits.

4.4.1 Thermal processes

Thermal processes use heat, or thermal energy, to inactivate and destroy pathogens present in healthcare waste. These methods are widely used in treatment facilities around the world [2]. The exact process depends mainly on the temperature level, the presence or absence of moisture, and the way heat reaches the waste mass. From a practical point of view, thermal treatment can be grouped into two main categories:

■ Low-heat processes, carried out in a moist or wet environment by using steam or vapour, as in autoclaves and microwave systems, or in a dry environment by using hot air, convection, conduction or infrared heating. These processes normally work between 100°C and 180°C. The temperature is high enough to kill microorganisms, but it does not create combustion or pyrolysis of the waste.

■ High-heat processes, mainly incineration and related thermal methods such as combustion, pyrolysis and gasification. These systems work at much higher temperatures, usually from about 200°C to more than 1000°C.

The difference between low-heat and high-heat technologies is not only the temperature. The waste changes in different ways. Low-heat treatment mainly disinfects the material and keeps most of its physical nature.

High-heat treatment changes the waste chemically and physically. It can reduce mass and volume strongly, but it also creates exhaust gases, ash and residues that need careful control.

Autoclaves

Autoclaves have been used for more than one hundred years for the sterilization of medical instruments. During the last decades, the same principle has been



adapted for the treatment of healthcare and medical waste, as shown in Figure 4.8. A waste autoclave works with heat, steam and pressure. Waste management companies use this equipment to treat biohazardous or infectious waste before the material is sent to its final disposal route. Pressurized steam is one of the most effective methods used for medical waste treatment. The autoclave is a metal vessel made to resist high pressure. It has a sealed door, pipes and valves that allow steam to enter and leave the chamber in a controlled way. Some autoclaves include a steam jacket around the main vessel. In this design, steam is introduced both into the jacket and into the inner chamber. The jacket warms the chamber walls, reduces condensation inside the vessel and allows the process to use steam at lower temperatures in a more stable way.



Figure 4.8. Autoclaves for thermal medical waste treatment and instruments disinfection compare with a steam equipment in Romania used in First World War

After treatment, the disinfected waste is usually compacted. It can then be sent to a landfill or to a waste-to-energy facility, depending on local regulations and the treatment chain used by the operator.

Advantages and limitations of the process are summarized below [2, 23, 30]:



- ❖ Low operation costs
- ❖ Adequacy for biological testing
- ❖ Less hazardous residues



- ❖ No change in waste characteristics
- ❖ Inapplicable for all types of waste
- ❖ Unknown air emissions

Air removal from the chamber is essential. If air remains inside the autoclave, steam cannot penetrate the waste uniformly and the treatment can be incomplete. Waste autoclaves also have one extra requirement when compared with instrument sterilizers. The air removed at the beginning of the cycle must be treated before release, because it can carry pathogenic aerosols. This is commonly done by steam treatment or by passing the air through a HEPA filter. Steam is lighter than air. For this reason, steam is introduced under pressure and pushes the air downwards towards an outlet placed in the lower part of the chamber. When the correct combination of time and temperature is achieved, small quantities of human tissue can technically be treated. Still, ethical, legal, cultural, religious and institutional rules may prevent this practice, even when the technology is available.

Types of waste possible to be treated [30]:





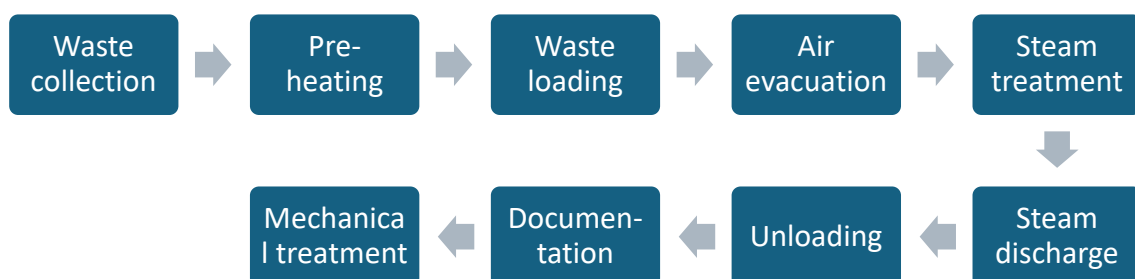
- Materials contaminated with blood and body fluids, sharps, isolation and surgery waste, laboratory waste, gauze, bandages, gowns and bedding.



- Chemical waste, volatile and semi-volatile organic compounds, chemotherapeutic waste, mercury, other hazardous chemical waste and radiological waste.

Autoclaves are generally not used for large anatomical remains, such as body parts. In these cases, it is difficult to define in advance the exact time and temperature needed for safe treatment. Another practical limitation is volume reduction. Autoclaves without post-treatment size reduction, and microwave systems without shredding reduce volume only slightly.

In hybrid autoclaves, continuous steam treatment systems and microwave units that include internal shredding or mixing, the situation is different. Depending on the shredding technology, the volume of waste can be reduced by about 60 to 80%. Steam-based technologies with a drying cycle can also reduce the mass by approximately 15 to 20%. Typical operations for an autoclave [30]:



Microwave technologies

Microwave treatment is also a moist, low-heat thermal process. The heat is produced through hot water and steam generated by microwave energy. The method works only when the waste contains water, because microwave radiation acts mainly on the water molecules and not directly on the solid components of the waste. For this reason, many units include a humidifier.

Mechanical treatment is often placed before the microwave stage. The waste is reduced to smaller pieces so that heat can reach the areas where infectious microorganisms may be present. A typical microwave frequency is around 2450 MHz, with a wavelength of approximately 12.24 cm. Smaller particle size improves heat penetration and makes the process more uniform. The whole operation usually takes place inside one enclosed vessel.

Bacteriological and virological tests are performed periodically to confirm that the process remains effective, as illustrated in Figure 4.9. Medical waste treatment by microwave exposure is usually less expensive than incineration. At the same time, it does not chemically destroy hazardous substances in the same way that incineration can. For this reason, the method is not recommended by the EPA, Environmental Protection Agency, for pathological waste treatment. Typical operations for a microwave system [30]:

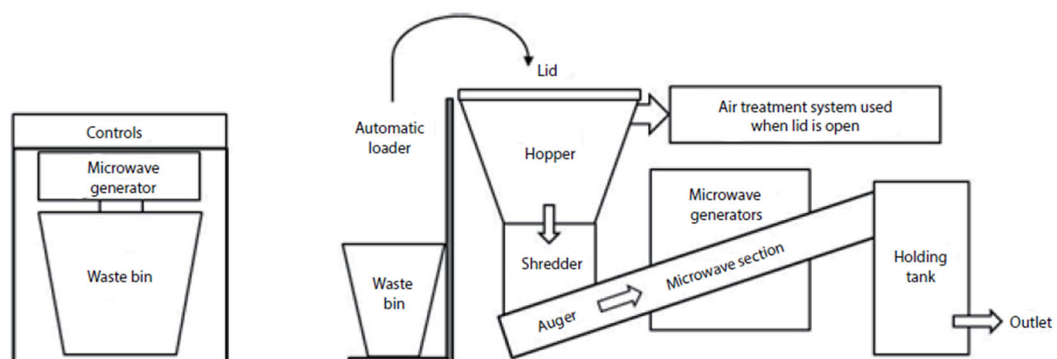
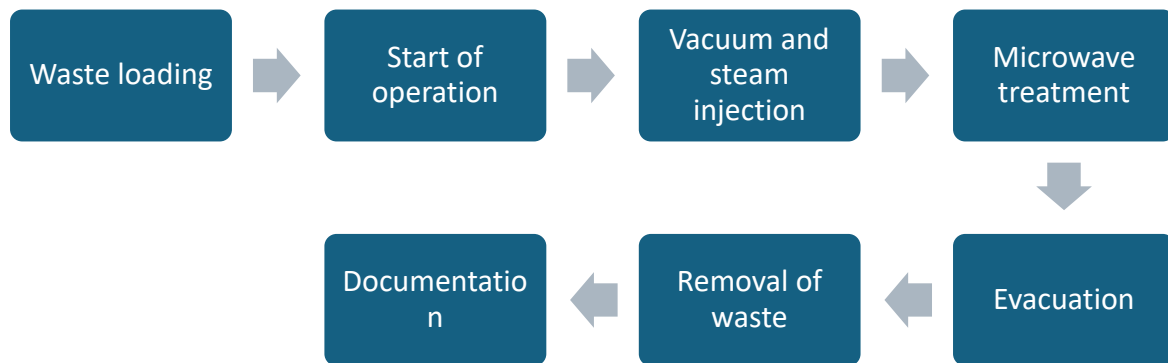


Figure 4.9. Schematic microwave technology [2]





Dry heat technologies

Dry heat technologies use hot air and do not add steam. They operate below the temperature at which combustion starts. In these systems, heat is transferred to the waste by conduction, when materials are in contact, by convection, through a moving flow of gas, and by thermal radiation, usually from infrared or resistance heaters. The process is simpler than wet thermal treatment in some aspects, but heat penetration must still be carefully controlled.

High-heat thermal treatment and incineration

High-heat thermal processes work from about 200°C to more than 1000°C. At these temperatures, the waste is changed chemically and physically through combustion, pyrolysis or gasification.

A medical waste incinerator should include a primary combustion chamber, also called a furnace or kiln, and a secondary chamber used for afterburning or post-combustion. It also needs air pollution control devices, often called flue-gas cleaning systems or emission controls, so that national and international pollutant limits can be respected. If wet gas cleaning is used, a wastewater treatment system is also needed. The chimney must be designed correctly and should be about 2.5 times higher than the highest nearby structure, as indicated in Figure 4.10.

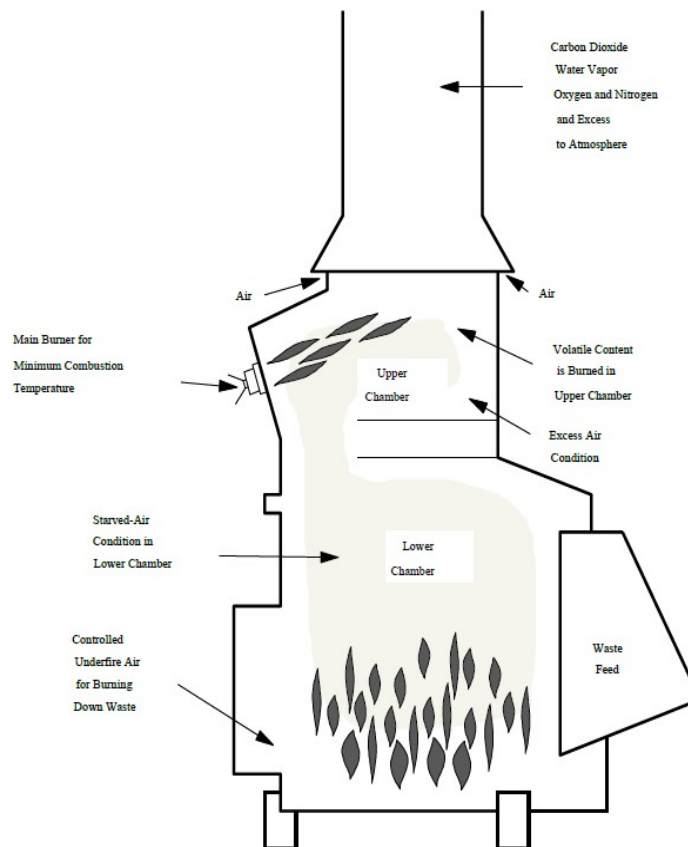


Figure 4.10. Incinerator [2]

Incineration is a combustion process. It converts organic and combustible waste into inorganic and non-combustible solid residues, together with gaseous combustion products such as carbon dioxide, oxygen and water vapour. Well-designed and correctly operated incinerators can reduce waste volume by about 80 to 90% and mass by about 75%.

The exhaust gases produced by waste incineration can contain many harmful substances. These may include particulate matter, nitrogen oxides, sulphur oxides, carbon monoxide, dioxins and furans, metals such as lead and mercury, acid gases, volatile chlorinated organic compounds and polycyclic aromatic compounds. Some pollutants are created when combustion is incomplete. Dioxins and furans can form under such conditions. The formation of incomplete combustion products depends on the duration of the combustion process, the



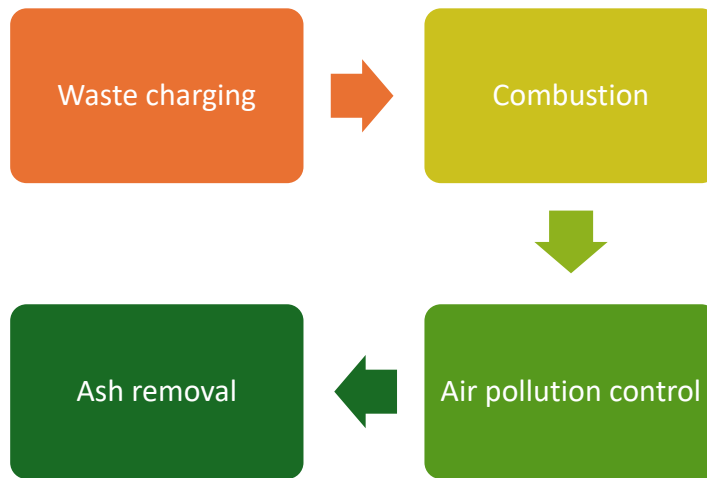
quality of gas mixing in the chamber and the combustion temperature. Good combustion efficiency needs the correct balance between temperature, residence time and turbulence.

Medical waste can be treated by incineration when the installation is designed for healthcare waste and when the process is operated under controlled conditions. This method is suitable for cultures and stocks from laboratory activities, especially when there is a risk that they contain infectious agents. It can also be used for sharps, such as needles, blades and similar objects, when they are contaminated or suspected to be contaminated. Materials containing blood, body fluids or biological residues may also be treated in this way, together with waste from isolation rooms, surgical departments and laboratories used for diagnosis, testing or research.

Incineration is also applied to soft waste produced during patient care. This category includes gauze, bandages, drapes, gowns, bedding and other disposable materials that may be contaminated. Pathological waste can be incinerated only in installations specifically designed for this purpose. In this case, the waste may include cadavers, large anatomical remains, body parts, organs, tissues and animal carcasses. Some chemical and pharmaceutical wastes may also be treated by incineration, but only when the installation operates at high temperature, usually above 1200°C, and has efficient air pollution control systems. This applies to laboratory chemical waste, thermally stable pharmaceutical waste, halogenated waste, plastics containing PVC and cytotoxic waste.

Normal medical waste incinerators should not receive materials that can create explosion risks, toxic emissions, equipment damage or radioactive contamination. Pressurized gas containers are dangerous because they may burst during heating. Large quantities of reactive chemical waste can create

unstable reactions. Silver salts and waste from photographic or radiographic processes are also unsuitable for standard incineration. The same caution applies to waste containing mercury, cadmium or other heavy metals, including broken thermometers, used batteries and lead-lined wooden panels. Sealed ampoules or vials may explode inside the chamber, while radioactive materials require a separate and strictly controlled management route [2,30]. Typical operations for an incinerator [30]:



A rotary kiln incinerator has an inclined rotating combustion chamber and a post-combustion secondary chamber, operating from 900 to 1200 °C.

A rotary kiln incinerator has an inclined rotating combustion chamber and a secondary post-combustion chamber. Typical operating temperatures are between 900 and 1200 °C.

Co-incineration means that medical waste is burned together with other waste categories. In this case, the temperature must be higher than 850 °C. The air supply and the residues must also be carefully controlled and monitored.

Pyrolysis is the thermal degradation of material by heat in the absence of oxygen, or with only a limited oxygen supply. In practice, a fully oxygen-free



atmosphere is difficult to maintain, so a limited amount of oxidation may still occur. In healthcare waste treatment, plasma pyrolysis uses highly ionized gas, called plasma, to convert electrical energy into heat. Temperatures may reach around 1650°C or even higher.

Gasification uses small and controlled quantities of oxygen, with steam often used as the gasification agent. The process transforms carbon-containing material, but it can still generate by-products. These by-products may contain high levels of toxic contaminants, so the process must be controlled carefully.

Table 4.2 Differences between incineration, pyrolysis and gasification [2, 30]

	Pyrolysis	Gasification	Incineration
Atmosphere	Inert/nitrogen	Gasification agent: O ₂ , H ₂ O	Air
Reaction temperature (°C)	250 – 700	500 – 1600	800 – 1450
Pressure (bar)	1	1 - 45	1
Stoichiometric ratio	0	< 1	> 1
Gas phase	H ₂ , CO, C _x H _y , H ₂ O, N ₂	H ₂ , CO, CO ₂ , CH ₄	CO ₂ , H ₂ O, O ₂
Solid phase	Ash, coke	H ₂ O, N ₂	NO ₂
Liquid phase	Pyrolysis oil, water	Slag, ash	Slag, ash

4.4.2 Chemical processes

Chemical treatment uses disinfecting agents to inactivate pathogens present in healthcare waste. The result depends on several practical factors. The chemical has to be suitable, its concentration must be correct, and all contaminated surfaces must remain in contact with the disinfectant for enough time. Temperature, pH, water hardness and the amount of organic matter in the

waste can also change the result. For this reason, chemical treatment is simple in principle, but it must be controlled carefully in practice.

The most common chemical systems are based on chlorine compounds, especially dissolved chlorine dioxide and sodium hypochlorite, which is the active substance in ordinary bleach [2, 23, 30]. Other systems use glutaraldehyde, quaternary ammonium compounds, lime slurry or calcium oxide. Ozone gas has also been developed for medical waste treatment, and practical experience with this approach has been reported at Dr. Negrín Hospital [31].

Some small-scale systems use chemical products that encapsulate or solidify sharps, blood and other body fluids before disposal. These systems do not treat large waste flows, but they may be useful in remote areas or in facilities where only small quantities of specific hazardous waste are generated.

Alkaline hydrolysis is a particular form of chemical treatment. It uses heated alkaline solution to digest tissues, pathological waste, anatomical parts and contaminated animal carcasses inside heated stainless-steel tanks. The system acts on organic material and converts it into a decontaminated aqueous liquid and solid residues that can be managed afterward, depending on national rules and local procedures.

The reduction in volume varies with the equipment. Shredding, grinding, mixing and the geometry of the vessel influence how efficiently the process works. Most chemical treatment systems lead to disinfection rather than full sterilization. The practical efficiency depends on the disinfectant, contact time, concentration, exposure of the waste, organic load and working conditions such as humidity and pH.

A clear limitation of chemical treatment is the continuous need for reagents. Chemicals must be purchased, stored, dosed, handled and controlled. This adds cost and also creates safety requirements for staff. Even so, chemical treatment

can be useful when the quantity of waste is limited or when the waste type is suitable for this method.

Chlorine compounds are cheap and effective, which explains their wide use. Sodium hypochlorite is easy to obtain, while chlorine dioxide is stronger and more reactive. These advantages come with problems. When chlorine-based substances react with organic material, they may form unwanted by-products, including chloroform and other persistent toxic compounds. The process must therefore be managed with attention to dosage, ventilation, residues and discharge.

Ozone works differently. Oxygen from air can be converted into ozone by an electrical discharge. Ozone is a powerful oxidizer and can inactivate microorganisms without producing the same by-products usually associated with chlorine chemistry. It is still dangerous for people if it escapes from the equipment. Ozone irritates and damages the lungs, so the treatment system must prevent exposure around the installation.

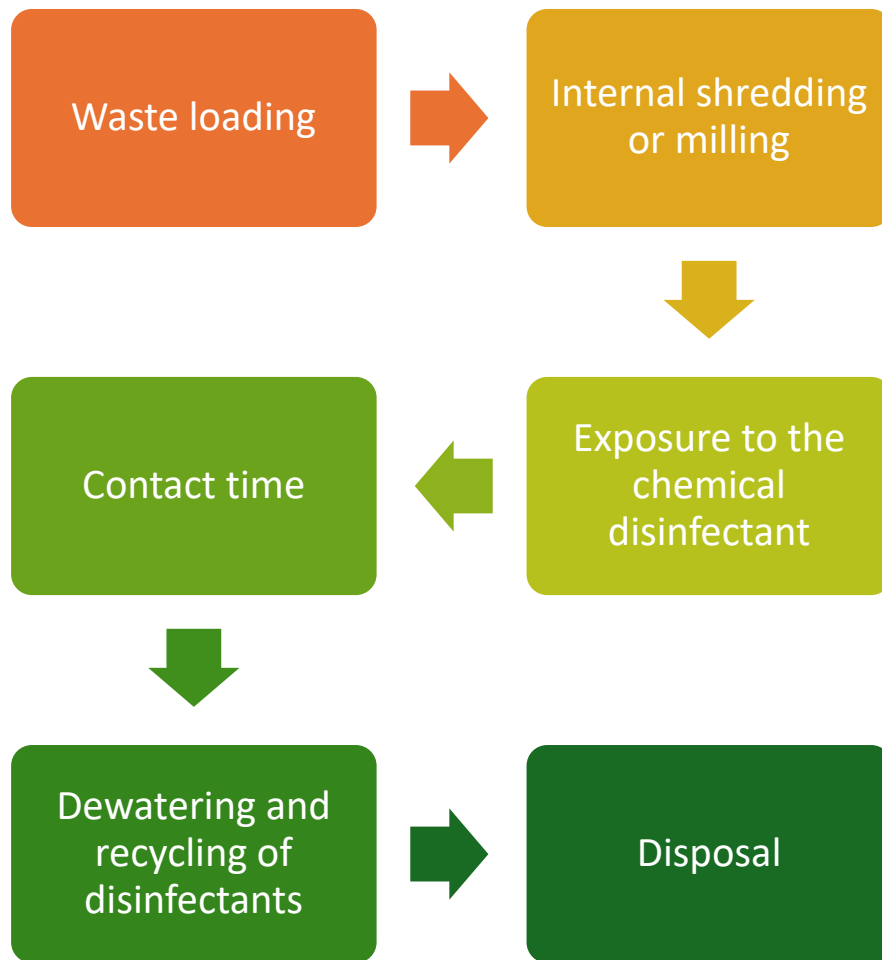
Alkaline agents are another option. Sodium hydroxide, also called lye, is highly corrosive. Calcium oxide, or quicklime, can be used in a less aggressive form. These alkaline agents break down proteins and other biological components. Their use requires strong precautions, because alkaline solutions can injure skin, eyes and respiratory tissues. The operator must think about both waste treatment and worker safety.

Chemical treatment is mainly suitable for liquid waste, such as blood, urine, faeces and some types of hospital sewage. Infectious waste, microbiological cultures and sharps can also be treated chemically in some systems, but only if the disinfectant reaches the contaminated surfaces at the correct concentration and for the required contact time.

Typical operations in chemical treatment systems [2, 30]:

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Alkaline hydrolysis, sometimes called alkaline digestion, converts animal carcasses, human tissues, anatomical parts and similar biological waste into a decontaminated aqueous solution. Fats are transformed into soaps. Soft tissues are broken down into peptides, amino acids, salts, sugars, ammonia and other soluble products [30].

A simple comparison helps to understand the process. An ice cube disappears in warm water because heat and contact with liquid act together. In alkaline hydrolysis, tissue is placed in a tank with water and alkali. Heat, and in some systems pressure, accelerates the breakdown of soft tissue. The remaining solid part is mainly bone material. The example is simple, but the real system must be operated with strict control of temperature, pressure, chemistry and discharge quality [2, 23, 30].



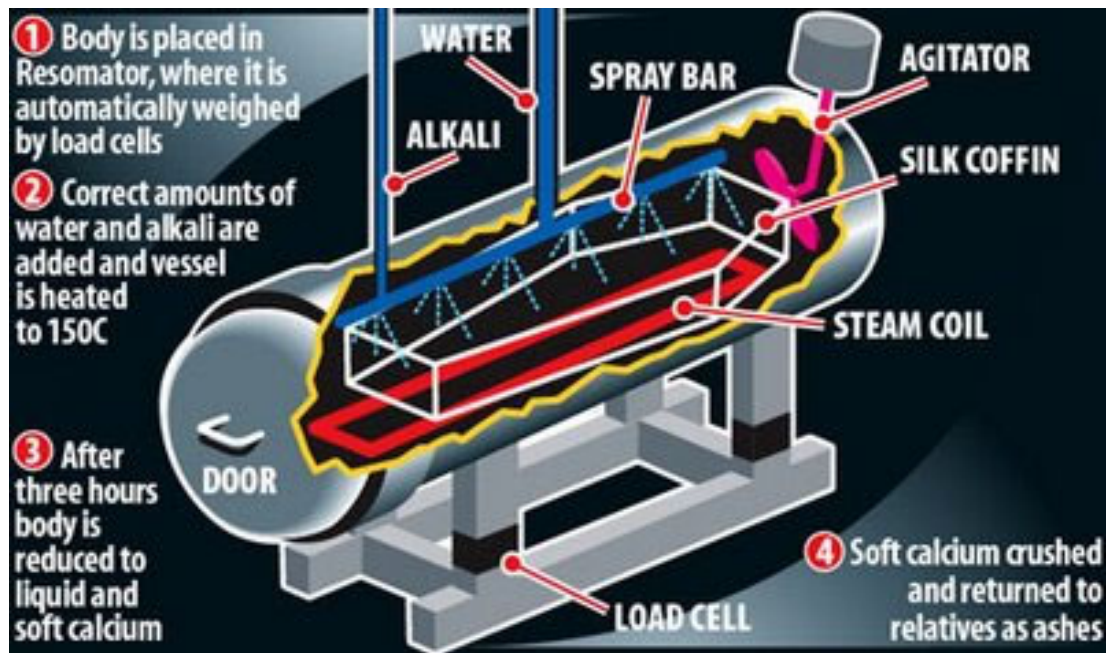


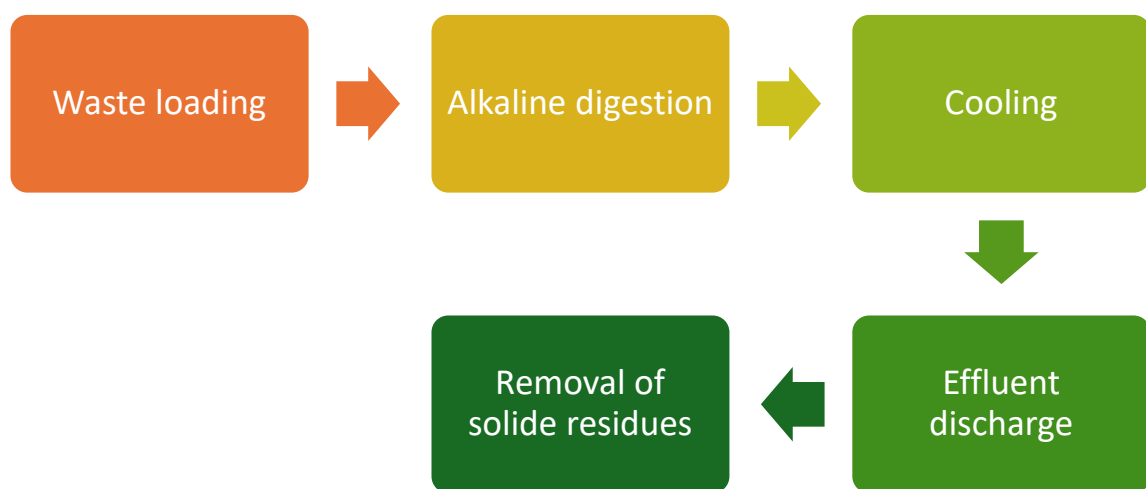
Figure 4.11. Alkaline hydrolysis [2, 23, 30].

Chlorine dioxide, ClO_2 , is often presented as an alternative to hypochlorite. For solid healthcare waste, internal shredding before or during disinfection is usually necessary. Without size reduction, the chemical may touch only the outside of the waste mass, while internal contaminated surfaces remain insufficiently exposed. Types of wastes for alkaline hydrolysis [30].

Suitable waste ■ Pathological waste, organs, tissues, cadavers, anatomical parts and contaminated animal carcasses.		Waste to avoid or manage with special caution ■ Waste containing aluminium, tin, zinc, magnesium, copper or galvanized iron, because hydrogen gas may be formed.
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<ul style="list-style-type: none"> ■ In some systems, biological stocks, cultures, liquid blood, body fluids and other infectious waste may also be treated. ■ Some chemotherapeutic residues may be accepted only when the equipment and local regulations allow this. 	<ul style="list-style-type: none"> ■ Concentrated acids and flammable liquids. ■ Organohalogen compounds, especially trichloroethylene. ■ Nitromethane and similar nitro compounds.
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Typical operations for alkaline hydrolysis:



Encapsulation is a chemical stabilization method. Sharps, blood or other body fluids are trapped inside a solid matrix before disposal. The waste is coated or surrounded by inert material. This does not have the same role as a complex treatment plant, but it reduces direct contact with hazardous items. In remote areas, even concrete may be used for small quantities of pharmaceutical waste when safer options are not available, Figure 4.12.

The usual method uses high-density polyethylene boxes or metallic drums. The container is filled to about three quarters with sharps, pharmaceutical residues, chemical residues or incinerator ash. The remaining volume is filled with a binding material such as cement, lime, clay, bituminous sand or plastic foam.



After hardening, the container is sealed and sent to a sanitary landfill or to a controlled burial pit, according to the local waste management procedure.



Figure 4.12. Encapsulation

Advantages and limitations of encapsulation:

Encapsulation is a simple and relatively safe method for managing small quantities of healthcare waste, especially when more advanced treatment options are not available. It does not require complex equipment, and the operating cost is usually low. For this reason, it can be useful in remote areas or in facilities with limited technical resources. The method is mainly applied to sharps and some pharmaceutical wastes, where the main objective is to isolate the hazardous material and reduce direct contact after disposal. By fixing the waste inside a solid matrix, encapsulation also lowers the risk for waste handlers and for people who may come into contact with discarded materials in poorly controlled disposal areas. However, encapsulation should be seen as a limited solution. It does not destroy the hazardous material, but only contains it. The treated waste still needs to be placed in a controlled landfill or in a protected

burial area. The method is also suitable only for small quantities of waste. Another important disadvantage is that the final weight and volume increase, because cement, lime, clay, plastic foam or other solidifying materials are added to the original waste. If the containers are damaged later, or if the disposal site is not properly managed, the waste may still create environmental and safety problems. For these reasons, encapsulation is useful in specific situations, but it should not replace proper treatment systems when these are available [2, 23, 30].

4.4.3 Irradiative processes

Some forms of radiation can inactivate microorganisms. Because ionizing radiation is already used for sterilizing medical instruments, the same principle has been tested for healthcare waste. Electron beams, Cobalt-60, Cesium-137 and X-rays have all been considered for this purpose. In the 1990s, electron beam treatment was demonstrated successfully for healthcare waste treatment. The effectiveness of irradiative treatment depends mainly on the absorbed dose inside the waste mass. If the dose does not reach all parts of the material, the treatment may be incomplete. UV-C radiation, also known as germicidal ultraviolet radiation, has also been used, but mainly as an additional method rather than as the main treatment for bulky healthcare waste. Typical values mentioned for healthcare waste are about 25-50 kGy for complete disinfection and about 5-10 kGy for microbial reduction.

4.4.4 Biological processes

Biological processes use natural degradation of organic matter. Some systems add enzymes to make the breakdown of organic infectious material faster. Composting and vermiculture are also biological methods. They have been used for hospital kitchen waste, digestible organic waste and placenta waste in



specific conditions. Burial of pathological waste, where allowed by law and culture, is another form of biological decomposition.

These processes are not universal solutions. They are suitable only for selected waste categories and only when the site, control measures and public health requirements are respected. The main idea is to use biological activity in a controlled way, without creating infection, odour, vector or water pollution problems.

4.4.5 Mechanical processes

Mechanical processes include shredding, grinding, mixing and compaction. They are usually used together with thermal or chemical technologies. Their purpose is practical. Smaller waste pieces allow better heat transfer, better steam penetration and better contact with disinfectants. Mechanical treatment can also reduce the volume of treated waste and make the waste unrecognizable.

Mechanical treatment has to be used carefully. Shredding untreated infectious waste in an open system is dangerous because aerosols can expose workers to pathogens. If shredders, grinders or mixers are part of a closed treatment system, the air from the mechanical section must be treated before release. Steam treatment or HEPA filtration may be needed, depending on the technology. Shredders cut waste into small fragments, as shown in figure 4.13. The equipment requires trained staff because many shredders are industrial machines with powerful rotating parts. In modern treatment lines, shredders are often integrated into closed chemical or thermal disinfection systems. Simple devices, such as modified grain mills, may be used only for already disinfected waste. For needles and syringes collected in large quantities, shredding can also support material recovery, but only when collection and transport are organized safely.

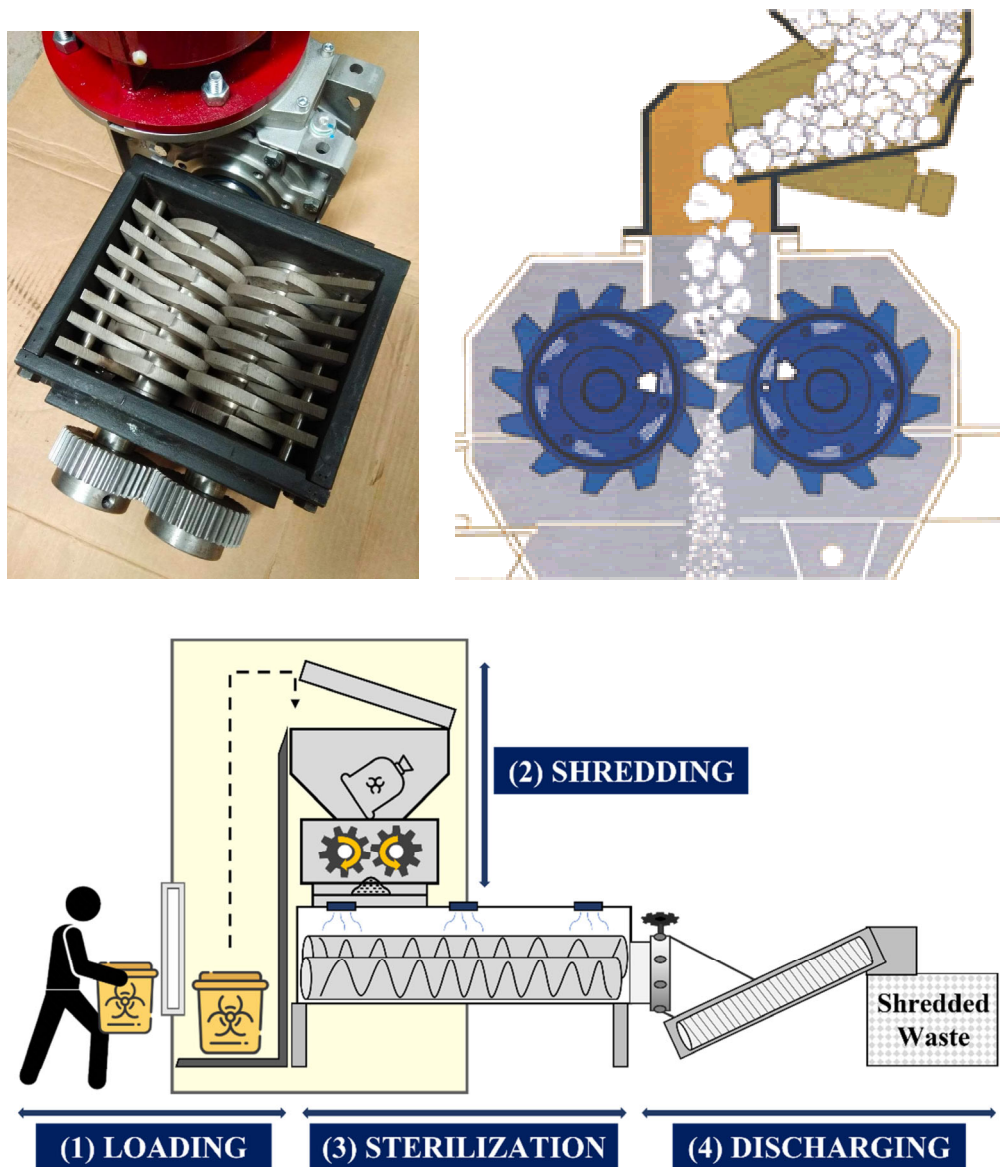


Figure 4.13. Shredders and integrating mechanical process into a medical waste processing stream [2, 23, 30]

Advantages and disadvantages of the shredders are presented below:



- They make the waste difficult to recognize.



- They require electricity.
- Some installations are expensive.



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- They prevent the reuse of needles and syringes after treatment.
- They reduce volume.
- They can facilitate recycling of selected plastics when a safe collection system exists.
- They improve chemical or thermal treatment when used inside closed and integrated systems.
- Large metal parts can damage the shredder.
- Shredding alone does not disinfect waste.
- Untreated waste may expose staff to airborne pathogens if shredded in an open system.
- Skilled staff and permanent monitoring are needed.

4.4.6 Burial in sanitary landfills, trenches, pits

Disposal of untreated healthcare waste in an uncontrolled dump is unsafe and should remain a last option. When no better solution exists, disposal in a sanitary landfill can be accepted only with strict precautions. The waste must be covered quickly. One possible method is to dig a trench into old municipal refuse, older than three months, place the healthcare waste there and immediately cover it with a layer of fresh municipal refuse of about two metres.

A sanitary landfill used for healthcare waste needs basic technical and administrative controls. Without these controls, the site can create risks for workers, scavengers, animals, groundwater and the surrounding population.

The following factors are essential for landfill design and use:

- Access to the site must be restricted and controlled.
- Competent personnel must be available for operation and supervision.
- The disposal areas must be planned before waste arrives.
- The bottom of the landfill must be waterproofed.
- The water table must be more than 2 metres below the bottom of the landfill.

- Drinking water sources and wells must not be located close to the site.
- Chemical waste should not be disposed of in these areas.
- Waste must be covered daily, and vectors such as insects and rodents must be controlled.
- The landfill must have a final cover to reduce rainwater infiltration.
- Leachate must be collected and treated.

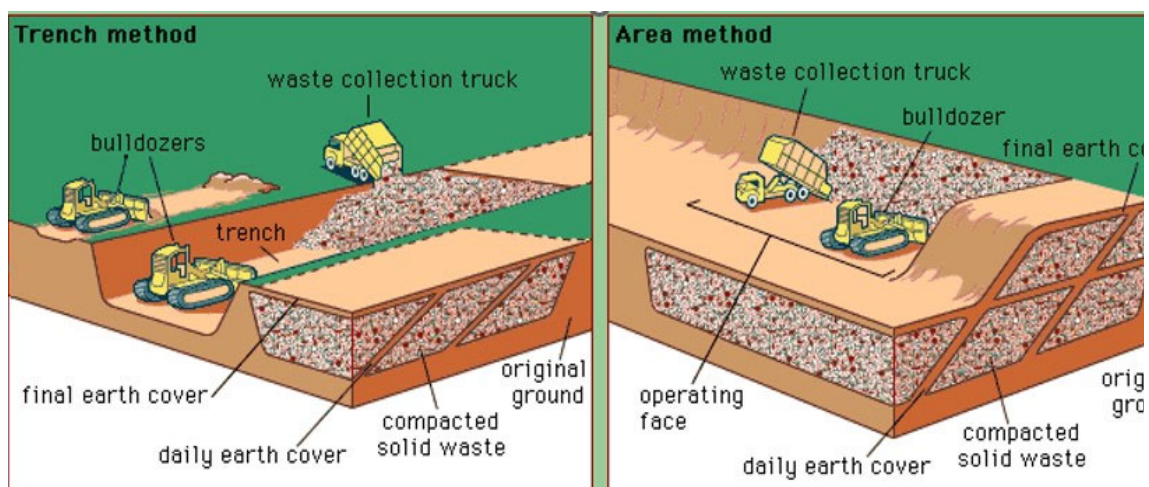


Figure 4.14. Sanitary landfilling

Advantages and disadvantages of sanitary landfill and trench method are presented below [2, 23, 30]:





- The method is simple and has low operating costs.
- It can use the existing municipal waste management system.
- If the landfill is well managed, scavengers cannot easily access healthcare waste.



- Healthcare waste is not treated and remains hazardous.
- The landfill must be secure, fenced and guarded.
- Scavengers and animals must be controlled.
- Good coordination is needed between waste collectors and landfill operators.
- The method may reduce attention to proper segregation at the healthcare facility.
- Transport to the landfill may be long and costly.
- Water pollution remains a risk if the site is poorly designed or managed.

Advantages and disadvantages of separate pit on the hospital site are presented below [2, 23, 30]:



- The pit is simple and relatively inexpensive to build and manage.
- Hazardous substances are not



- Healthcare waste is not treated and remains hazardous.
- There is a risk of water pollution.
- Odour can become a problem.
- Vectors such as insects and rodents must be controlled.

transported outside
the hospital area.

■ Control by the
healthcare facility is
easier.

■ Space is needed around the hospital.

Protecting life also means protecting the place where people live. Clean soil, clean water and a safe working environment are part of healthcare. For this reason, the collection, management, treatment and final disposal of medical waste must be organized with care, for patients, for staff and for the community [32].

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CHAPTER 5

DIGITAL TECHNOLOGIES AND SMART SYSTEMS IN HOSPITALS

The concept of smart systems in healthcare institutions is discussed in this chapter. The first section presents the Hospital Information Management System (HIMS) as an integrated system that cannot be reduced to software alone, because its operation depends on hardware, network infrastructure, data security, trained personnel and common standards. The second section presents the role of hospital 3D units as engineering services that transform medical imaging data into biomodels, surgical guides and phantoms for clinical planning, training and patient specific treatment.

5.1 IT INFRASTRUCTURE OF HOSPITALS

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A hospital is one of the most technically demanding environments that an engineer or administrator can operate within.



Unlike a standard office building or commercial facility, a hospital must function continuously, twenty-four hours a day, seven days a week, 365 days a year. Failure of critical information systems is not simply an operational inconvenience; it can directly affect patient safety, compromise clinical workflows, and result in diagnostic or treatment errors. For this reason, the design, implementation, and management of hospital IT infrastructure must be treated with the same discipline as any other safety-critical engineering domain [1, 2].

The amount of information generated by a modern hospital is enormous. Every patient encounter, laboratory tests, radiological images, prescriptions, billing transactions, and staff activity generate data that must be captured, stored, Accessed on , and protected. This data flows between departments, between clinical systems, and increasingly between institutions and national health registries. Managing this flow effectively is the core mission of the hospital IT department and the Hospital Information Management System (HIMS) that it operates [3, 4].

This article examines the full spectrum of hospital IT infrastructure, from the physical environment of the data center to the software modules of HIMS, from network topology to cybersecurity policy, and from current operational practice to future technological trends. The goal is to provide a structured and accessible explanation suitable for healthcare engineering students, clinical managers, and anyone seeking to understand how digital systems support the delivery of modern healthcare.

5.1.1 The Role of Information in Hospital Operations

Before examining technical infrastructure, it is important to understand what information means in a hospital context. Information is produced, processed,

stored, served, and protected at every level of a healthcare facility. A patient's journey through a hospital generates a continuous stream of data: demographic information at registration, clinical assessments in the ward, laboratory results from the pathology department, imaging studies from radiology, medication records from pharmacy, and billing data from the finance department. All these pieces of information must be linked, accurate, accessible, and protected.

Effective use of information technology in hospitals has been shown to improve the quality of clinical care, reduce duplication and error, speed up billing cycles, improve resource utilization, and support compliance with regulatory requirements. These are not abstract benefits. They translate directly into better patient outcomes, lower operational costs, and a safer working environment for healthcare professionals.



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PROCESS INTERACTION RATING TABLE



MAIN PROCESS		SUB PROCESSES																												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
CORPORATE SERVICES	1.Organisational Structure	A	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	2.Quality Management	C	A	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	3.Risk Management	C	C	A	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	4.Social Responsibility	C	B	B	A	A	B	A	A	C	C	C	C	C	C	C	A	A	A	A	B	B	A	B	A	A	A	A	A	A
PATIENT and STAFF FOCUSED SERVICES	5.Human Resources	C	C	B	C	A	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	
	6.End of Life Services	C	B	B	B	B	A	B	B	C	C	C	C	B	C	C	C	C	A	A	A	A	C	B	C	B	B	B	A	A
	7.Patient Rights	C	B	B	A	A	A	B	C	C	C	C	C	C	C	C	C	C	A	B	C	C	A	B	B	B	A	A	A	C
	8.Staff Rights and Safety	C	C	C	B	C	A	B	A	B	B	B	B	B	B	B	B	A	B	B	B	B	B	B	B	A	B	B	B	B
HEALTHCARE SERVICES	9.Inpatient	C	B	B	B	C	C	C	C	A	C	C	C	C	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	
	10.Outpatient	C	B	B	C	C	A	A	C	C	A	C	C	C	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	
	11.Emergency Patient	C	B	C	B	B	C	C	C	C	C	A	C	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C		
	12.Maternity Services	C	B	B	B	B	B	B	C	C	C	C	A	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C		
	13.Psychiatry	C	B	C	C	B	B	C	C	C	C	C	C	A	B	B	C	C	B	B	B	C	C	C	C	C	C	C		
	14.Dialysis	C	B	B	B	B	B	B	C	C	C	C	B	B	A	C	C	C	C	C	C	C	C	C	C	C	C	C		
	15.Intensive Care	C	B	C	B	C	B	B	C	C	C	B	B	C	A	C	C	C	C	C	C	C	C	C	C	C	C	C		
	16.Pharmacy	C	B	B	A	B	B	C	C	C	B	C	C	C	C	C	A	C	A	B	C	B	C	C	A	C	C	C		
	17.Operation Rooms	C	B	B	B	C	C	C	C	A	C	C	C	B	B	C	C	A	C	C	C	C	C	C	C	C	C	C		
	18.Sterilization	C	B	B	A	C	B	B	C	C	C	C	C	C	C	C	A	C	A	A	A	A	C	C	B	C	C	C		
	19.Transfusion	C	B	C	A	A	B	C	C	C	C	C	C	C	C	A	C	A	A	A	B	C	B	C	A	C	C	C		
	20.Radiology	C	B	B	A	B	A	B	C	C	C	C	C	C	C	C	B	C	B	A	A	B	C	C	A	C	C	C		
	21.Laboratories	C	B	B	A	B	A	B	C	C	C	C	C	C	C	C	A	C	A	C	A	A	C	C	B	B	C	C		
SUPPORT SERVICES	22.Facility Management	C	B	C	A	B	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B		
	23.INFORMATION MANAGEMENT	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C			
	24.Archive	C	B	B	A	A	B	B	B	C	A	A	C	C	A	C	B	B	A	B	A	C	A	C	A	A	A	A		
	25.SCM	C	B	B	A	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	A	C	C		
	26.Clinical Engineering	C	B	B	A	A	A	A	A	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	A	B		
	27.Waste Management	C	B	B	A	C	A	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	B	C	B			
	28.Outsourcing	C	B	B	A	B	A	A	A	C	C	C	C	C	C	C	B	C	B	C	C	C	B	C	A	A	B			
	29.Accommodation Services	C	B	B	C	A	B	C	C	C	C	C	C	C	C	C	A	C	C	C	A	B	C	B	A	C	A	C		
		AFFECTED																												
A		INACTIVE																												
B		INDIRECT IMPACT																												
C		DIRECT IMPACT																												

Table 5.1. Process Interaction Rating Table [1]

The process approach, which forms the cornerstone of modern Quality Management Systems (QMS), necessitates evaluating organizational activities

not merely as isolated entities, but rather through their dynamic interconnections. Indeed, the ISO 9001:2015 standard (Clause 4.4.1) explicitly requires organizations to determine both the sequence and the interaction of their operational processes. However, to achieve operational excellence and secure resource optimization, simply identifying the existence of these interactions is insufficient; their degree of impact on the overarching system must be rigorously analyzed through qualitative or quantitative methods.

To this end, Table 5.1 (Process Interaction Rating Table) presents a methodological matrix that maps management, operational, and support processes. By scoring the specific inputs, outputs, and mutual dependencies of these workflows, the table systematically highlights systemic risks and areas pinpointed for continuous improvement [5].

The IT department of a hospital carries a correspondingly broad set of responsibilities. In a typical hospital IT department, the core duties include keeping all systems running securely and reliably, supporting both clinical and administrative workflows, protecting sensitive patient data in compliance with applicable data protection laws, and driving the digital transformation of the institution. These responsibilities are carried out by multiple specialized units, each with their own area of expertise [1].

5.1.2 Hospital IT Department Structure

Modern healthcare institutions are highly complex socio-technical ecosystems where clinical outcomes are inextricably linked to the reliability and efficiency of Information Technology (IT) infrastructures [4, 6]. Within a hospital, the IT department does not merely function as a technical support office; instead, it acts as the backbone of the entire clinical and administrative workflow [7]. To ensure uninterrupted patient care and data integrity, hospital IT departments

are structurally segmented into specialized sub-units. Based on operational data in many healthcare IT departments, these sub-units are traditionally categorized into three core domains: the Software Unit, the Hardware Unit, and the System and Network Unit. It is discussed the distinct responsibilities of these sub-units and examine how their intersection ensures organizational continuity.

Software Unit

The primary mandate of the Software Unit revolves around the maintenance, optimization, and continuous support of the Hospital Information Management System (HIMS). HIMS serves as the central repository and operational engine for patient records, billing, laboratory orders, clinical prescriptions, etc. The software team is responsible for bridging the gap between raw data generation and clinical decision-making with HIMS. [4]

Key operational responsibilities of this unit:

- **Query Engineering and Statistical Reporting:** Developing complex database queries to extract statistical data, thereby enabling hospital administrators to monitor performance indicators and resource allocation.
- **Bug Debugging and Patch Management:** Continuously identifying software anomalies, executing debugging protocols, and deploying updates to eliminate operational friction in clinical workflows.
- **Problem-Solving and Customization:** Aligning the software interface with the evolving regulatory and medical requirements of the healthcare facility.
- **Software Project Development:** Analyze and develop software projects that hospital needs or adopt outsourced software to hospital.



Hardware Unit

Whereas the software layer controls the information, the Hardware Unit provides the availability and readiness of the actual hardware necessary for the use of this data. As the first point of contact in end-user desktop support, the Hardware Unit works in close collaboration with the medical personnel, namely doctors, nurses, and administration staff. The functional areas covered by the Hardware Unit include the lifecycle management of terminal devices and involve the following:

- Personal Computers (PC) and Laptops: Installation, setup, and maintenance of terminals in ambulatory clinics, emergency departments, and ICUs;
- Peripherals and Print Devices: Management of highly available print terminals, label printers used to generate patients' identification bands, and barcode scanners used for safe medication delivery;
- Device Provisioning: Making sure that any hardware failure does not impact clinical operation through the deployment of backup terminal devices.

System and Network Unit

The System and Network Unit represents the critical core of the hospital's technical infrastructure, managing the on-site data center and securing the peripheral boundaries of the network. Given that healthcare facilities function continuously (24/7/365), this unit operates under rigorous high-availability constraints, utilizing a dedicated team of technicians who remain perpetually on call [1].

Because system maintenance can disrupt live clinical operations, this unit executes high-risk updates and structural overhauls during the least busy

intervals, primarily at night and at weekends. The responsibilities of this team include [1]:

- **Data Center and Server Maintenance:** Overseeing physical and virtual server environments to guarantee maximum uptime and prevent data corruption.
- **Firewall and System Security:** Implementing good cybersecurity protocols, managing intrusion prevention systems, and maintaining firewall configurations to protect sensitive electronic health records (EHR).
- **Router and Switch Management:** Configuring and monitoring the core and distribution network switches to maintain low-latency connectivity across geographically distributed hospital blocks.
- **Integration of Medical Devices:** Connecting complex diagnostic hardware (such as MRI, CT scanners, and patient monitors) to the central network, ensuring fast data transmission via HL7 or DICOM protocols to the HIMS layer. [1, 4]

The allocation of responsibilities among specialized IT teams helps reduce operational risks and improve the efficiency and reliability of healthcare information systems. Dedicated teams focus on infrastructure, software applications, cybersecurity, and network services, ensuring that clinical and administrative systems remain secure, available, and interoperable across the healthcare environment [4]. Ultimately, the disciplined orchestration of these three sub-units is a fundamental prerequisite for maintaining patient safety and operational excellence in modern healthcare delivery.

5.1.3 Hospital Information Management System (HIMS)

HIMS stands for Hospital Information Management System. It can be defined as a system through which the management of hospitals executes their



administrative, financial, and clinical functions. The first thing that one should know about this system is that it is not a standalone software. It is rather a collection of different software packages dealing with certain functions of a hospital, and having the same data infrastructure, enabling exchange of information among various departments without any redundancy [4, 8, 9].

Benefits of HIMS

A HIMS will incorporate all clinical, financial and administrative processes into one integrated information system, thereby preventing the inherent disconnection usually observed in healthcare operations. Through a central data source, HIMS can achieve many positive impacts in different institutional levels, eventually resulting in a synergy of efficiency and safety.

Improvement in Clinical Quality of Care and Prevention of Errors

There is better quality of care because the healthcare practitioners will always have updated and accurate information on each patient. This can reduce the risk of decisions made on incomplete knowledge.

Also, because different modules of a HIMS such as Pharmacy, Laboratory, and Nursing share the same database infrastructure, any information entered one module can be seen widely in hospital, thus minimizing transcription mistakes and unnecessary duplication of tests [10].

Financial Optimization, Charge Capture, and Resource Utilization

Beyond clinical use, HIMS helps hospitals stay financially healthy and use resources efficiently. In complex hospital environments, money losses often happen because of delayed or missed billing during emergency care or long patient stays. HIMS solves this problem by connecting billing protocols directly to live clinical activities [11]. As a result, billing cycles become faster, problems with insurance companies decrease, and billing mistakes are greatly reduced.

At the same time, HIMS gives administrators a real-time view of the hospital's physical and human assets. Through special logistics and facility modules, managers can easily monitor bed availability, equipment status, and nursing workloads [12]. This clear overview allows for better bed management, optimized surgery scheduling, and strategic staff allocation. Ultimately, this reduces patient stay times and helps the hospital serve more patients.

Regulatory Compliance, Data Security, and Governance

Today, following strict healthcare data rules is a major challenge for institutions. HIMS naturally supports these compliance rules with strong, built-in safeguards. The system automatically enforces role-based access controls (RBAC). This ensures that private patient health information (PHI) is only seen by authorized staff, which aligns with global regulations like HIPAA and GDPR [13, 14].

In addition, HIMS platforms create detailed, unchangeable digital audit trails. These trails log every time data is created, viewed, changed, or deleted. Combined with automatic data saving and encryption, these audit trails provide the exact evidence hospitals need during official inspections or legal audits [15]. Consequently, data security changes from a basic reactive IT policy into a proactive, permanent part of hospital management.

Medical Research, Sustainability, and Strategic Decisions

Apart from daily care benefits, the modern HIMS evolution creates a positive impact on such aspects of hospital operation as medical research, sustainability, and strategic management. In terms of wider perspectives, a centralized HIMS may be considered as an essential part of a giant data centre for clinical and epidemiological studies. With a lot of structured information available, this



system is a solid foundation for big data analysis and machine learning applications for healthcare predictive modelling [3].

Moreover, HIMS is an important tool in eco-friendly management and Green Hospital model implementation. With the help of the HIMS, paper records give way to digitized procedures. That makes it possible to avoid such problems as expenses on physical documentation storage, printing, and transportation. Furthermore, similar digital control allows minimizing the amount of expired medical equipment and supplies, thanks to timely inventory management [9].

Finally, on a higher management level, the integration of BI dashboards with HIMS enables the change of the decision-making process for the better. It becomes possible to base one's strategies on real-time key performance indicators rather than outdated reports [8].

A smart implementation of HIMS is a strategic solution capable of bringing many benefits to healthcare facilities. With HIMS in place, all departments are connected, and there are no more difficulties for efficient information management and data protection.

As a result, the two objectives of efficient healthcare management may be achieved: high efficiency and sustainable performance, along with maximum patient safety and treatment efficiency.

Elements of HIMS

Software Modules

The following table summarizes the main software modules that compose a typical HIMS, their primary functions, and their principal user groups.



Table 5.2. Main software modules commonly found in modern HMS.

HIMS Module	Primary Function	Key Users
Electronic Health Records (EHR)	Centralized patient data: history, diagnoses, medications, notes	Physicians, nurses, specialists
Radiology Information System (RIS)	Manages radiology orders, workflows, and reports linked to DICOM images	Radiologists, technicians, physicians
Laboratory Information System (LIS)	Tracks lab test orders, sample processing, and results reporting	Lab staff, clinicians
Pharmacy Management	Drug dispensing, inventory, prescription validation, and adverse event alerts	Pharmacists, prescribers
Patient Administration Management	Admissions, discharges, transfers, bed management, scheduling	Registration staff, department admin
Finance & Administration	Billing, invoicing, insurance claims, budget monitoring,	Finance department, administration
Clinical Decision Support (CDS)	AI-assisted diagnostic suggestions, drug interaction alerts, care protocols	All clinical users
Support Services Management	Food service, transport, housekeeping, waste management, and technical maintenance tasks	Support staff, unit coordinators
Operating Room (OR) / Theatre Management	Schedules surgeries, tracks OR utilization, manages pre-op/post-op workflows, and surgical staff logs	Surgeons, anesthesiologists, OR nurses
Human Resources & Shift Scheduling (HRM)	Manages clinical staff rotas, attendance tracking, credentials, and medical licensing compliance	Hospital executives, HR department
Procurement & Supply Chain Management	Tracks consumables, vendor contracts, and automated stock reordering	Purchasing department, suppliers



HIMS Module	Primary Function	Key Users
Engineering & Asset Management	Tracks medical device calibration schedules, preventive maintenance, and equipment downtime logs, inventory management	Biomedical department, IT department
Quality Assurance & Incident Reporting	Logs medical errors, patient complaints, infection control metrics, and accreditation compliance documentation	Quality managers, department staff, hospital board

Each of the modules should be able to work individually as well as share information with other modules in an efficient and consistent manner. For instance, the EHR module gets lab results from LIS, radiology reports from RIS, and pharmacy information from the Pharmacy Management module. The whole record of the patients in digital form is built through the integration of information received from various sources. Integration is enabled using patient identification and the same architecture of the database used in each of the systems. The EHR module is part of the entire process. It depends on the other modules to provide the required information. The accuracy of the patients' records would be ensured if the information comes from other systems. Patient identification is important in ensuring that the right patient information is recorded. [16].

5.1.4 Hardware Components

The software modules of HIMS run on a hardware platform that must be carefully designed to meet the availability, performance, and security requirements of a healthcare environment. The key hardware components include servers, storage units, network devices, and user terminals [4].

User terminals are the points at which clinical and administrative staff interact with the system. These range from standard desktop computers at nursing stations and administrative desks to medical panel PCs mounted at patient bedsides, tablet computers used for ward rounds, self-service kiosks in outpatient areas, and specialized clinical workstations in radiology and pathology departments. Barcode readers and label printers are used extensively in pharmacy, laboratory, and patient identification workflows, where the accurate association of specimens, medications, and wristbands with the correct patient record is a fundamental safety requirement [1, 4, 17].

5.1.5 Server Infrastructure

Servers are the computational heart of the hospital's IT infrastructure. They execute the HIMS application logic, host the databases that store patient data, run the virtualization platforms that consolidate multiple workloads onto fewer physical machines, and provide the processing capacity for analytics and reporting. Because the systems they support are critical to patient care [4], hospital servers are designed around four key engineering principles.

The first principle is **redundancy**. Critical components, including power supplies, hard disk drives, and network interface cards, are duplicated so that if one component fails, a backup takes over immediately without any interruption in service. Redundancy is not merely desirable in a hospital server; it is a fundamental design requirement [18].

The second principle is **scalability**. As the hospital grows, or as the volume of digital information increases, the server infrastructure must be able to accommodate increasing workloads by adding resources without requiring replacement of the entire system [18]. The third principle is **manageability**. Modern servers include out-of-band management interfaces such as IPMI, iLO,

and iDRAC that allow remote monitoring, diagnostics, and even remote power cycling, reducing the need for physical presence in the datacentre [19].

The fourth principle is **serviceability**. Servers used in hospitals are designed for rapid component replacement, with hot-swappable drives and power supplies that can be changed without taking the server offline [18].

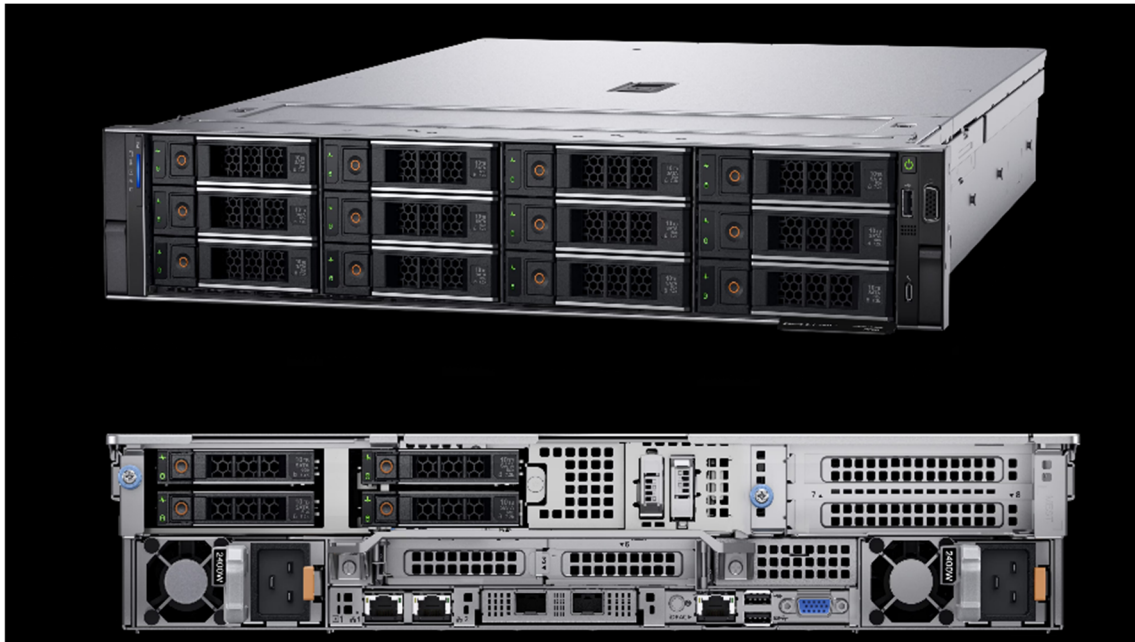


Figure 5.1. Front and Back Panel of a Server System [20, 21]

IMPORTANT: In a hospital, server downtime is not measured only in lost productivity. It is measured in clinical risk. A server failure that takes the prescribing system offline, for example, can delay medication administration. Server design must therefore prioritize availability above almost all other considerations.

5.1.6 Storage Solutions: NAS and SAN

Hospitals generate enormous quantities of data. A single CT scan can produce hundreds of megabytes of image data. An MRI study can generate gigabytes. Multiplied across thousands of patients and millions of examinations over decades, the total storage requirement becomes large. Hospital storage

infrastructure must therefore be designed for capacity and also for performance, reliability, and long term archival capability.

Two principal storage technologies are used in hospital IT environments: Network Attached Storage (NAS) and Storage Area Network (SAN).

Network Attached Storage (NAS)

NAS is a dedicated file storage device connected to the standard hospital network. It provides file-level access, meaning that users and systems retrieve complete files using protocols such as SMB/CIFS for Windows environments and NFS for Linux or Unix systems. NAS devices operate with their own embedded operating system and present storage as shared network folders.



Figure 5.2. Front and Back Panel of a NAS [22]

They are particularly well-suited to centralized file sharing, document storage, backup repositories, media archives, and Network Video Recorder (NVR) storage for the hospital's CCTV system. NAS solutions are generally simpler to deploy and administer and are lower in cost than SAN, making them an appropriate choice for workloads where extreme performance is not required [18].



Storage Area Network (SAN)

SAN is a high-performance storage solution that presents storage to servers at the block level, meaning that from the server's perspective, the storage appears as a locally attached disk, even though it is physically located in a dedicated storage array connected via a separate, high-speed storage network. SAN uses protocols such as iSCSI or Fibre Channel for communication.

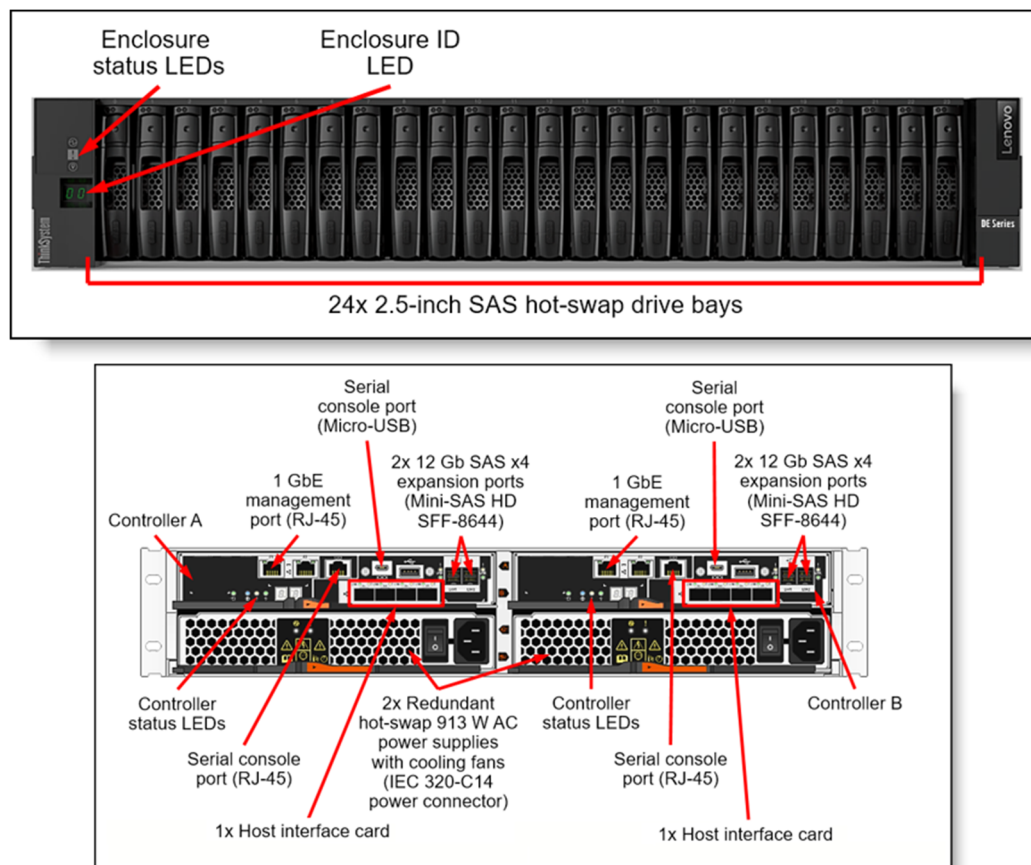


Figure 5.3. Front and Back Panel of a Storage [23]

The Fibre Channel variant uses dedicated optical fibre connections, providing extremely low latency and extremely high throughput. SAN is the preferred storage architecture for the most demanding hospital workloads, including the HIMS databases, virtual machine storage platforms such as VMware or Hyper-V, and any application where storage performance directly affects clinical system responsiveness [18]. Although both provide shared storage, they differ

significantly in their architecture, performance characteristics, and appropriate use cases. Table 3 shows key differences between NAS and SAN.

Table 5.3. Key Differences Between NAS and SAN Storage in a Hospital Context [24, 25]

ASPECT	NAS (Network Attached Storage)	SAN (Storage Area Network)
Storage Type	File-level storage	Block-level storage
Protocols	SMB/CIFS (Windows), NFS (Linux/Unix), FTP	iSCSI, Fibre Channel
Connectivity	Standard Ethernet network (LAN)	Dedicated storage network (Fibre Channel)
Access Method	Files and folders accessed via network share	Blocks accessed like local disks
Operating System	Has its own OS for managing file shares	Acts as raw storage presented to hosts, managed by array controllers
Typical Usage	File sharing, backups, archiving	Databases, virtual machines, high-performance apps
Performance	Moderate (limited by Ethernet and file protocol overhead)	High (low latency, optimized for speed)
Complexity	Easier to set up and manage	More complex to deploy and administer
Cost	Generally lower cost	Higher cost (especially Fibre Channel)

5.1.7 Network Devices

From enterprise campuses to healthcare facilities, modern networked environments depend on a layered architecture of specialised hardware and protocols. A Local Area Network (LAN) is a network architecture that connects devices (such as computers, servers, and printers) in a limited geographical area to communicate and share resources. LANs can be wired via physical Ethernet



cables or deployed as wireless networks (WLANs, Wi-Fi) using industrial Wireless Access Points [24].

The hospital network is the infrastructure through which all digital communications flow. It connects user terminals to servers, servers to storage, medical devices to clinical applications, and the hospital to external systems, including national health registries and laboratory networks. A well-designed hospital network must be reliable, performant, secure, and capable of being managed and monitored in real time.

Core devices that constitute a contemporary Local Area Network (LAN) are the network switches, the routers, and the firewalls [24].

Network Switches

A switch is defined as a hardware component that functions mainly at Layer 2 of the OSI reference model. The main function of a switch is to connect many end devices, such as computers, servers, printers, IP telephones, and other types of networking devices in a single LAN and deliver the data frame to the desired recipient only without flooding the whole LAN, unlike hubs [25].

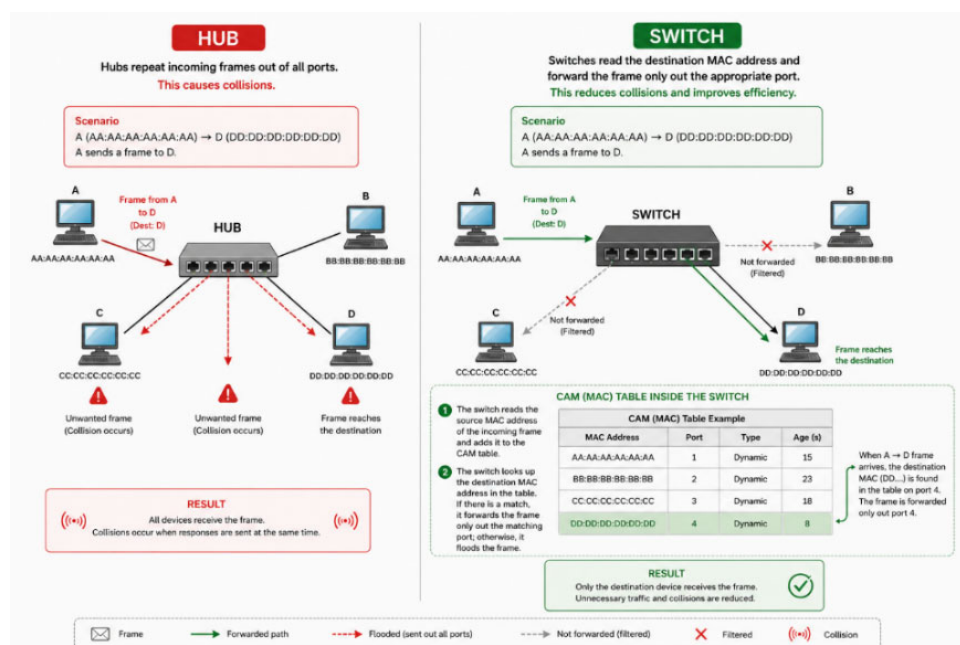


Figure 5.4. Hub and Switch Difference [24, 25]

The operation of selective data delivery sets switches apart from their predecessors, the hubs, which would forward the input signal blindly to all ports, leading to poor performance as utilization grew.

The function of selective forwarding of data is accomplished using the MAC Address Table, also referred to as the CAM (Content Addressable Memory) Table, in switches. The MAC address table maps the address of the device connected to the switch to a particular port, which means that when an incoming frame comes to a switch via any port, the switch identifies the destination address and then forwards the frame using that information alone. In case the address is unknown to the switch, it will flood the frame to all ports but the source one, thereby learning the topology of the LAN as well [25].

Beyond raw forwarding, modern switches implement a range of security and quality-of-service features. Port security allows an administrator to restrict which MAC addresses may communicate through a given port, thereby limiting the risk of unauthorised device attachment. MAC address filtering provides an additional layer of access control. These capabilities make switches the backbone of any contemporary LAN [26].

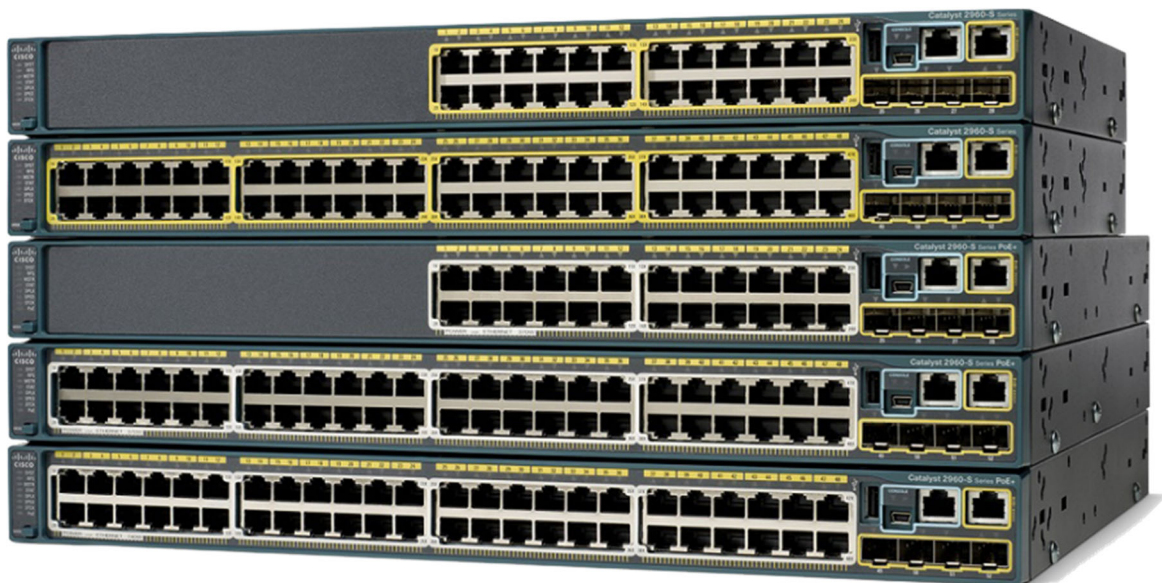


Figure 5.5. Example of Network Switches [27]



Types of Switches

In general, network switches can be divided into three main classes depending on configurability and features provided by the switch. First, there are unmanaged switches, which are the easiest switches available. They work using plug-and-play technology, do not need to be configured in any way, and only provide basic Layer 2 functionality. Although these devices can be quite cheap and suitable for smaller networks, they cannot segregate traffic, implement QoS, or monitor the traffic [24].

On the other hand, managed switches provide rich possibilities for configuration, where an administrator can configure VLANs, STP to avoid loops, QoS, port mirroring, and gather useful statistics using such technologies as CLI, web GUI, and SNMP. Such configurability makes these devices a common choice in hospitals, universities, and companies [26].

Finally, layer 3 switches combine features of switching and routing, implementing the functionality in the same chip. Thanks to that approach, these switches can forward packets between VLANs without a dedicated router. These switches are very useful in the distribution and core network layers in hierarchical networks [25].

Network Routers

Routers are meant to join several different networks together, while switches can only function in one network. This is achieved by making intelligent decisions about how to forward the data packets from one network to another. Routers function at the third layer (network layer) of the OSI model; as opposed to MAC addresses used by switches, they base their forwarding decisions on IP addresses [25]. In each router, there is a routing table, which is essentially a

database with all the network prefixes for which this router knows where to send data next [24].

Apart from their main forwarding function, enterprise routers perform various additional functions. They support Network Address Translation (NAT) that allows enterprises to allocate private IP addresses internally but appear to be using just one public IP address externally [26]. They manage access control lists (ACLs) to perform traffic filtering when data leaves the network. At the same time, they prioritize delay-sensitive traffic like voice and video. Finally, routers are used to create Virtual Private Networks (VPNs) between distant locations [25].

Types of Routers

There is a range of performance levels and capabilities of routers. SOHO routers are equipped with routing, access points, and switch functionalities, making it an all-inclusive device that can be used in homes. The forwarding ability, security systems, and overall performance of these routers have been intentionally made inadequate to keep costs down [24].

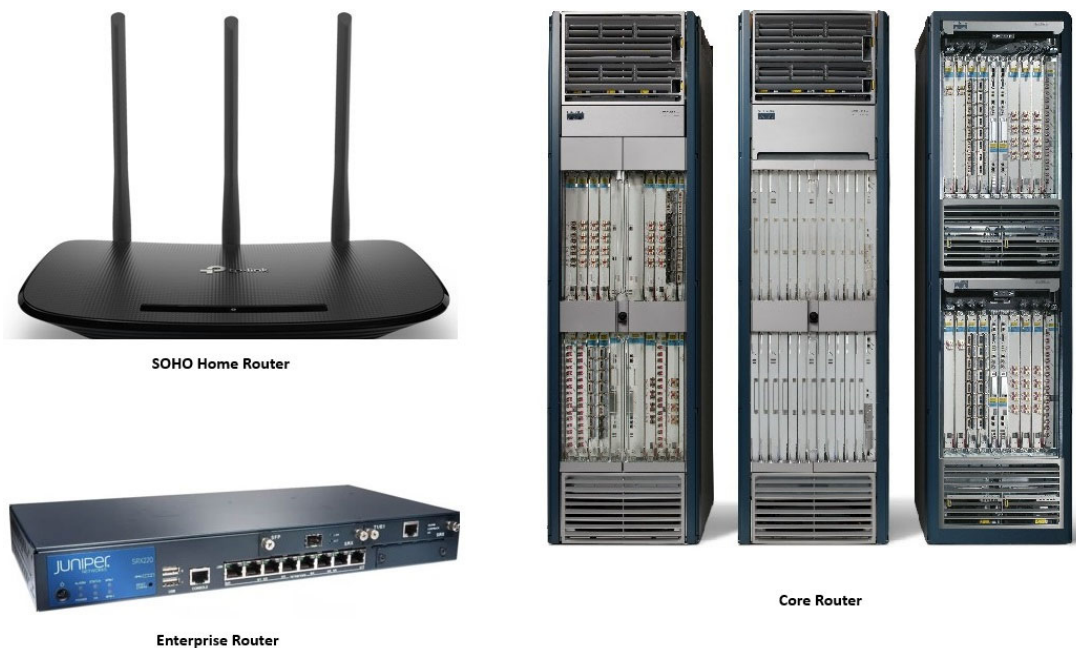


Figure 5.6. Examples of router types [28, 29]



Enterprise routers offer enhanced availability and high throughput in terms of the services provided. The routers can support hardware accelerations, redundancy in power supplies, interface cards, and more routing protocols. Core routers are also referred to as backbone or carrier grade routers. These are at the highest level of hierarchy. ISPs and large-scale data centres use core routers for handling gigabit per second level traffic along with hundreds of thousands of prefixes in their routing table [25].

Firewall

A firewall can be defined as a security control device that is built through hardware, software, or both. Firewalls filter traffic passing from one segment of the network into another, depending on the security policies set for the two different networks. Standard deployment location of a firewall is between the corporate network of an organization and the outside network, such as the internet; however, firewalls are also commonly used within a network as a demilitarized zone (DMZ) and to enforce segmentation between departments or VLANs [25]. Packet filtering firewalls were developed early and relied on examination of each packet separately and filtering of network traffic using rules related to the IP addresses, transport layer port numbers, and the protocol number. Though being a very efficient process, packet filtering lacked security since it was susceptible to spoofing and had no way of looking into the entire transaction context. Stateful inspection firewalls came about around the mid-1990s and relied on filtering traffic based on an entire connection and not on separate packets [26].

Next-Generation Firewalls

Modern deployments are more likely to utilize Next-Generation Firewalls (NGFWs), which are built upon the foundation of stateful inspection and add

additional features such as application-layer awareness, identity-based enforcement, and inline IPS functions. With the help of an NGFW, it becomes possible to distinguish among multiple applications that use the same port (such as different web apps that utilize TCP port 443) and enforce controls based on their identity, rather than using only port and protocol information [30].

The other notable feature of an NGFW is its ability to terminate encrypted site-to-site and remote access connections. It generates logs that create an auditable trail and contribute to regulatory compliance. For example, in the healthcare sector, where patient data is protected by laws, NGFW log generation is an important part of an organization's information security management system [31].

VLAN

Virtual Local Area Networks (VLANs) are critical security and management structures in local area networks. A VLAN is a logical subdivision of a physical network, created at the switch, that groups devices into isolated broadcast domains regardless of their physical location.



Figure 5.7. Examples for the firewall (NGFW) [32].

VLANs allow a single physical network infrastructure to carry traffic from multiple logical networks simultaneously, with each VLAN functioning as an independent network [24, 25].



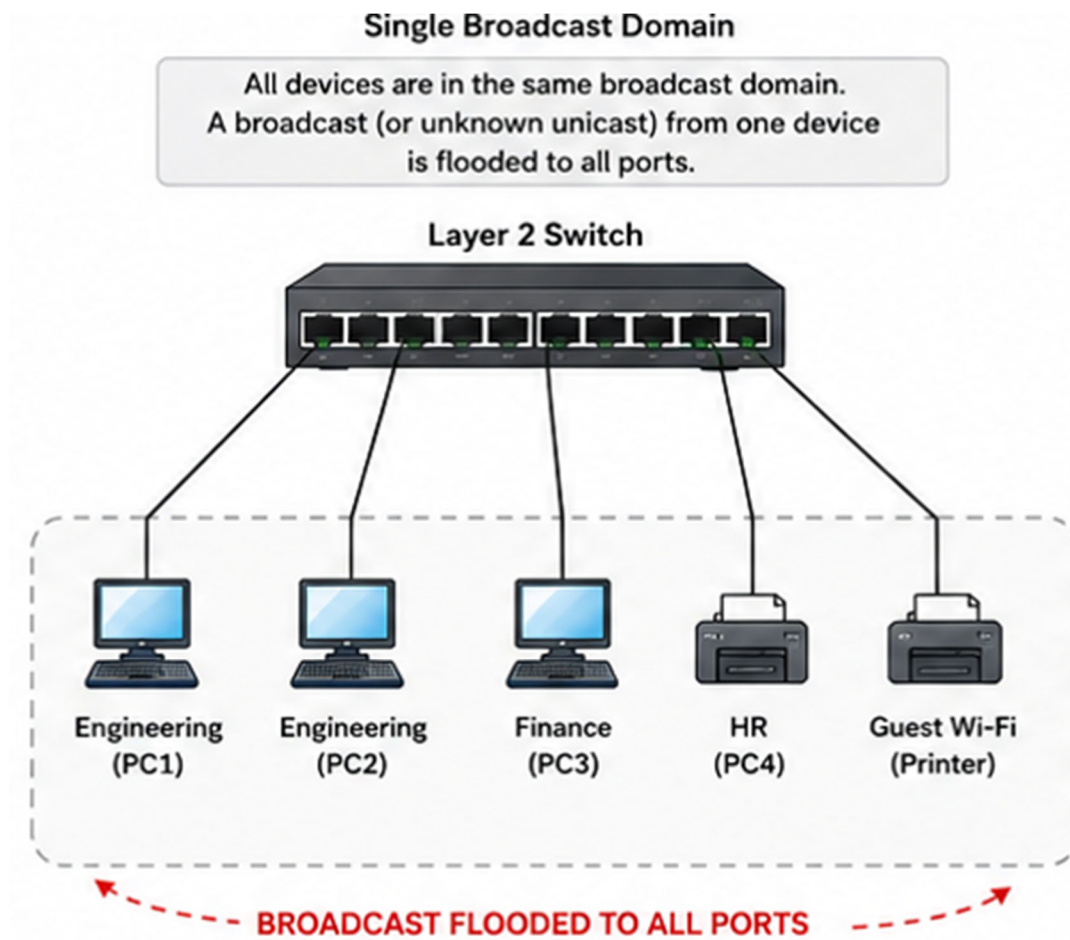


Figure 5.8. A basic network without VLANs.

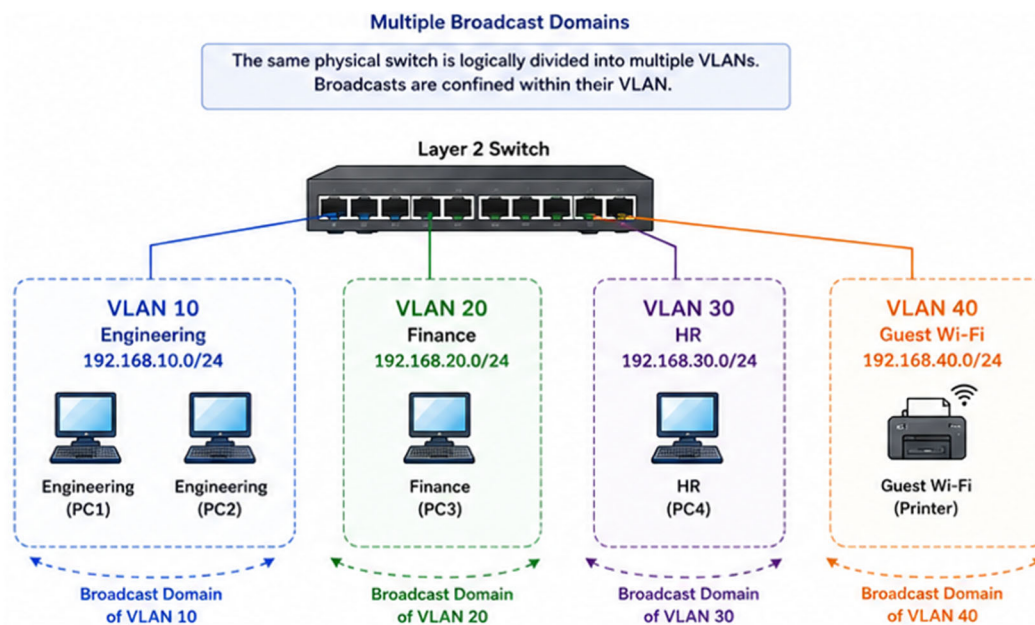


Figure 5.9. A basic network with VLANs.

Communication between VLANs requires routing, either by an external router or a Layer 3 switch. The IEEE 802.1Q standard defines the mechanism by which VLAN membership information is carried in Ethernet frames as a four-byte tag appended to the standard header. These tagging and untagging operations are made by a router or a layer 3 switch [33].

VLANs play a vital role in a hospital setting. First, they segregate the clinical LANs from the administrative LANs by isolating the high-volume data movement in one segment and preventing it from affecting the other segment's efficiency. Second, they segregate medical equipment from the computer systems; hence, a possible hacker will have to gain access to less secure devices before having a foothold in the system. Third, the security policy can be implemented at the interface point between the two segments rather than at the organization's periphery. In other words, switches form the backbone of a hospital's security strategy [24, 25]. Below is a sample of a hospital VLAN list.

Table 5.4. VLAN segmentation example for hospitals

VLAN Name	Segment	Connected Devices
Clinical VLAN	Isolated clinical traffic	EHR workstations, nurse stations, medical panels, computers used in clinics
HIMS Server VLAN	Application servers	HIS servers, LIS, RIS, Database servers
Medical Device VLAN	Device integration	Patient monitors, Ventilators, imaging systems
Management VLAN	Out-of-band administration	IPMI/iLO/iDRAC interfaces, UPS, PDU monitoring
Guest / Patient VLAN	Visitor internet access	Patient tablets and phones, guest Wi-Fi clients, in room multimedia devices



Administration VLAN	Management offices	Computers of Management Departments
BMS VLAN	Smart building automation systems	HVAC controllers, central UPS management cards
Security / CCTV VLAN	Physical security systems	IP cameras, access control panels, badge readers
VOIP	Real-time voice and emergency signals	IP phones, call center desks, emergency notification panels

Wireless Network

Wireless networking, as defined in IEEE 802.11 standards, is now an integral part of modern-day networks. Wireless Access Points (APs) help provide wireless connectivity that connects any wireless device to the wired switched network via radio-frequency connection.

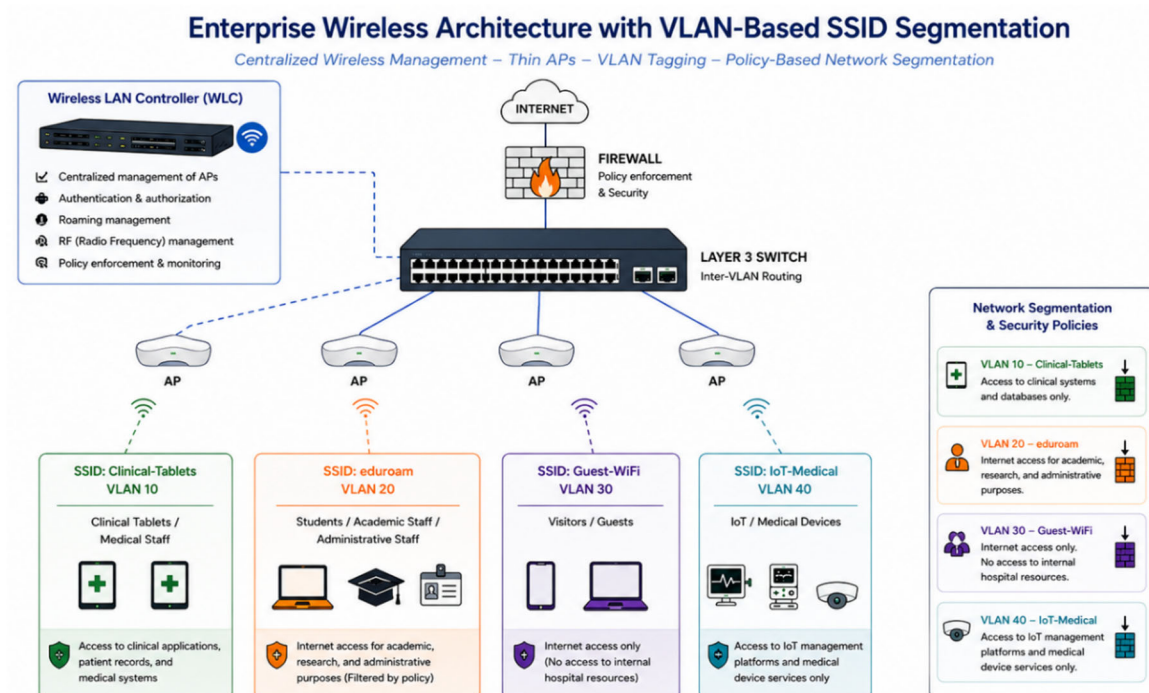


Figure 5.10. Illustration of wireless network VLAN-based SSID segmentation [24, 25, 26, 33].

Enterprise-class APs are usually thin clients whereby all management and configuration activities are centralized on one Wireless LAN Controller (WLC) which performs functions such as authentication, roaming, radio frequency configuration, and firewall enforcement amongst others [34].

Connection of the wireless infrastructure to the switching fabric is done using VLAN tagging, where typically each wireless SSID is assigned to a specific VLAN. This helps in segregating devices such as the hospital laptops, clinical tablets, visitor devices, and IoT devices into logically segregated networks, each governed by different firewall policies and access policies.

This approach of network segregation closely mimics the VLAN segregation explained in the VLAN section, highlighting the importance of integrating switches with VLAN for all other services [25].

Inter-VLAN Routing

Figure 5.11 illustrates a hospital network architecture designed with a single Layer 3 (L3) switch using VLAN segmentation.

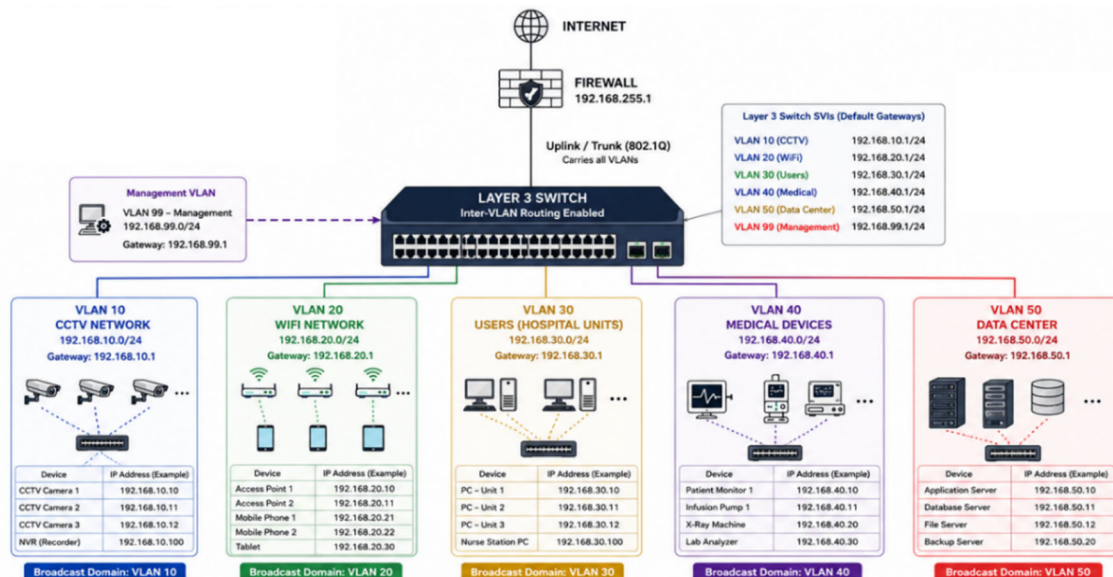


Figure 5.11. Illustration of modern hospital network architecture

In this model, different departments and services, such as CCTV systems, Wi-Fi networks, hospital users, medical devices, and the data center, are separated into independent VLANs with their own IP subnets and gateway addresses.

The Layer 3 switch performs both switching and inter-VLAN routing inside the same device, allowing secure and efficient communication between VLANs without requiring an external router. This architecture improves network performance, scalability, traffic management, and security in modern hospital environments.

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5.2 HOSPITAL 3D UNITS: ENGINEERING SOLUTIONS FOR CLINICIANS AND PATIENTS

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5.2.1 What is a Hospital 3D Unit?

It is an engineering service that provides physicians with additional tools to improve patient care. The work is fully personalized and specific to each clinical case and requires a multidisciplinary approach. It begins with the acquisition of the patient's medical images through non-invasive examinations such as computed tomography and/or magnetic resonance imaging, performed by medical imaging technologists, work keeps going on by engineers who transform these 2D images into 3D images and, in some cases, also manufacture a custom made medical device. And the process culminates in the surgical or interventional treatment carried out by the physicians [1,2].

Services provided by the 3D Unit

The three main pillars of this department's work to support physicians are:

- Biomodels
- Surgical guides
- Phantoms

Biomodels

A biomodel is a three-dimensional representation of the anatomy of interest obtained from 2D medical images. This is carried out using what is known as medical image segmentation software, which must meet a series of technical and legal requirements before it can be used in clinical practice. Depending on



the nature of the structures to be visualized, data obtained from computed tomography and magnetic resonance imaging can even be combined [3]. This software produces a virtual 3D model that allows the patient's anatomy to be observed and the tissues of interest to be isolated for a better understanding of the case. The main premise is that physicians communicate to the engineers which anatomical region they wish to visualize, so it is not necessary to represent all the anatomy contained within the region of interest, but only the anatomy that is relevant to the patient's pathology. Once the virtual model has been obtained, it must be validated by the physician who made the request, since medical specialists have the clinical knowledge required to verify that the result corresponds to reality. In some cases, the physician only needs the virtual model because they wish to understand the relationship between the anatomical structures and their positions. In other cases, however, the resulting model must be 3D printed [4].

The advantages of printing the biomodel include:

- **Full scale.** It provides an awareness of the model's dimensions and allows them to be compared with the size of the surgical instruments or even with the physician's own hands, since during surgery they may sometimes need to rely on touch.
- **Plate pre-contouring.** By having the anatomical arrangement at full scale, the fracture reduction can be simulated and the plate for osteosynthesis treatment can be selected and, where necessary, pre-contoured. This saves operating theatre time because this part of the work is performed beforehand. Pre-contoured plates must be sterilised before they are used on the patient.
- **Communication with the patient.** A patient who is going to undergo surgery usually has no medical knowledge and may be frightened. These

factors combined make the case more difficult to understand and may sometimes lead patients to withhold consent for surgery, even when it is necessary. The printed biomodel allows the physician to explain in a simple manner what will be done during the operation, helping the patient to understand the situation correctly and feel reassured.



Figure 5.12 3D printed biomodels [5]

Surgical guides

These are devices placed directly on the patient's exposed tissue that allow the virtual surgical plan to be accurately transferred to the patient in the operating theatre. They carry much greater responsibility than biomodels because they are directly involved in the performance of the procedure.

The process begins with the segmentation of the anatomical region of interest requested by the physician and after analysing the clinician's requirements, whether positioning and/or cutting is needed, a virtual surgical plan is prepared with the positions, angles and dimensions required to solve the surgeon's problem. This plan is verified by the prescribing clinician, who can also view a simulation of how the anatomical region of interest will appear after the planned procedure has been carried out. Once approval has been obtained, the



personalized medical device is manufactured by 3D printing using a biocompatible material [6].

A particular feature of these devices is that they are single-use and may only be used for the patient for whom they were designed, both because of the patient's anatomy and because of the specific problem to be solved. Although human beings share the same general anatomy, such as the same muscles, bones, etc., small geometric variations make each person unique, consequently, these devices can only be positioned on a specific anatomical region of the patient, which greatly improves the accuracy of the surgical plan [7].

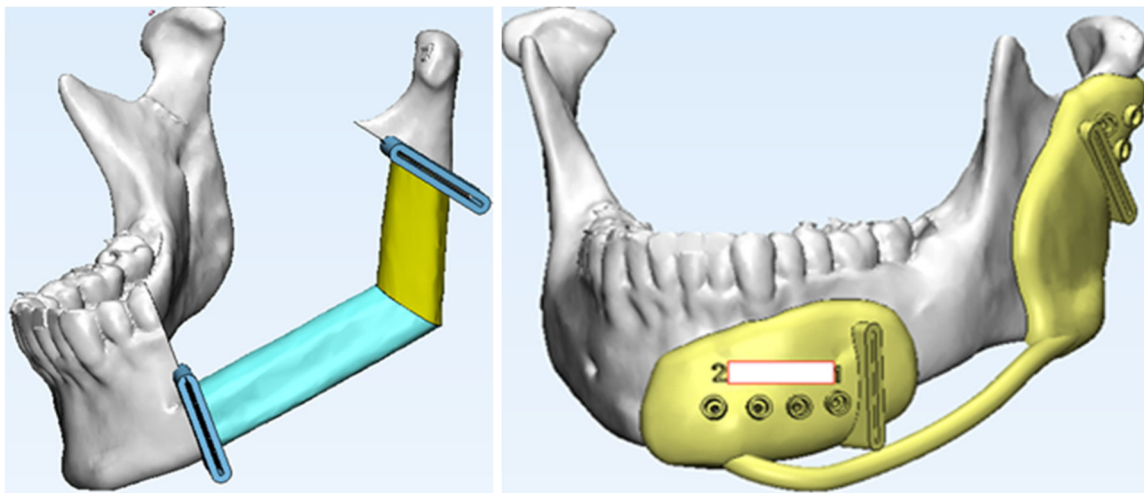


Figure 5.13 Customized cutting guides [7]

Phantoms

These are models that reproduce the anatomy so that their characteristics and geometry resemble those of the actual tissues.

They are used to train students and residents by allowing them to practice surgical procedures in a way similar to real life procedures but without the pressure of operating on a human being, therefore providing considerable educational value [2].

Their other main use is for preoperative practice in complex clinical cases that are going to be treated so, performing the procedure on these models makes it possible to rehearse the surgical plan and maximize the chances of success.

Workflow

The process begins when a physician requires additional tools to approach a complex case, since this service is not necessary for simple and routine procedures. The complete process is described below:

1. The physician submits a request to the 3D Unit specifying their needs, the medical images to be used, the anatomy and region of interest to be segmented, and the expected outcome.
2. The engineer securely accesses the DICOM images obtained by computed tomography and/or magnetic resonance imaging and stored on an internal hospital platform. The aim is to ensure that the slice thickness of each image meets the criteria required to provide adequate image resolution: ≤ 1.25 mm for biomodels and ≤ 1 mm for surgical guides.
3. The virtual model is obtained using medical image segmentation software. Segmentation may be performed manually, semi-automatically, automatically or using artificial intelligence.
4. The prescribing clinician validates the segmentation.
5. When digital planning is required, the physician and the engineer carry it out together.
6. Based on the specific requirement, whether a virtual biomodel, printed biomodel, virtual surgical plan, surgical guides, phantoms or a combination of some of these, the product is manufactured by 3D printing when necessary.

7. The manufacturing technology and specific materials are selected according to the intended use of the printed product.
8. Post-processing of the manufactured product.
9. Quality control of the manufactured product.
10. When sterilisation is not required, the product is delivered to the physician. When sterilisation is required, the corresponding request and the product's sterilisation instructions are sent to the Sterilisation Department.
11. Evaluation by the physician of the work performed and verification of correspondence between what was manufactured and what was observed in the surgical field [2].

5.2.2 Technical equipment and software

IT infrastructure

The data processed in the 3D Unit contain information that should only be accessible to the professionals involved in the clinical case, it is therefore essential to have secure spaces for storing medical images and the files generated based on them. The following resources are used to meet this requirement:

- The hospital application used to view and download medical images. Personal access credentials are required.
- Password protected personal access to the computers in the 3D Unit.
- Storage space on the hospital network that can only be accessed by 3D Unit staff for backup purposes.

Software

Medical image processing requires software designed to ensure that the information obtained from DICOM images corresponds to what is displayed in the software interface. Medical image segmentation software must therefore have CE marking and be validated for clinical use.

Computer-aided design software is also required to design devices such as surgical guides. These devices require not only organic shapes (a part of the guide is in contact with the anatomy) but also geometric features with precise dimensions that meet the mechanical requirements necessary for their correct use.

Software for surgical planning is also required. This software must allow the creation of reference planes based on medical images, measurements, and the rotation and displacement of elements within the 3D reconstructions. Software companies commonly integrate medical image segmentation and computer-aided design into the same product or provide them as complementary modules to the base software. Programs for mesh processing and post-processing are also required to optimize or repair the elements obtained from segmentation.

Finally, manufacturing preparation software is needed to convert the intended manufacturing configuration of the segmented and designed elements into instructions that the 3D printers can understand and execute.

Technological equipment and tools

Due to the large volume of data involved, this service must have high-performance computers with powerful graphics capabilities to process and handle medical image data, as well as all the files derived from them, in order to meet physicians' requests.



3D printers are used to manufacture custom-made medical devices. They enable layer-by-layer additive manufacturing without geometric shape restrictions, making them ideal for organic forms such as human anatomy. Two 3D-printing technologies are mainly used for in-hospital manufacturing:

- **FDM (Fused Deposition Modeling).** Due to its printing speed and access to inexpensive materials, it is used to manufacture biomodels that do not require materials with high technical performance and that are intended for visual planning and plate pre-contouring.
- **SLA (Stereolithography).** Using a medical-grade printer allows for manufacturing with biocompatible material, which is suitable for sterilisation and use in contact with the patient. It is also used for biomodels when physicians wish to handle them in the operating theatre. This technology requires two additional machines to complete the manufacturing process. Resin is a viscous material and leaves residues attached to the part after printing, so the manufactured product must be placed in a machine containing isopropyl alcohol to remove the remaining resin. Finally, the washed part must be dried naturally to allow any residual isopropyl alcohol to evaporate and then placed in a curing machine. The curing machine uses ultraviolet light under controlled temperature and time conditions to give the part the required mechanical properties.

The 3D-printed product must be post-processed using tools to remove the supports and obtain the final part. Scissors and tweezers are therefore required.

Personal protective equipment includes gloves for handling resin and isopropyl alcohol, as well as safety glasses, because the supports may occasionally fly off while they are being removed.

Finally, measuring equipment is required to verify the correct manufacture of the custom-made medical device. There are two possible approaches: using physical measuring devices such as a calliper, or using a scanner to obtain a mesh of the manufactured object, import it into the computer and compare it with the mesh used for manufacturing.

Facilities

It is important for the work area and the manufacturing area to be clearly differentiated and physically separated, since additive manufacturing using 3D printing releases particles that should not be inhaled, while isopropyl alcohol can generate flammable vapours. In addition, as a collective protective measure within the manufacturing area, local exhaust ventilation and continuous air renewal must be provided. The required parameters are established in the facility design according to the number and type of machines and the quantity of isopropyl alcohol stored.

Regulatory framework, licenses and quality management system

Given that all this work is carried out to improve patient treatment and that the patient's health is at stake, a regulatory framework and quality management systems must be established to guarantee patient safety, promote good practice and ensure high standards of treatment.

Regulation 745/2017 [8] is the regulatory framework in Europe, also known as the MDR (Medical Device Regulation), and regulates the design, manufacture, clinical trials and placing on the market of medical devices. According to the level of risk, the following classification is established:

- **Class I (low risk).** Non-invasive or temporary-use products that do not come into contact with critical internal areas of the body, e.g. biomodels, bandages, etc.



- **Class IIa (medium risk).** Devices intended for short-term use or that are moderately invasive, e.g. surgical guides, contact lenses, etc.
- **Class IIb (medium-high risk).** Devices that directly affect the patient's health, e.g. permanent implants, medication pumps, etc.
- **Class III (high risk).** Products intended to remain in the body for a long period or to save lives, e.g. joint replacement implants, pacemakers, etc.

In addition, the legal framework must comply with the regulations of each country, with the more restrictive requirements taking precedence. In Spain, for example, Real Decreto 192/2023 regulates medical devices by adapting the European legislation.

To carry out this activity, an application must be submitted to a regulatory authority, which is responsible for conducting an audit and verifying compliance with regulatory and quality standards. If the report is favourable, a Medical Device Manufacturer License is granted and the activity may begin. In Spain, the Regional Ministry of Health of each Autonomous Community is responsible for granting the license.

Finally, although it is not a requirement for carrying out these duties, certification in accordance with ISO 13485, the international standard for quality management systems focused on medical devices, helps to structure and control the processes of design, manufacture, validation, traceability and incident management. This certification is granted following an audit performed by an auditing body, thereby ensuring compliance with good practice and promoting a continuous improvement cycle.

Benefits and outcome evaluation

Technical knowledge does not replace clinical knowledge, and clinical knowledge does not replace technical knowledge. This is the main benefit, having a



multidisciplinary team capable of approaching problems from different perspectives and providing unique solutions through the diversity of its knowledge. In addition, having engineers within the hospital enables face-to-face communication. The benefits can be classified as follows:

- **Clinical benefits.** Better understanding of complex anatomy, improved preparation before surgery, possibility of anticipating complications, possibility of shorter operating times, which reduces fatigue, and better communication among the different specialists involved in the case.
- **Benefits for the patient.** Better understanding of their condition and the procedure and the possibility of shorter procedures, which may result in less time under anaesthesia and reduced exposure to potential infections.
- **Educational benefits.** Training without risk to the patient, repeatability of certain procedures, and education involving uncommon conditions and anatomical variations.
- **Management and economic benefits.** Time optimization, better coordination among departments, reduced use of consumables and lower costs in certain cases, and the development of knowledge within the hospital itself.

There are several ways to evaluate these outcomes:

- Ongoing communication with the professionals involved in the case, including, when necessary, completion of a survey at the end of the case in order to obtain quantitative data for analysis in addition to qualitative feedback.
- Preparation of technical reports to improve the reproducibility of successful cases and, above all, to document failed prototypes and learn from errors.

- Economic reports quantifying the savings associated with reduced operating theatre time and lower use of consumables.

Clinical case example. Pre-contouring a mesh for orbital fracture

The human body is not perfectly symmetrical, but certain anatomical regions on both sides are very similar. For this reason, in these cases the healthy orbit can be segmented, the so-called “mirror method” can be applied and a healthy orbit can be simulated in the location where the fracture is actually present. This allows the surgeon to pre-contour a mesh before entering the operating theatre, reducing operating time, improving accuracy and reducing the possibility of damaging the tissues surrounding the orbit while inserting and bending the mesh *in situ*.

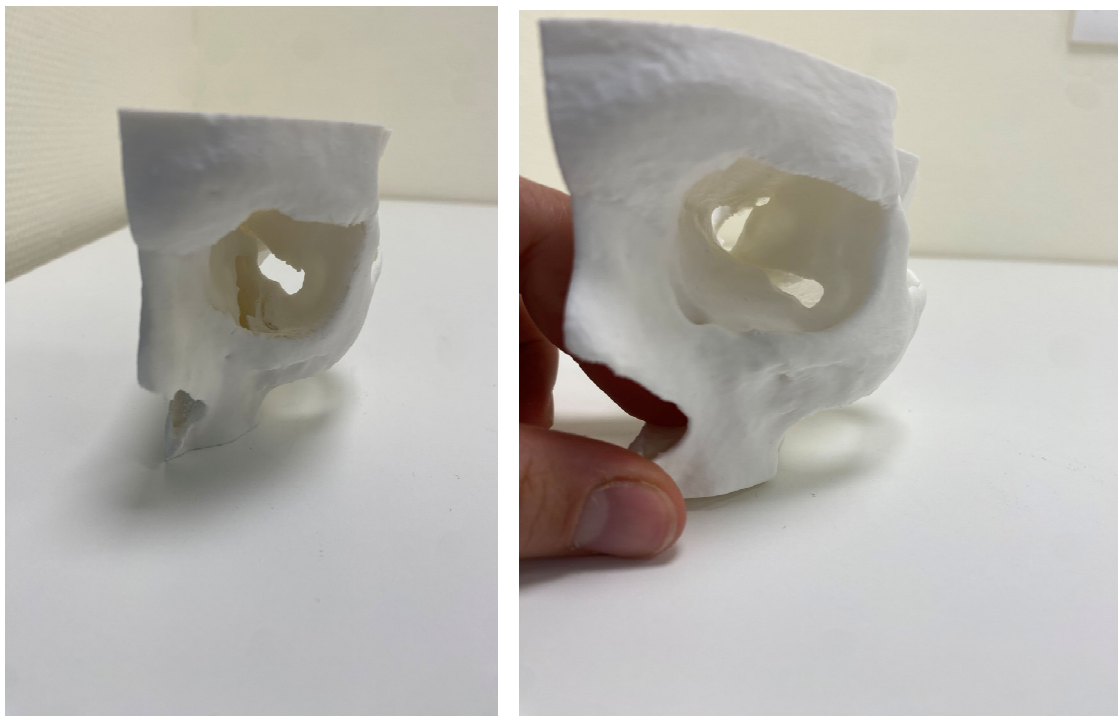


Figure 5.14 3D printed orbit

To pre-contour the mesh, the reconstructed orbit must be printed. The biomodel does not need to be manufactured from a biocompatible material, since it fulfils

its purpose outside the operating theatre and does not need to be taken into it. Only the pre-contoured mesh must be sterilised.

In addition, the fractured orbit can be segmented and printed to verify that the pre-contoured mesh covers the defect before the procedure is performed.

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CHAPTER 6

MEDICAL EQUIPMENT AND TECHNICAL DIAGNOSTICS

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This chapter presents the main technical principles used in medical equipment and diagnostic systems, with focus on biomedical imaging and X-ray physics. It explains how images are produced, processed and evaluated, from radiation generation to digital image quality and communication standards.

6.1 FUNDAMENTAL CONCEPTS IN BIOMEDICAL IMAGING AND X-RAY PHYSICS

6.1.1 Introduction and medical imaging

For the hospital engineer, medical imaging equipment represents the pinnacle of multidisciplinary integration [1]. A diagnostic imaging suite is not a



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standalone device; it is a node within a larger network (PACS/DICOM), a thermal load on the HVAC system, and a significant consumer of stable electrical power.

Understanding the physics of X-rays is the first step in managing the lifecycle of these systems—from site planning and shielding calculations to quality assurance (QA) and maintenance. We approach imaging through the lens of **Signal-to-Noise Ratio (SNR)**, **Modulation Transfer Function (MTF)** and **System Reliability**.

Medical imaging is the process of creating images of the human body's internal structures for diagnostic and treatment purposes. The definition of imaging in health physics is not limited to "photography"; it refers to mapping the physical properties of tissues, such as attenuation coefficients, proton density, or metabolism [1]. The radiation source should not be viewed as some kind of lamp emitting X-rays; it must be understood as a very accurate system of energy distribution. The requirements of safety and contrast require the highest level of control. The image quality depends on the stability of the electron cloud and the impact velocity on the anode [1]. This process is controlled by three factors:

- A. kVp (Peak kilovoltage) - The Energy Control:** The term refers to the highest electrical potential difference between the cathode and the anode. The energy of the accelerated electrons depends on it. We have the generator, which provides us with a stable high-voltage DC signal. Today, high-frequency generators (20-100 kHz) are used to reduce "voltage ripple". Low ripples (practically constant potential) provide the coherent energy of the generated photons. If kVp ripples, the beam penetration changes, making the image non-uniform.
- B. mA (Tube Current) - The Quantity Control:** The quantity measures the number of electrons going from the cathode to the anode per second.

This value is proportional to the number of X-ray photons generated. Filament circuit calibration is extremely important here. The temperature of the filament should be controlled precisely, and for this purpose, it is necessary to regulate precisely the current. So, we regulate the number of thermionic-emitted electrons. Space charge effect: low kVp and high mA can cause electron repulsion and limit the current. For mA stabilization, we need to compensate for it.

- C. Exposure Time (ms) and mAs:** $\text{mA} \times \text{s} = \text{mAs}$ When multiplying, we get the total amount of radiation (photon flux). Important switching accuracy is needed. The modern high-end devices use automatic exposure control (AEC) where an ionization chamber behind the patient controls exactly when to stop the power supply to the generator [2].

The raw X-ray spectrum produced by the anode is unsuitable for use. It contains many low-energy photons that are biologically harmful and clinically useless [3].

Low-energy photons do not have enough energy to pass through the patient and reach the detector. Instead, they are absorbed by the skin; this increases the Patient Dose without contributing a single pixel to the diagnostic image.

Solution: To improve "Input Quality," we need to "harden" the beam. For this purpose, low-energy photons are absorbed to shift the average energy of the X-ray beam to a higher value.

Inherent Filtration: Present in the equipment's structure. The X-ray tube includes a glass or metal housing, insulating oil, and an exit window. Typically corresponds to approximately 0.5-1.0 mm Al (aluminum) equivalent.

Added Filtration: Thin metal plates (usually aluminum or copper) are placed in the beam path. For diagnostic systems operating above 70 kVp, the total filtration is legally required to be at least 2.5 mm Al equivalent.



Beam “quality” is determined not by examining filters but by measuring HVL. The Half-Value Layer (HVL) is the thickness of a specific material (usually Al) that reduces the beam intensity to exactly half of its original value. HVL is a precise measure of the beam’s “hardness” [1]. If the HVL is too low, check whether the added filters have been removed or the kVp calibration has deviated.

Table 6.1. Engineering summary table: Input controls

Parameter	Engineering Mechanism	Quality Objective
kVp Stability	High-frequency inverter/rectifier	Maximize penetrability; minimize ripple-induced noise.
mA Precision	Filament current feedback loop	Control photon density (flux) for optimal SNR.
Total Filtration	Al or Cu plates + Inherent housing	Remove “soft” radiation; minimize Entrance Skin Dose (ESD).
Focal Spot Size	Anode angle and focusing cup geometry	Minimize geometric unsharpness (penumbra).

Mastering these “input” parameters is crucial; only then can a clean signal with a high SNR be obtained, which is fundamental to every medical diagnosis.

6.1.2 Modulation & Transduction:

During interaction with matter, the patient acts as a spatial modulator. As X-rays pass through the body, they are attenuated according to the tissue’s physical properties (Z , ρ , and electron density) [1].

Table 6.2. Important Notions About Modulation

Signal	The “Shadow” cast by the anatomy
Noise (Scatter)	This is the engineer’s greatest enemy. Compton scattering creates non-isotropic photons that do not carry anatomical information [4].

Anti-Scatter Grid A mechanical filter is placed before the detector to absorb oblique scatter. Engineers must calibrate the grid ratio to balance image contrast against the necessary increase in dose (Bucky Factor).

The transduction phase involves digitizing the patient's analog "shadow," converting it from photons to electrons. Analyzing the hardware architecture and engineering metrics of these detectors, **In hardware architecture**, the key component is the **Flat Panel Detector (FPD)**, which consists of a large-area integrated circuit called a **Thin Film Transistor (TFT)** matrix. The method of deposition of charge onto this matrix defines the system type.

Indirect Conversion (Scintillator Based) is a dual-step procedure.

- **The Scintillation layer** in which X-ray photons interact with a scintillator material made up of **Cesium Iodide (CsI)** or **Gadolinium Oxysulfurate (Gd_2O_2S)**. Energy conversion takes place in the form of visible photons [3,5]. Often, CsI is grown in the form of needle-shaped crystals acting as fiber optics for minimizing light diffusion and retaining resolution.
- **The Photodiode layer**, where an array of **Amorphous Silicon (a-Si)** photodiodes receives photons and generates an electrical charge in TFT pixels [3,5].

In the case of direct conversion, this is a one-step procedure in which the conversion of light is omitted entirely to avoid "blurring."

- **Photoconductor Layer:** An Amorphous Selenium (a-Se) photoconductor layer is employed. Upon being exposed to X-ray photons, the a-Se generates electron-hole pairs.
- **Electric Field:** The high electric bias is used on the selenium photoconductor material. In this process, the electrons are directed downwards to the TFT electrodes with little sideways spreading.



This results in better spatial resolution of the image, hence making it the preferred choice for digital mammography. To maintain a hospital's imaging fleet, an engineer must quantify detector performance using two primary transfer functions. These are **Detective Quantum Efficiency (DQE), Fill Factor, and Pixel Pitch**. DQE is the "Figure of Merit" for any digital detector. It measures how much of the Signal-to-Noise Ratio (SNR) present in the X-ray beam is preserved in the final digital image [1,2].

$$DQE = \frac{SNR_{out}^2}{SNR_{in}^2}$$

Low DQE: Means the detector is "noisy." To compensate for this noise and get a clear image, the technician must increase the radiation dose to the patient.

High DQE: Means the detector is highly efficient. This allows for dose reduction while maintaining diagnostic quality. Engineers monitor DQE to determine when a detector is reaching its "end-of-life." In a TFT matrix, there is an array of pixels. The whole surface area of pixels cannot respond to the radiation, but only some portions, where switching transistors and data lines are placed in the rest.

Fill Factor is expressed as the fraction of the area of the pixel that is sensitive to radiation. Increasing the fill factor helps to increase the sensitivity of the sensors [1,2]. **Pixel Pitch** is the distance between the centers of two consecutive pixels. Decreasing pixel pitch (for instance, 100–140 µm) increases spatial resolution [2].

Table 6.3. A Technical Comparison for System Selection

Engineering Feature	Indirect (CsI)	Direct (a-Se)
Conversion Step	X-ray → Light → Charge	X-ray → Charge

Spatial Resolution	Good (limited by light spread)	Excellent (no light spread)
DQE Performance	High (very efficient at low doses)	Moderate to High
Environmental Sensitivity	High	Sensitive to temperature/humidity
Primary Hospital Use	General Radiography, Fluoroscopy	Mammography, High-resolution Orthopedics

The transduction stage is a battle against noise. All processes, from the selection of the scintillator material to the polarization voltage applied to the α -Se layer, are designed to ensure that the maximum number of X-ray photons are converted into usable data bits with minimum electronic interference [3,5].

Quantization:

During the quantization phase, the physical signal is converted into data [3,5]. This phase is a subject of high-speed electronics and digital signal processing (DSP). Below, the digital signal procedure is detailed, utilizing standard **International Electrotechnical Commission (IEC)** display protocols [1]. In a **Flat Panel Detector (FPD)**, sampling depends on the physical geometry of the thin-film transistor (TFT) matrix.

The Nyquist Criterion: According to the Nyquist-Shannon sampling theorem, to accurately reconstruct a signal, the sampling frequency must be at least twice the highest frequency present in the signal.

Spatial Frequency (lp/mm) (resolution): Measured in pairs of lines per millimeter. The maximum spatial frequency ($f_{\max}$) that a system can resolve is defined as [2]:

$$f_{Nyquist} = \frac{1}{2 \times Pixel\ Pitch}$$



If the pixel pitch is 140 μm , the Nyquist limit is approximately 3.57 lp/mm [2]. Attempting to visualize structures smaller than this limit leads to aliasing artifacts, causing high-frequency data to appear as low-frequency patterns (Moiré patterns). While sampling frequency determines how “sharp” the image is, **Bit Depth** determines how many “shades of gray” the system can distinguish. This is the core of the **Analog-to-Digital Converter (ADC)** performance.

Quantization Levels: The bit depth (2^n) defines the number of discrete gray levels.

- **12-bit:** 4,096 gray levels.
- **14-bit:** 16,384 gray levels.
- **16-bit:** 65,536 gray levels (Standard for high-end DR and CT).

Dynamic Range & Latitude: A wide dynamic range is required for the detector to simultaneously capture the high-intensity signal passing through the lungs and the low-intensity signal passing through the spine without clipping.

Signal-to-Quantization Noise: Increasing bit depth reduces quantization error, ensuring that the subtle contrast in soft tissues is not lost in the rounding of digital values [6]. Before an image is sent to the PACS, the raw data from the TFT must be corrected for hardware imperfections. These are the calibrations you perform during **Quality Assurance (QA)**.

A. The Offset Correction, Dark Current Calibration

Even without X-rays, the detector produces a small amount of electrical noise (dark current). The system takes a “dark image” without radiation and subtracts this noise baseline from the actual clinical image [1].

B. The Flat-Field Correction, Gain Calibration

No detector is perfectly uniform; some pixels are more sensitive than others, and the X-ray beam itself is more intense in the center than at the edges (Heel

effect). A “flat-field” image is taken with a uniform phantom. The system calculates a gain factor for every individual pixel to ensure a uniform response across the entire detector surface [1].

C. Defect Interpolation: A typical 35× 43 cm detector has over 7 million pixels. Some of these are “dead” (unresponsive) pixels.

Table 6.4. Digital Acquisition

Technical Feature	Engineering Control	Reference / Standard
Spatial Sampling	Determined by the pixel pitch of the TFT array.	Nyquist-Shannon Theorem
Quantization	Managed by the ADC Bit-Depth (14-16 bit).	DICOM (Grayscale Standard)
System Calibration	Gain/Offset maps stored in the acquisition workstation.	AAPM TG-75 / IEC 62220-1
Data Throughput	Speed of the LVDS (Low-Voltage Differential Signaling) or Fiber Optic link.	High-speed Interface Engineering

It is important to determine the coordinates of these dead pixels and to average the values of the functional pixels surrounding the dead pixel by evaluating the nearest neighboring pixel or using linear interpolation [1, 6]. The Quantization stage is the bridge between physics and informatics. An engineer must ensure that the ADC is calibrated, the pixel pitch is appropriate for the clinical task (e.g., smaller pitch for mammography), and the preprocessing algorithms are updated to correct for detector aging. These factors collectively determine the **Modulation Transfer Function (MTF)**.

D. The Output: In this final stage of the imaging chain, raw digital data is transformed into a clinically useful diagnostic image and integrated into the hospital’s digital infrastructure. For us, this process involves ensuring data integrity and interoperability and mathematically optimizing the visual signal.



Leveraging global **Digital Imaging and Communications in Medicine (DICOM)** and **National Electrical Manufacturers Association (NEMA)** standards [1, 6], the output phase is detailed below.

6.1.3 Digital Imaging and Communications in Medicine (DICOM) Standard:

DICOM standard is the “language” of hospital engineering. It is not merely a file format but a complete network protocol. Every image consists of a pixel matrix and a DICOM header. The engineer must ensure the system correctly populates “Tags” (Standardized by **DICOM PS3.3, table 6.5**).

The X-ray machine acts as a Service Class User (SCU) that “pushes” data to the Picture Archiving and Communication System (PACS), which acts as the Service Class Provider (SCP).

By **DICOM Part 14 (GSDF)**, a critical engineering task is calibrating medical monitors to the **Grayscale Standard Display Function**. This ensures that the gray levels produced by the detector are visually consistent across all workstations in the hospital.

Table 6.5. Standardization of DICOM

Patient Demographics	Name, ID, Birthdate
Technical Metadata	<i>kVp, mAs</i> , Focal Spot Size, and Filter material
Dose Reporting	Dose Area Product (DAP) and Air Kerma must be tagged for regulatory compliance and patient safety tracking.

■ Post-Processing: Mathematical Image Optimization:

After the raw data is obtained, the image processing stage begins. This stage requires adjusting the spectrum between the visible region and the X-ray beam. The detector captures a wide dynamic range (e.g., 16-bit, over 65,000 shades of gray), but the human eye can only distinguish about 30–90 shades

[2, 6]. The system applies to a logarithmic transformation or a non-linear LUT. This maps the raw data values to a specific range of “Brightness” and “Contrast” (Window Level and Window Width) suitable for the specific anatomy (e.g., a “Chest LUT” vs. a “Bone LUT”).

At High-Pass Filtering, to make fine structures such as fractures or lung markings more visible, engineers utilize spatial frequency filters [1]. An unsharp masking or high-pass filter is applied to the digital matrix. This mathematically increases the contrast between structural boundaries, effectively “sharpening” the image [6].

At Low-Pass/Adaptive Filtering, in low-dose images, “Quantum Mottle” (statistical noise) can obscure diagnosis. Spatial or adaptive filters (like Median Filters) are used to smooth the image data [1]. Here, the engineering challenge is to reduce noise without blurring the edges of the anatomy.

6.1.4 Technical Performance Metrics Belonging to Quality Assurance

As a summary of QA, hospital engineers evaluate the success of the output stage using the following standards:

Table 6.6. Standards and metrics for the output stage of medical imaging.

Component	Standard / Metric	Engineering Responsibility
Data Format	DICOM PS3.0	Ensure interoperability between Modality, PACS, and RIS.
Display Quality	AAPM TG-18 / DICOM Part 14	Calibration of diagnostic monitors (Luminance/Contrast).
Communication	HL7 / IHE Profiles	Integration of the imaging chain with the Hospital Information System.
Image Fidelity	Peak Signal-to-Noise Ratio (PSNR)	Assessing the quality loss during compression (Lossless vs. Lossy).



Summary for the Hospital Engineer: The “Output” is where the physics of the X-ray becomes a clinical decision. A failure in DICOM tagging can lead to a lost record, and a poorly calibrated LUT can hide a tumor. The hospital engineer’s role is to maintain the mathematical and procedural integrity of this transition, ensuring that the work of the X-ray tube and the detector is accurately delivered to the radiologist’s eyes.

Here is a chain approach that allows a hospital engineer to perform **Root Cause Analysis (RCA)**. If an image is “noisy,” the engineer investigates the generation (low mAs) or the detection (low DQE/low SNR) rather than just looking at the final picture [6].

Table 6.7. The imaging chain

Stage	Component	Engineer’s Primary Concern
Generation	Generator/Tube	Thermal management, kVp accuracy, and focal spot size.
Modulation	Patient/Grid	Scatter reduction, Grid alignment (centering).
Detection	FPD/PSP	DQE, fill factor, pixel pitch.
Acquisition	ADC/Processor	Quantization error, signal-to-noise ratio (SNR).
Output	PACS/Monitor	DICOM compliance, display calibration (DICOM Part 14).

6.1.5 THE PHYSICS OF X-RAY PRODUCTION

X-rays, which are electromagnetic ionizing radiation [3,5], are a cornerstone of diagnostic radiology. They are produced through atomic interactions occurring at the anode in X-Ray Tubes.

The X-Ray Tube is based on the Coolidge design, a study of high-vacuum physics and thermodynamics. This component is the most critical consumable item in

the imaging chain [1,5]. Prof. Dr. Uğur Çevik describes the X-ray tube as a vacuum-sealed diode designed to manage extreme kinetic and thermal energy [6]. In the **Electron Source Control system**, the cathode is the negative electrode, responsible for the space charge, or electron cloud [1]. Thermionic emission is an important subject in the electron source control system. The hospital engineer monitors the Filament Current (measured in amperes). This current heats the tungsten filament (chosen for its high melting point of 3422°C) to a temperature at which electrons “boil off” its surface [1].

The filament is embedded in a nickel or molybdenum cup, which is called the **Focusing Cup**. By applying negative potential to this cup, the engineer ensures the electron beam is electrostatically compressed into a narrow stream directed at a specific **Focal Spot** on the anode.

Filament evaporation is the leading cause of tube failure. Engineers must verify the “boost” and “standby” current settings to prolong the cathode’s life.

Once the electrons are released, they must be accelerated to relativistic speeds to produce X-rays upon impact in a High-Voltage Circuit. The High-Voltage Generator applies a peak kilovoltage (kVp) across the tube gap. This creates an electric field that pulls the electrons toward the anode [1,6]. The energy of a single electron reaching the anode is defined as:

$$E = q \times V$$

where q is the elementary charge, and V is the applied voltage [2, 6].

The vacuum within the glass or metal envelope must be maintained at 10^{-6} to 10^{-7} torr. Any residual gas molecules would collide with electrons, causing ionization and irregular current surges that can damage the generator.

When the electron stream hits the anode target, a massive energy conversion occurs [1]. Only a portion of this kinetic energy results in Bremsstrahlung or



Characteristic X-rays; the huge amount is the production of heat (99% Heat and 1% X-Ray) [2,6].

Most electrons interact with the outer shell electrons of the target atoms, causing excitation and vibrations, i.e., heat. In this case, the heat needs to spread over a wider projection area, and it is also important to design oil-filled enclosures to achieve overall cooling.

Since the target material itself absorbs some of the photons emitted from the anode, the radiation intensity is higher on the cathode side than on the anode side. We call this as **Anode Heel Effect** [1]. We must take this into account when positioning the tube for specific anatomical examinations (for example, thicker body parts should be placed on the cathode side, not the anode side) [2,6].

Table 6.8. Engineering specifications for maintenance

Component	Technical Indicator	Maintenance Action
Filament	Resistance / Emission current	Monitor for thinning/evaporation.
Vacuum Envelope	Dielectric strength of oil	Test oil for carbonization/bubbles.
Rotating Anode	Stator noise / Rotor coast time	Check bearings and rotation speed (<i>RPM</i>).
Focal Spot	Spatial resolution / Pinhole test	Calibrating to prevent "blooming."

An X-ray tube is a very precise instrument working under conditions of great stress. It is possible to determine if a vacuum leak, filament break, or an overheating of the anode is causing the problem based on our knowledge of the Coolidge principles, in particular the distinction between heating the filament (amount) and acceleration of the high voltage (quality) [1,2,6].

Mechanisms of Emission

There are two mechanisms for producing X-rays:

1. **Braking Radiation, Bremsstrahlung:** Takes place when a high-speed electron interacts with the nucleus of the atom of the target material. The energy lost is converted into a photon. This generates a continuous spectrum.
2. **Characteristic Radiation:** Takes place when an incident electron knocks out an electron from the K or L shell of the atom of the target material. The energy released when the outer-shell electron replaces the missing inner-shell one is converted to a photon. This produces a discrete spectrum.

6.1.6 INTERACTION OF X-RAYS WITH TISSUE

Understanding the interaction between X-rays and tissue is crucial for both Image Quality Optimization and Structural Shielding Design. In this process, the patient is considered, before the signal reaches the detector, as a complex attenuator modulating the signal [1,6].

Primary Interaction Modes

In the diagnostic energy spectrum range (20 keV to 150 keV), the "signal" is created by the competition between these two physical phenomena, which are the Photoelectric Effect and Compton Scattering [7].

The Photoelectric Effect

When an X-ray photon enters tissue, it interacts with an electron in the inner shell (K-shell) of the atom in the tissue, knocking it out of its orbit and annihilating itself in the process. The probability of this interaction (P_{pe}) belongs to the material's atomic number (Z) and the photon energy (E):



$$P_{pe} \propto \frac{Z^3}{E^3}$$

Because of the Z^3 dependency, bone ($Z \approx 13.8$) absorbs far more radiation than soft tissue ($Z \approx 7.4$). This creates the high-contrast “silhouette” required for diagnosis [2].

If the kVp is set too high, E^3 increases, reducing the photoelectric effect and causing the image to look “washed out” (low contrast) [2,6,7].

Compton Scattering

Compton scattering occurs when a photon interacts with an outer-shell electron. Only a portion of the energy is transferred; the photon is scattered in a new direction with reduced energy [4].

Unlike photoelectric absorption, Compton scattering is almost independent of Z . It depends primarily on the electron density (number of electrons per gram) and the physical density (ρ) of the material [4].

Scattered photons hit the detector at random angles, creating a uniform “fog” or “veil” that reduces the Signal-to-Noise Ratio (SNR). This is the primary source of **occupational dose**. In a fluoroscopy suite, the engineer must ensure that lead shielding (aprons and barriers) is positioned to intercept these non-isotropic scattered photons.

Figure 6.1. Gives the relative dominance of the photoelectric effect and Compton scattering across diagnostic X-ray energy ranges.

The photoelectric effect predominates at lower photon energies and contributes to image contrast, whereas Compton scattering becomes more significant at higher energies and increases image noise and occupational exposure [4,7].



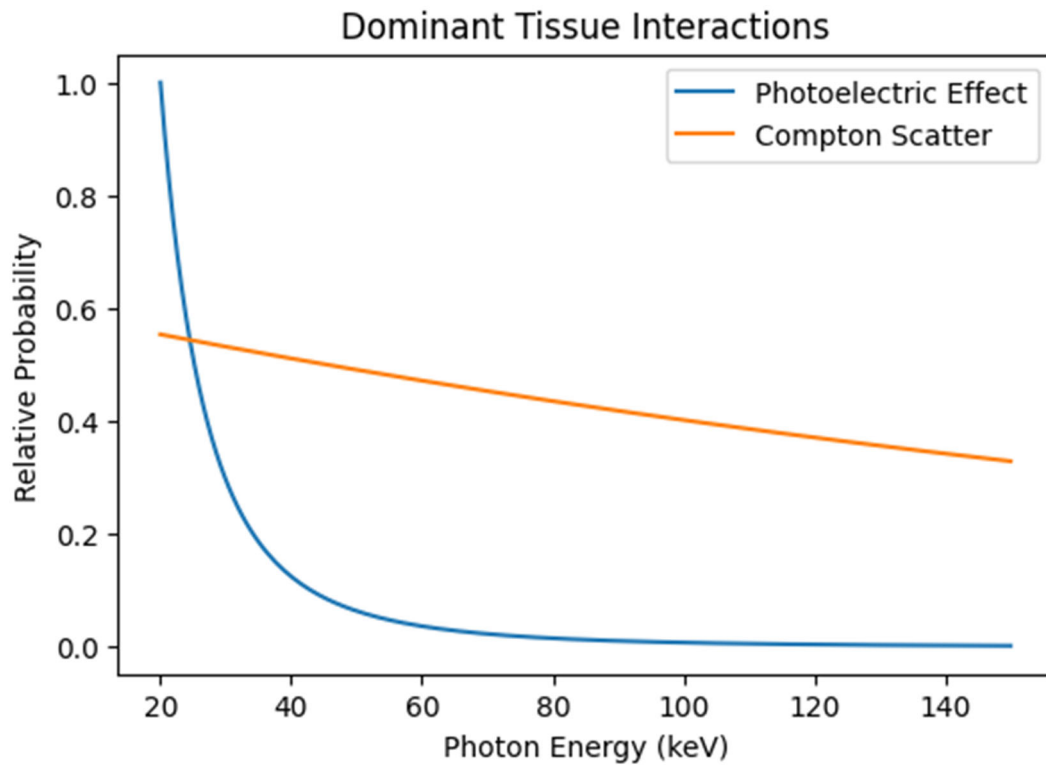


Figure 6.1. Photoelectric vs Compton Interaction [4,6,7].

The Attenuation Formula

The X-ray beam decreases exponentially. Using **Beer-Lambert's Law**, we can calculate how much energy will reach the detector or how thick a wall of lead is needed for security.

The **Linear Attenuation Coefficient (μ)** is the probability of a photon being removed from tissue per unit thickness by absorption or scattering, and it is the sum of all interaction probabilities.

$$\mu = \mu_{\text{photoelectric}} + \mu_{\text{compton}}$$

The intensity (I) of an X-ray beam with an initial intensity I_0 after passing through a material of thickness x is calculated using the following equation:

$$I = I_0 e^{-\mu x}$$

Where:



I_0 : the initial intensity

e : Euler's number

x : the thickness of the tissue or shielding material [2].

In armor and quality testing, the **Half-Value Layer (HVL)** concept, which reduces density by 50%, is used to simplify the attenuation formula. The mathematical relationship between μ and HVL is given below [2,6].

$$\mu = \frac{\ln(2)}{HVL} \approx \frac{0.693}{HVL}$$

By mastering these interactions, we can troubleshoot low contrast by adjusting kVp to favor the Photoelectric effect or high noise by optimizing the grid or collimation to reduce Compton scatter reaching the detector [4,7].

Table 6.9. Interaction Comparison

Property	Photoelectric Effect	Compton Scattering
Mechanism	Complete Absorption	Incoherent Scattering (Deflection)
Atomic Number (Z) Dependency	High (Z^3)	Independent of Z per unit mass, but proportional to Z per atom
Energy (E) Dependency	$1/E^3$ (Dominates at low energies)	Decreases slowly as energy increases
Engineering Result	Image Contrast (White areas on film)	Image Noise and Occupational Dose
Hardware Solution	Optimal kVp selection	Anti-scatter grids and Lead shielding

6.1.7 DIGITAL IMAGING CONCEPTS

Today, with the transition to digital detectors, chemical processes have given way to solid-state physics to maximize the detector's quantum efficiency (DQE).

The difference between **Computed Radiography (CR)** and **Digital Radiography (DR)** lies in the hardware conversion method and the level of integration.

Computed Radiography is an indirect digital system that functions as a bridge between analog and digital.

Here, the detector is a **Photostimulable Phosphor (PSP)** plate, typically made of Barium Fluorohalide ($BaFX:Eu^{2+}$). When X-rays strike the plate, electrons are trapped in F-centers, which are one of the color centers in a latent state. The cassette is placed in a digitizer. A red helium-neon (HeNe) or solid-state laser scans the plate row by row, energizing and exciting the trapped electrons. The electrons emit light as they return to their ground energy level. This is called photoluminescence (PL) [5]. The laser light must operate synchronously with the **Photomultiplier Tube (PMT)** that collects this blue light. Spatial resolution is limited by the light scattering of the laser light within the plate and the size of the phosphor crystals.

Digital Radiography represents "Direct-to-Digital" technology, in which the detector is hardwired or wirelessly connected to the acquisition workstation. DR uses **Thin-Film Transistors (TFT)** or **CMOS** arrays. The conversion happens instantly; there is no physical transport of a cassette [6].

While a CR cycle takes 60–90 seconds per image (plate transport, scanning, erasing), a DR system displays the image in <5 seconds. DR detectors generally have a much higher **DQE (up to 65-75%)** compared to CR (approx. 30%). This allows us to calibrate the systems for significantly **lower radiation doses** while maintaining the same image quality.



The Engineer's Calibration Toolkit, the Image Quality Parameters:

The quality is not subjective; it is quantified by mathematical functions.

Spatial Resolution and the Modulation Transfer Function (MTF)

Spatial resolution allows us to distinguish small, high-contrast objects that are located very close together, such as microcracks.

The MTF is the ultimate measure of an imaging system's resolution. It describes the system's ability to preserve the contrast of an object at different spatial frequencies (line pairs per millimeter - lp/mm) [6].

An MTF of 1.0 (100%) means the image is a perfect representation of the object. As the object gets smaller (higher frequency), the MTF drops. For us, a "sharp" system is one where the MTF remains high at high frequencies. In Figure 6.2, it can be observed the modulation transfer function (MTF) curves for imaging detectors with different spatial resolution characteristics. Higher MTF values at elevated spatial frequencies indicate superior preservation of fine anatomical detail and improved system sharpness [6].

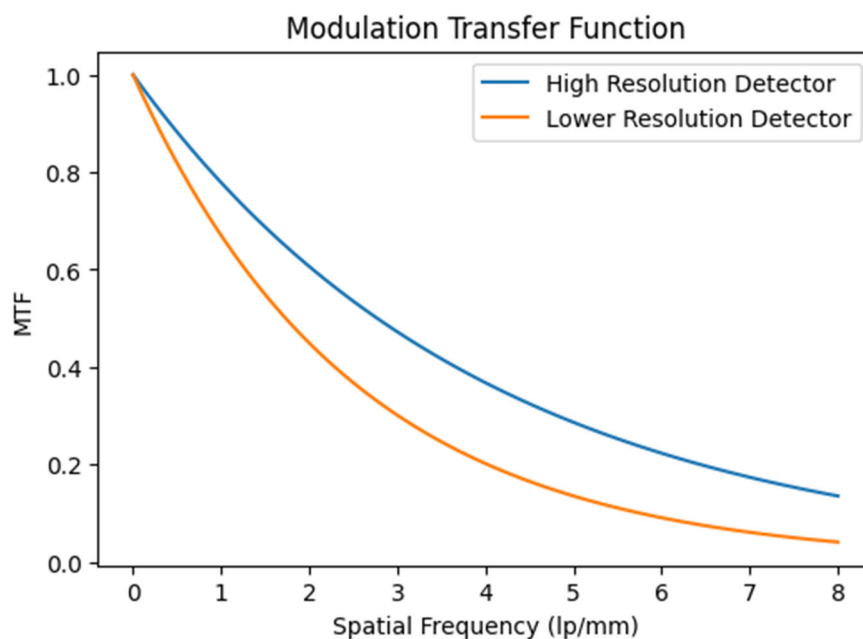


Figure 6.2. Modulation Transfer Function (MTF)

Contrast Resolution and Bit Depth

It is a measure of the spatial resolution of the imaging system. It defines how much of the object's physical contrast can be preserved and transferred to the image by the detector at different spatial frequencies (lines per millimeter - lp/mm).

Signal-to-Noise Ratio (SNR) is the ratio of the "useful" information (the X-ray signal) to the "unwanted" information (electronic noise or scatter).

Quantum Mottle is the "grainy" appearance caused by a lack of X-ray photons (low *mAs*).

$$SNR = \frac{\text{Average Signal Value}}{\text{Standard Deviation of Background Noise}}$$

If the SNR is low, the engineer must determine if the fault lies in the **generator output** (not enough photons) or the **detector electronics** (high dark current/electronic noise) [2,6].

Table 6.10. Quality Metrics Comparison Table

Metric	Primary Hardware Limiter	Target for Hospital Engineer
Spatial Resolution	Pixel Pitch / Laser Spot Size	Maximize lp/mm via small pixel size (100–140 μm).
Contrast Resolution	ADC Bit Depth / Detector Noise	Ensure 14-bit minimum for diagnostic workstations.
DQE	Scintillator Efficiency / Fill Factor	Aim for >60% to minimize patient radiation dose.
Artifact Management	Pre-processing Algorithms	Perform regular "Gain" and "Offset" calibrations.

Every millimeter of resolution and every tone of contrast is the result of precise calibration of the TFT array, ADC bit depth, and MTF curve. Understanding these parameters is crucial for performing mandatory Quality Assurance (QA) tests according to international standards (e.g., AAPM or IEC).



In healthcare engineering is important to know the medical imaging chain, following diagnostic data from high-vacuum physics to digital informatics from the standpoint of biomedical engineering. A medical imaging suite is a highly complex, multidisciplinary node where clinical success depends solely on accurate hardware calibration and environmental integration, as the literature makes clear. The ability to regulate the input parameters, namely kVp stability, mA precision, and filtration engineering, is crucial for producing a clean diagnostic signal with an ideal signal-to-noise ratio. Essential engineering practices include minimizing voltage ripple through contemporary high-frequency generators and upholding a stringent minimum of 2.5 mm Al equivalent filtration. Together, they guarantee a consistent, highly penetrable X-ray beam while shielding the patient from soft, medically hazardous radiation.

The physical interactions between X-rays and human tissue function as a complicated spatial modulator at the baseline of image generation. The image's basic contrast is determined by the ongoing conflict between Compton scattering and the photoelectric effect. Compton scattering is still the engineer's worst adversary, even though the Z^3 dependency of the photoelectric effect beautifully maps anatomical changes to generate the vivid contrast required for diagnosis. The main radiation risk to hospital employees is caused by the introduction of non-isotropic scattered photons, which produce a homogeneous "fog" on the detector. A thorough understanding of these interactions is necessary to mitigate these effects, enabling engineers to choose the optimal kVp to prioritize contrast over scatter-induced noise and improve anti-scatter grid ratios. A significant step toward solid-state physics and instantaneous image transduction has been taken with the technological transition from computed radiography to digital radiography. This chapter demonstrated the main trade-offs between indirect and direct conversion techniques by analyzing

the hardware architecture of flat-panel detectors. To attain a high detective quantum efficiency, which is highly valued for lowering patient radiation doses, indirect systems use CsI or Gd_2O_2S scintillators. On the other hand, amorphous Selenium ($a-Se$) direct conversion arrays fully avoid the light conversion stage to remove blurring. Direct conversion is the gold standard for high-precision clinical applications like digital mammography because of its structural benefit, which maximizes spatial resolution.

Finally, the quantization and output phases act as the last link between hospital informatics and raw physical signals. Strict adherence to mathematical sampling requirements, such as matching the Nyquist-Shannon theorem with the actual pixel pitch, and reliable 14-to-16-bit analog-to-digital conversion, is necessary to provide clinical-grade image fidelity for capturing minute soft tissue details. Additionally, standard quality assurance duties such as gain calibrations and dark current are essential for regulating detector aging and fixing hardware flaws. Hospital engineers protect the system's mathematical and procedural integrity by enforcing international standards like DICOM PS3.0 and calibrating diagnostic monitors to the Grayscale Standard Display Function.

Engineers can do efficient root cause analysis by using an organized, chain-link approach to the imaging process. Understanding how each step from electron acceleration to network output affects the modulation transfer function instead of only assessing the finished image guarantees that the X-ray tube and detector's work is delivered to the radiologist's eyes perfectly and safely.

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CHAPTER 7

ADVANCED ENGINEERING TECHNOLOGIES FOR HEALTHCARE

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This chapter explores the seismic retrofitting methods used to protect hospital buildings and ensure they remain fully operational after an earthquake. It compares traditional retrofitting techniques such as adding shear walls and column jacketing, with innovative technologies such as seismic isolators and energy dampers.

7.1 GLOBAL DEVELOPMENT OF SEISMIC ISOLATION AND STRUCTURAL RETROFITTING SYSTEMS FOR HOSPITAL BUILDINGS AND THE TURKISH EXPERIENCE

7.1.1 Introduction: Seismic Vulnerabilities in Healthcare Facilities

In earthquake resistant structural design, the main principle is to prevent the



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total collapse of a structure when it is subjected to stress exceeding its capacity, and to ensure life safety. However, hospital buildings are far more critical structures as they have to continue to operate following an earthquake under the immediate occupancy principle [1,2]. As it is usually not possible for patients inside to evacuate the building on their own, and because the medical equipment in the building is quite expensive, it is of utmost importance for these buildings to make it through earthquakes with no structural, or non-structural damage.

Therefore, current earthquake regulations require hospital buildings to be designed to keep their functionality after a disaster [3]. Previous earthquakes have shown that hospital buildings with fixed foundations are highly prone to sustain structural damage and experience functional disruptions during intense earthquakes [4]. According to studies conducted by Qu et al. (2023) [5] in the 11 cities affected by the 6 February 2023 Kahramanmaraş earthquake, among the fixed foundation hospital buildings, 20 sustained severe damage, 21 sustained moderate damage, and 93 sustained slight damage, rendering them mostly unfit for use.

After an earthquake, it is important not only for the structural integrity to be maintained, but also for the medical equipment inside the building to be operational without any disruptions [6–9].

Shi et al. (2014) [10] carried out a shake table test for a 4-storey hospital building with base isolation, analysing the movement of medical equipment during a long-period oscillation and near a fault line. They discovered that the isolation reduced the storey reaction and the damage sustained, however they also observed movement in equipment not locked in place.

This section shows the traditional and innovative methods used to retrofit structures that experienced performance loss due to exposure to earthquakes,

winds, and other dynamic effects and environmental conditions throughout their service lives. Additionally, the chapter presents the historical development, applicability, and application areas of seismic isolation systems in Turkey, which are important to increase the seismic endurance and increase the capacity to provide uninterrupted service after an earthquake, especially in hospital buildings. Furthermore, the performances of hospital buildings with seismic isolation during major earthquakes in Turkey and in the world will be analysed, and the contributions of these systems to the earthquake safety and operational continuity of healthcare facilities will be presented.

7.1.2 Retrofitting Methods

Traditional Retrofitting Methods

Traditional methods are based on the idea of limiting the large inter-storey drifts that might occur during the earthquake by providing the structure with additional rigidity and endurance. In this context, the most common applications are adding in-situ shear walls between the existing frames, column jacketing procedures that increase the columnar cross-section/reinforcement, and retrofitting using carbon fiber reinforced polymer (FRP).

Adding in-situ shear walls between frames significantly increases the horizontal load bearing capacity, in-plane rigidity, and energy dissipation capacity of the system [11–14]. It has been proven in experiments that building these walls inside the frame greatly increases the structural endurance compared to externally added walls [15,16]. In order for the reinforcement wall to work monolithically with the existing system, certain steps must be meticulously taken in the construction site.

The cover on the surfaces of the existing columns and beams must be chiselled away, roughening the surface. Anchors are used to ensure load transfer. The

columns at the ends of the wall are usually sheathed to turn them into “boundary zones”. Also, the wall must continue from the foundation to the roof uninterrupted. Another common method is column jacketing where the cross-section of the existing reinforced concrete columns are enlarged to increase their bearing capacity. In this method, the concrete cover of the existing column is removed and the surface is roughened. New stirrups are usually placed at very close intervals such as 10 cm to prevent shear failure during an earthquake and maximise the wrapping effect. Connecting the newly added reinforcements to the column jacket on the upper storey by drilling through the ceiling slab is critical for moment transfer. Following this, new high-strength concrete is poured, typically 15 cm thick. Column jacketing prevents brittle failure by substantially improving the rigidity and ductility [17,18].

Analyses and experiments confirm that “hybrid” applications where wall addition and jacketing are combined demonstrate superior seismic performance by limiting top storey displacements [19–21]. Carbon fiber reinforced polymers are widely used to enhance the bending and shear capacities of column and beam elements due to their light weight, high strength, and rapid applicability [22,23].

Innovative Technologies

Although the capacity improvement approach of traditional methods prevent the total collapse of buildings and loss of life, it allows structural damage to occur within the structure. This makes them an unacceptable solution for buildings that need to provide uninterrupted service after an earthquake, especially hospital buildings [24]. The fundamental idea underlying innovative technologies is to directly dampen the seismic demand affecting the building instead of pushing the capacity of the structure. The use of dampers in hospital buildings is especially important as these devices can be easily integrated into

existing frames without disrupting operations inside the hospital or evacuating inpatient wards.

Dampers effectively control storey drifts and accelerations by converting seismic energy into heat [25,26]. A study conducted by Alkhaled (2024) [27] determined that viscous dampers substantially reduced roof acceleration and base shear force. In the analyses carried out by Armaly et al. (2019) [28] it was observed that friction dampers decreased top storey acceleration by 31.22% and top storey displacement by 50%. It has also been proven with shake table tests that these devices reduce dynamic responses [29].

Furthermore, in the retrofitting of a typical five-storey public hospital it has been demonstrated that using dampers is a far more rational solution compared to the traditional method of adding shear walls [30]. Placing dampers in the external axes maximises their energy absorption capacity [31]. Suk et al. (2024a) [32] examined in experiments the friction type technological damper system developed to improve the seismic performances of reinforced concrete frames.

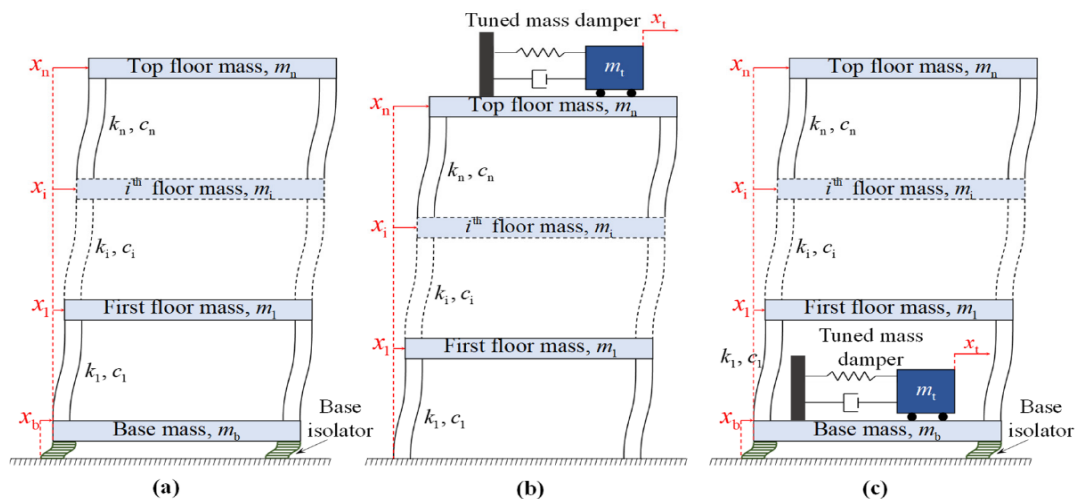


Figure 7.1. (a) Base isolator, (b) tuned mass damper and (c) base isolator–tuned mass damper hybrid system [37].

Cyclic loading tests carried out on half scale frames showed that in the frame where the damper was placed, horizontal load carrying capacity increased by

42-75%, while its energy dissipation capacity increased by 85-220%. Suk et al. (2024b) [33] investigated how a hybrid retrofitting method where a technological damper system was used alongside carbon fiber reinforced polymer wrapping affected the seismic performance of reinforced concrete frames. It was found that the hybrid system increased the horizontal load bearing capacity by 76-122% and increased the energy dissipation capacity by 51-156%, while significantly reducing the damage levels. Another key element underlying the idea of energy dissipation is buckling-restrained braces (BRBs). BRBs, which solve the problem of buckling under pressure by wrapping the steel core inside with a special sheath, act as a structural fuse for the building, giving it the ability to self-center [34–36]. Furthermore, seismic damper mechanisms can be used alongside isolators to decrease the extreme displacement demand, to which foundation isolators are subjected. For example, Banerjee and Matsagar (2023) [37], found that the joint use of elastomeric isolators and tuned mass dampers (TMDs) reduced isolator displacement by 9-27% (Figure 7.1).

7.1.3 Traditional vs. Innovative: A Practical Comparison

When retrofitting hospital buildings, deciding which method to use is critical to ensure the structural integrity of the building and also to ensure that the medical equipment is protected and healthcare services can be provided with no interruptions. Traditional methods usually rigidify the structure, transferring more seismic energy to the structure and amplifying the quakes, which may lead to the damage of expensive medical equipment. Moreover, heavy construction work and lengthy construction process necessitate the evacuation of the hospital and for the building to be out of service for months. On the other hand, innovative technologies such as seismic isolators and dampers dissipate the seismic energy, significantly reducing the quakes. They allow intervention

without evacuating the patients. A summary comparison of traditional and innovative methods across different parameters is presented in Table 7.1.

Table 7.1. Traditional vs. Innovative Retrofitting Methods in Healthcare Facilities

Criterion	Traditional Methods (Wall Addition & Jacketing)	Innovative Methods (Seismic Isolators & Dampers)
Structural Approach	Increases rigidity and load bearing capacity. Transfers the seismic forces to the structure.	Decreases seismic demand, dissipates energy before it enters the structure or at specific points.
Architectural Impact	Very high. Restricts areas of use and requires major architectural alterations.	Minimal. Can be generally limited to basement/foundation level or the external façade.
Hospital Evacuation	Required. Operation has to be on hold for a long period of time	Not required. Medical operations and surgeries can continue uninterrupted.
Equipment Safety	Poor. Increased storey acceleration leads to delicate medical equipment being toppled and damaged.	Successful. Storey accelerations are extremely low, therefore medical equipment is protected.
Cost Implications	Direct construction costs are lower, however hospital evacuation and renovation works create significant costs.	Direct construction costs are higher (~15-20%) however operational and medical equipment losses are eliminated.

IMPORTANT: In healthcare engineering, the success of a seismic retrofit is not measured only by whether the building is standing or not, it is also measured by the continued operability of the hospital. While traditional retrofitting methods may prevent structural collapse, they often rigidify the building which amplifies the shaking inside and risks severe damage to sensitive and life-saving medical equipment. The ultimate goal is operational continuity, which makes the choice between traditional and innovative retrofitting a clinical decision just as much as an engineering one.



7.1.4 Seismic Isolation in Healthcare Facilities

While dampers are highly successful in improving the seismic performance of the superstructure, it is mandatory to completely prevent structural damage in hospitals which contain delicate and expensive medical equipment. The ultimate solution to meet this performance goal is not in increasing the capacity of the structure, but in seismic isolation technologies which largely dampen the seismic forces transferred to the structure between the foundation and the superstructure [38–40]. However these systems must have the strength to withstand service loads [40–43]. Isolators separate the structural frequency and earthquake frequency by extending the structure’s natural vibration period. Spectral accelerations decrease and most of the seismic input energy is dissipated by the isolator system [44–46]. In seismic isolation systems, the superstructure moves like a rigid block [24]. This technology is quite effective in decreasing the acceleration response at each storey level [47]. In accordance with the regulations, high-damping rubber bearings (HDRBs), lead rubber bearings (LRBs), elastomeric isolators, and friction pendulum systems (FPS) are predominantly preferred in hospitals [48,49].

The worldwide success of isolation technology has been confirmed with earthquake records. In studies conducted by Çelebi (1996) [50], Nagarajaiah and Xiaohong (2000) [51], and Housner and Masri (1994) [52], the University of Southern California (USC) hospital building which had base isolation performed successfully during the 1994 Northridge earthquake (Mw 6.7). It was documented that the isolators dissipated the energy successfully, the top displacement was only 36 mm when the capacity was 260 mm, and damage to the hospital was completely prevented (Çelebi, 1996) [50]. Similarly, during the 2010 Darfield earthquake in New Zealand with a magnitude of Mw 7.1, the isolated Christchurch Women’s Hospital performed very well [53]. During the

2011 Tohoku earthquake, hospitals in Japan with base isolation sustained almost no damages when compared to fixed base structures [54] and during the 2016 Central Italy earthquake, hospitals with base isolation continued to operate with minimum structural damage [55].

In accordance with practices and legal regulations in Turkey, in 2013, the Turkish Ministry of Health made seismic isolators mandatory in the construction of hospitals with more than 100 beds in first- and second-degree seismic zones [56]. In line with this, Atatürk University Faculty of Medicine in Erzurum was designed with seismic isolation [57] and the Başakşehir Çam and Sakura City Hospital, which opened in 2020, became the world's largest building equipped with seismic isolation, containing 2068 isolators. The real performance of the systems in place in Turkey was demonstrated during the 6 February Kahramanmaraş earthquakes [58,59]. In the earthquake zone, 11 hospitals all equipped with FPS isolators sustained no damages during the severe quakes, and it was documented that the isolators operated well below their designed displacement limits [60].

Images of hospital buildings equipped with isolators after the Kahramanmaraş earthquakes are presented by Kaatsız et al. (2025) [60] in the field study they conducted, some of which can be seen in Figure 7.2.





Figure 7. 2. Hospital buildings equipped with isolators and isolator statuses after the earthquake [60]

In studies conducted by Qu et al. (2023) [5] it was found that out of seven hospitals with no isolators, three became unfit for use, whereas hospitals with isolators remained in operation immediately after the earthquake. Additionally, studies conducted by Kim et al. (2025) [61] analysing a hospital building equipped with isolators in Adana, confirmed that accelerations were effectively reduced.

7.1.5 Performance Validation in Healthcare Facilities

The superiority of innovative technologies in healthcare facilities has been scientifically validated through analytical modelling and laboratory tests. The performance of friction surfaces used in damping devices has been analysed through material testing in experimental studies. Full-scale shake table tests carried out by Sato et al. (2011) [62] show that the storey acceleration has been

reduced to safe limits. Nikfar and Konstantinidis (2019) [63] have shown that the movement and velocity demands of wheeled medical equipment during seismic events were effectively limited in hospitals equipped with isolators.

Analytic modelling and seismic evaluations also support this success. Rezaei Rad and Banazadeh (2018) [64], Nazarnezhad and Naderpour (2021) [65], and Chanda and Debbarma (2021) [66] have validated the probabilistic seismic reliability of structures with base isolation. Song et al. (2024) [67] have developed analytical design methods that simultaneously optimise the isolation system and medical equipment in order to increase the endurance of hospital buildings with base isolation. Şen et al. (2024) [68] analysed the performance of a hospital building equipped with isolators that was still under construction during the Kahramanmaraş earthquakes, and verified the permanent displacements observed after earthquakes through non-linear analyses. Öztürk (2025) [69] compared structure designs where traditional methods were used and those where isolators were used in order to analyse the effect of FPS isolators on seismic performance in a hospital building. The results of numerical analyses showed that seismic isolation lengthens the structural period and by doing so reduces earthquake forces, storey drifts, and structural deformations. It was also emphasised that although the cost of the isolator system is around 20% higher, it significantly increases the earthquake resistance of hospital buildings.

7.1.6 Post-Earthquake Inspection and Maintenance

The ability of seismic isolation and damper systems achieving their goal of “uninterrupted use” in healthcare facilities, depends on correct design and on the hospital’s operation and maintenance culture. It is of vital importance that the seismic gaps, which are left to allow isolators to carry out the calculated

large horizontal displacements during an earthquake, are kept empty at all times. Anything left in these gaps by hospital staff (storage materials etc.) may strike the system and lock the isolation mechanism, thus causing the building to sustain severe damage. Additionally, it is important that pipes (oxygen, medical gas, water etc.) passing through isolation storeys to upper storeys are never anchored with rigid ties and that these pipes have flexible connections that can tolerate isolator displacement [70]. As for dampers, the environmental conditions (humidity, temperature fluctuations etc.) they are exposed to throughout their service life, which can last years, might affect bolt pretension or friction surfaces. Therefore, it is essential for operational safety, so that the system can operate at the targeted optimum slip load, that devices undergo periodic calibration and physical inspection [71].

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CHAPTER 8

HOSPITAL INFRASTRUCTURE CASE STUDIES

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This chapter discusses good practices in managing the information technology area of Manisa Celal Bayar University Hafsa Sultan Hospital, a tertiary hospital. Real applications are reflected under the leadership of theoretical engineering principles. Unlike other institutions, hospital information technology units must support requirements such as uninterrupted clinical operations, legislation, and interoperability with various medical systems.

8.1 BEST PRACTICES OF MANISA CELAL BAYAR UNIVERSITY HAFSA SULTAN HOSPITAL

8.1.1 Data Center Management, Backup and Business Continuity

The digitalization of healthcare has transformed the hospital data center from a support and records room to the central hub of healthcare. Electronic Health



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Records (EHR), Picture Archiving and Communication Systems (PACS), Laboratory Information Systems (LIS), and Hospital Information Management Systems (HIMS) all rely on continuous, reliable, and secure IT infrastructure. A service interruption in the infrastructure turns into a clinical risk rather than a financial loss. [1, 2].

The complexity of this environment distinguishes it from a typical corporate data center. Healthcare data are classified as sensitive personal data under both the Turkish Personal Data Protection Law [3] and the European Union's General Data Protection Regulation (GDPR) [4]. This data is required both by clinicians within seconds and by auditors years later; in such cases, access controls must be implemented while storing the data, and performance must be considered. [5]. Furthermore, as clinical workflows operate 24 hours a day, 7 days a week, 365 days a year, carrying out scheduled maintenance becomes a task that requires careful organization to minimise service disruption.

In this section, it is outlined the components that make up a hospital data center; it is also explained why each design decision was made, and how the resulting architecture is maintained and developed in practice.

This section reflects the layers of the infrastructure, including the physical plant, power, cooling, networking, storage, security, and governance. Each of these is examined in turn.

8.1.2 Strategic Importance of the Hospital Data Center

A hospital data center is not merely a room full of servers. As operational experience has shown, it is the hospital's nerve center. Without it, patient care services and hospital management would be severely disrupted. To illustrate this, consider the following figure:

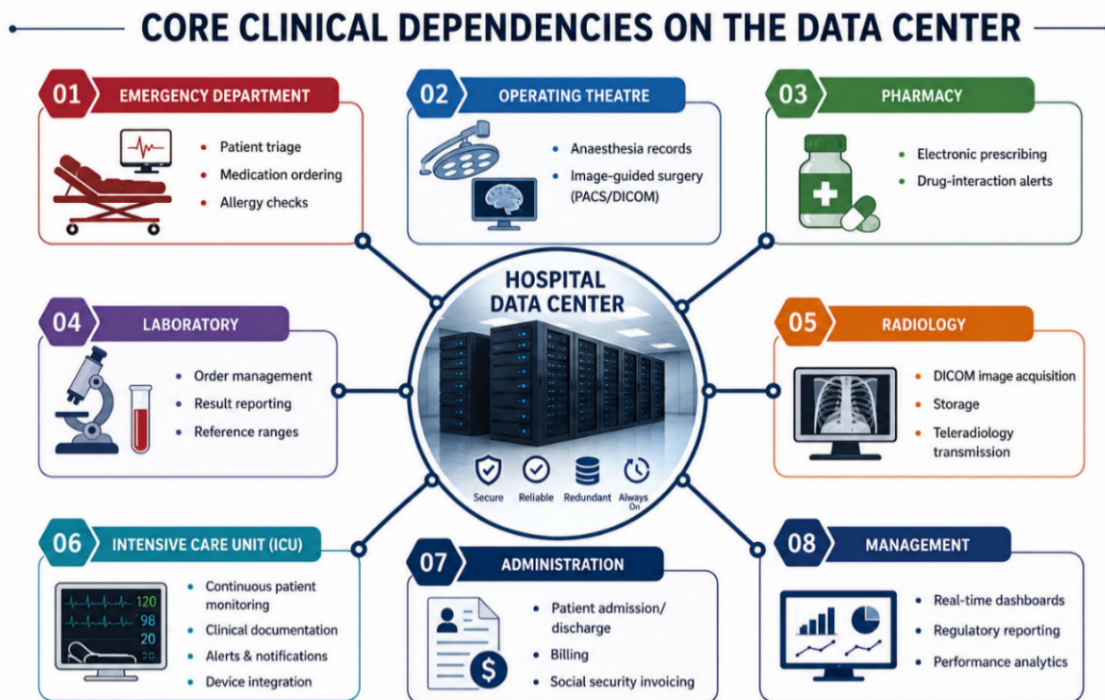


Figure 8.1. Hospital data center dependency of core clinical and administrative services [6, 7, 8, 9]

The dependencies outlined above give rise to certain service-level requirements. Recovery Time Objectives (RTO) for critical clinical applications are typically measured in minutes. Recovery Point Objectives (RPO) for patient data should generally be close to zero, meaning that any loss of transactional data is unacceptable [10]. Achieving these objectives depends on architectural decisions that affect every layer of the infrastructure, as explained in the following sections.

8.1.3 Physical Infrastructure: Core Equipment and Layout

The physical layer of a hospital data center comprises all tangible components such as racks, cabling, power systems, cooling units, fire suppression systems, access control, and environmental sensors. TIA-942 (Telecommunications Infrastructure Standard for Data Centers) and ISO/IEC 11801:2017 provide

internationally recognised design guidelines that regulate the layout plan, cabling routes, and minimum redundancy classifications [11, 12].

Server Racks and Cabinets

Modern hospital data centers commonly deploy all-in-one rack solutions that integrate cooling, UPS, fire suppression, and access-control systems within a single cabinet enclosure. These solutions offer numerous advantages; no raised floor is required, targeted and close cooling so high energy efficiency, they are modular and scalable, and easy to maintain.



Figure 8.2. All-in-one rack cabinet front and rear view. (1. Automatic Fire Suppression, 2.IN-ROW Precision Air Conditioning, 3. Rack-Mounted Modular Online UPS, 4. UPS

Battery Pack, 5. Surge Protected PDU for cabinet UPS, 6. Surge Protected PDU for facility UPS, 7. Access Control System management for data center and cabinets).

In terms of basic rack specifications, racks in server rooms are typically 19 inches wide and range in height from 42U to 48U, with a load-bearing capacity of between 1,000 and 1,500 kg. To prevent electrostatic discharge, they must be grounded. Raised-floor systems are common in dedicated big data centers and they provide under-floor air delivery and cable pathways; however, for space-constrained hospital environments, in-row cooling and power solutions without raised floors are increasingly preferred [13].

Network Switches and Patch Panels

A hospital generates large volumes of data every second. This data is transferred to the data center via the network. For example, a single fluoroscopy image can take up several gigabytes. Switches with high packet processing capacity and low latency are required for these transfers.

Switches with high bandwidth and fibre interfaces for storage area connections are used in hospital networks. These devices also require Ethernet interfaces to connect systems such as servers and workstations.

ISO standards and structured cabling practices require the use of patch panels for all copper terminations to provide a clean, documented, and manageable layer.

Category 6A or higher cabling standards support 10 gigabit ethernet to every server, while inter-switch and storage links commonly use 10G, 25G, or 40G fibre channels depending on traffic profile [11,12].



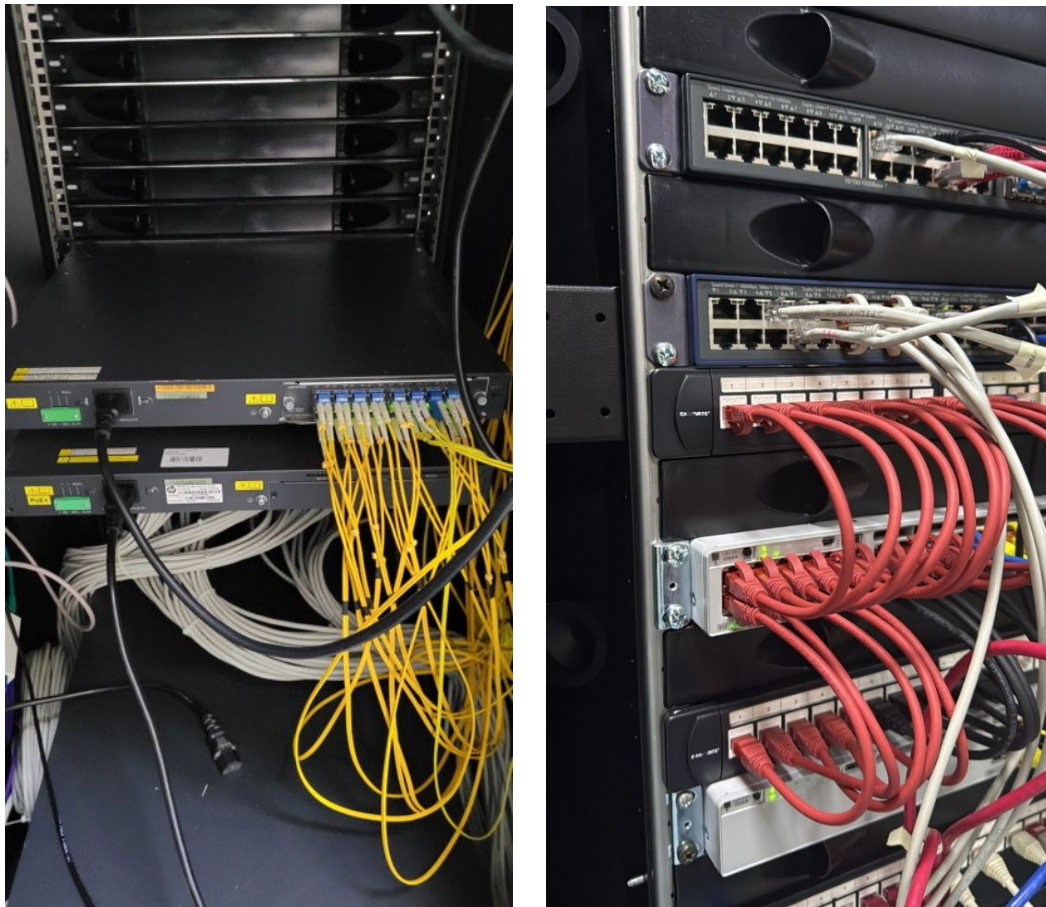


Figure 8. 3. Backbone layer 3 switch with fiber and ethernet modules.

Power Distribution Units (PDUs)

Power distribution units installed within the server racks convert the electricity from the power sources into multiple 230V/16A or 32A circuits required by servers, storage devices and network equipment. The critical design principle is dual feeding source; each cabinet receives power from two entirely separate PDUs, each fed from a different Uninterruptible Power Supply (UPS) circuit.

Hardware (server and storage) with dual Power Supply Units (PSUs) can therefore survive the complete loss of one supply path without interruption. PDUs feature a range of outputs and connection interfaces, such as IEC C13 and C19 sockets, to support different types of equipment. There are types of PDUs as basic, switched, metered and intelligent PDUs.



Figure 8.4. Different types of PDUs with different kinds of connection interfaces [14]

Intelligent PDUs with remote monitoring capabilities provide real-time per-outlet current measurements, overload alerts, and remote switching—capabilities that are essential for capacity planning and for isolating faults without physical access to the data center [14].

Uninterruptible Power Supply (UPS)

Uninterruptible Power Supply (UPS) systems serve two distinct functions: they protect equipment from power-quality anomalies (voltage spikes, sags, harmonic distortion) and they provide bridge power during the interval between a mains failure and the startup of emergency generators. Hospital electrical regulations require that life-critical systems be supported by generator backup within ten seconds of mains failure [15].

A two-tier UPS architecture—cabinet-level modules plus a centralised facility UPS—provides layered protection. Cabinet UPS units condition power and



handle microsecond-level fluctuations; facility UPS units sustain the load during generator transfer.



Figure 8.5. Rack mounted cabinet UPS and facility UPS used for data center

The diagram from figure 8.6 illustrates the electrical power distribution architecture of a data center, highlighting the redundant power paths from the main utility sources down to individual server racks.

The power supply from two separate transformers to which the facility's two separate generators are connected, feeds into the data center electricity distribution panel. The transfer switch in the panel combines the two sources into a single supply.

This circuit supplies power to the air conditioning, lighting and other systems requiring electricity. Similarly, this circuit is connected to the UPS located within the cabinet.

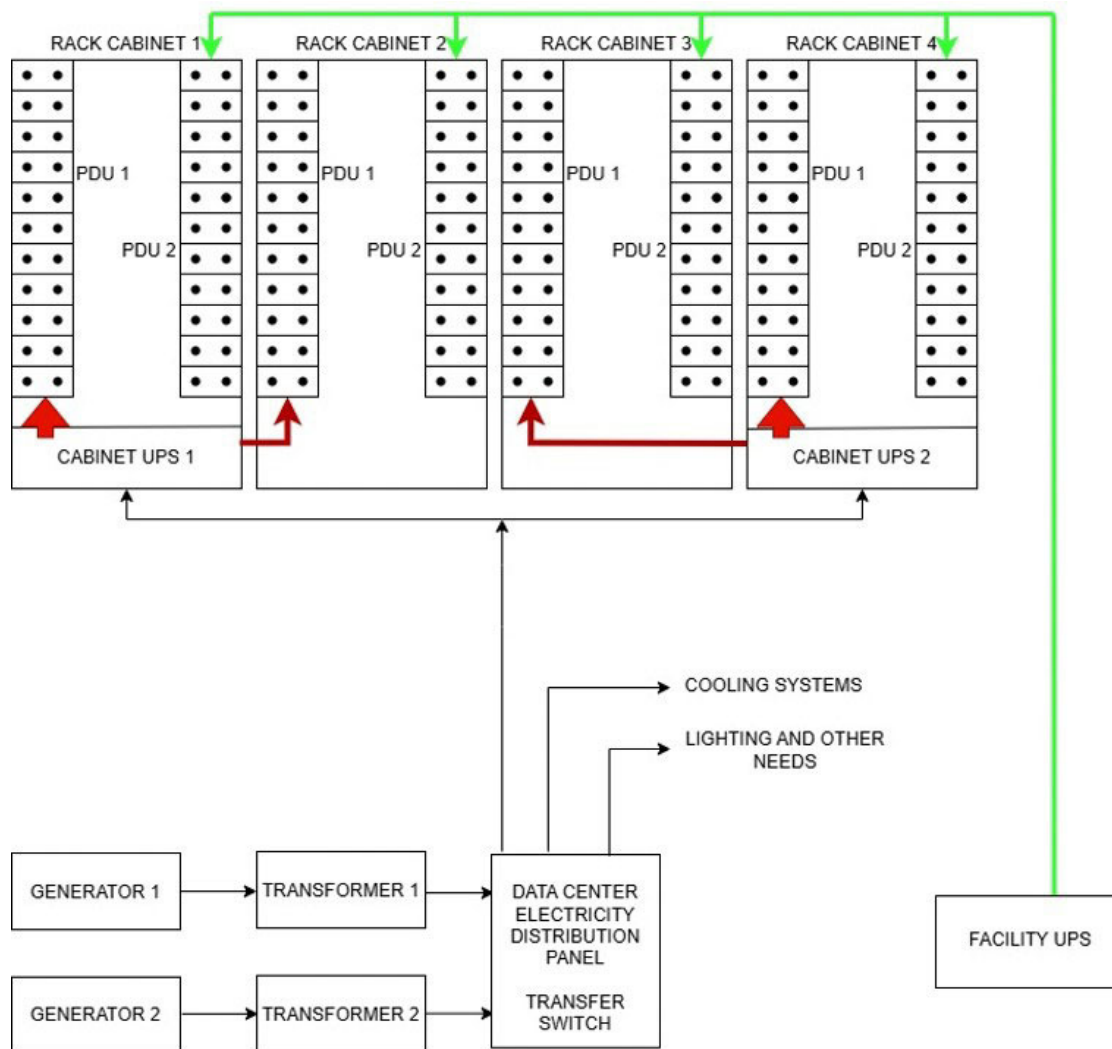


Figure 8.6. Schematic overview of the data center power distribution and ups redundancy architecture.

The core design principle shown in the server area is dual-feed independence for high availability. The load is divided between two central uninterruptible power supplies: Cabinet UPS (labelled 1 for cabinet 1 and 2 and labelled 2 for cabinet 3 and 4) and facility UPS. The infrastructure contains four server cabinets, labelled from Rack Cabinet 1 to 4. Each individual cabinet is equipped with two separate



power distribution units, PDU 1 connected to cabinet Ups and PDU 2 connected to facility UPS, to ensure fault tolerance.

Static Transfer Switch (STS)

Not every device used in a data center may have a spare PSU. Indeed, many network switches have only a single power supply unit. In this case, it will not be possible to utilise the two PDUs in the infrastructure. In such circumstances, an STS must be used to ensure power redundancy. An STS continuously monitors two independent power sources (S1: Cabinet UPS; S2: Facility UPS) and executes an electronic transfer between them within 4–8 milliseconds—fast enough to prevent connected equipment from losing power [16].

Unlike a mechanical Automatic Transfer Switch (ATS), which may take tens of milliseconds to transfer, the STS uses thyristor (SCR) switching with no moving parts, making it suitable for sensitive IT loads. The transfer is transparent to the connected equipment because modern power supplies hold their output stable across brief input interruptions of this magnitude [16].

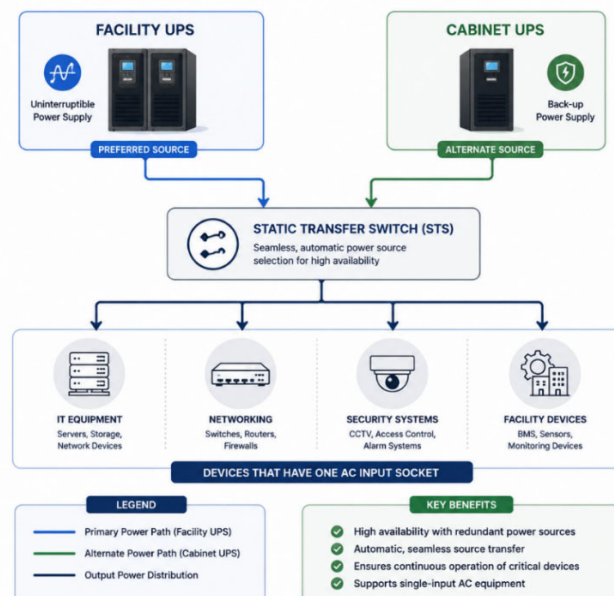


Figure 8.7. Redundant STS-based power architecture for single-PSU devices in data center



Figure 8.8. Front and back panel views of STS

8.1.4 Thermal Management and Cooling Systems

Thermal management is one of the most critical parts of data center design. Servers and UPS systems produce a lot of heat: a single 1U server can release 200–400 W, and a full 42U rack can easily exceed 15–20 kW [17]. Running systems constantly above recommended temperature levels speeds up component aging, raises error rates, and finally causes major hardware failure.

Airflow Fundamentals

The basic rule of data center cooling is keeping cold air away from hot air. Every server takes in cold air from the front and pushes out hot air from the back. If hot and cold air mix together, it causes four major problems [17]:

- Cooling efficiency decreases because the cooling unit must re-cool air that has already been partially heated by servers.



- Air entering servers becomes hotter than the supply temperature, causing internal component temperatures to rise above design limits.
- Hot spots develop in areas of poor airflow, exposing specific servers to disproportionately high ambient temperatures.
- Risk of condensation increases at the interface between cold supply and warm room air, potentially causing corrosion or short circuits

Cooling System Architecture

To manage thermal loads efficiently, the system features an in-cabinet (in-row) cooling architecture that separates hot and cold airflow. The front side of the rack forms a cold aisle, whereas the rear side forms a hot aisle. Server devices pull cold air from the front to regulate their temperature and release the generated heat through the rear exhaust. Inside each server, a row of high-performance internal fans is responsible for driving this airflow directly across critical components like CPUs and memory modules (Figure 8.9).

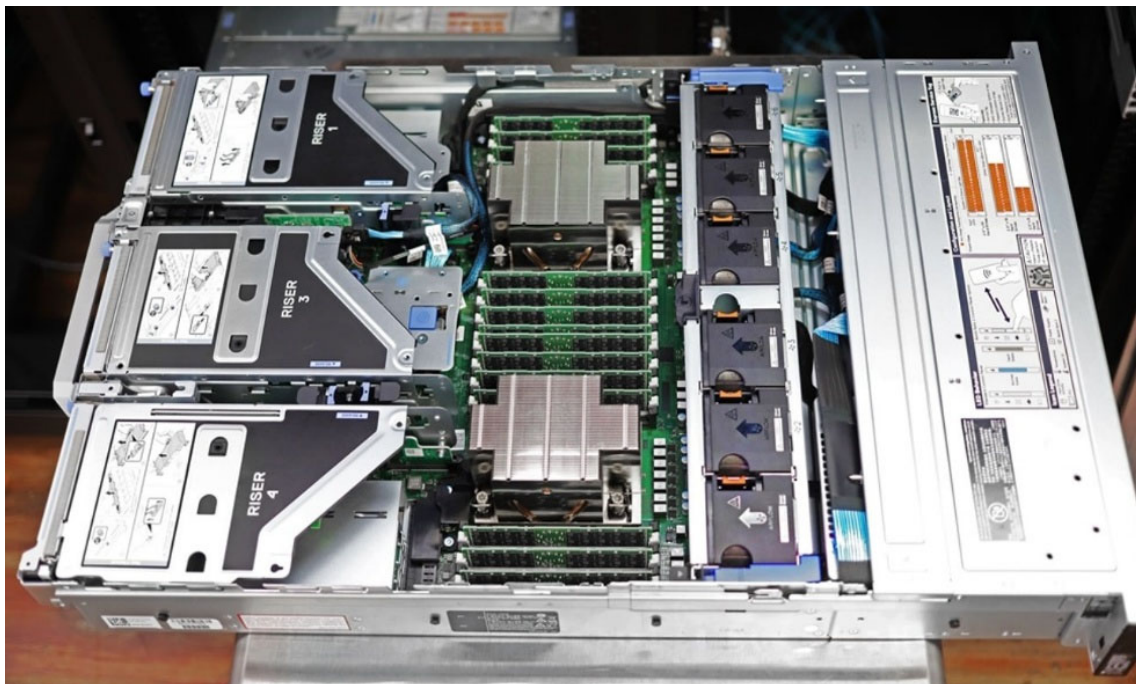


Figure 8.9. Server internal structure design with airflow fundamentals

These fan speeds are dynamically managed by the server's embedded firmware. By monitoring real-time thermal sensors, the firmware automatically speeds up or slows down the fans to optimize airflow and prevent overheating while saving energy. The in-row cooling unit then collects this hot exhaust air from the rear, cools it, and forces it back to the front to maintain a continuous cooling cycle. Physical containment such as curtains or hard panels enclosing either the cold or hot aisle improves cooling efficiency [16].



Figure 8.10. Physical layout of the server cabinets, in-row cooling and wall-mounted secondary cooling system.

In addition to the in-cabinet cooling units, the data center room features a wall-mounted backup air conditioning system with enough capacity to handle the entire thermal load. This system provides room-level redundancy but operates on a manual control principle. In the event of a primary cooling failure or during



periods of extreme thermal stress, data center operators must manually activate this secondary unit. Once turned on, this backup system successfully stabilizes room temperatures, protecting the server hardware from heat-related risks.

This physical arrangement, including the centralized server racks, in-row cooling unit and the independent wall-mounted cooling unit, is clearly presented in Figure 8.10.

Humidity and Temperature Monitoring

The hospital's data center does not utilise a centralised Building Management System (BMS) or Data Center Infrastructure Management (DCIM) framework; instead, a redundant sensor architecture comprising two independent temperature and humidity monitoring devices is employed (Figure 8.11). This setup comprises a wired IP-based monitoring device and an independent wireless RF (Radio Frequency) sensor unit. Both systems continuously monitor environmental measurements in accordance with established industry standards.

According to ASHRAE guidelines, data centers should ideally maintain a temperature range of 18–27 °C and a relative humidity (RH) of 20–80% [17]. Going beyond these values introduces serious risks. For example, extremely low humidity (below 40% RH) significantly increases the risk of electrostatic discharge (ESD), which can permanently damage integrated circuits in server boards [18]. High humidity levels (above 60% RH), on the other hand, cause moisture condensation on cold metal surfaces, leading to hardware corrosion or short circuits.

In this architecture, sensors function as an early warning system. These monitoring units have automatic warning features. When temperature or humidity measurements deviate from thresholds, devices instantly generate

real-time SMS messages and email alerts, transmitting them to network administrators. Because the secondary wall-mounted room cooling system is not automated, this instant communication channel is critical. It provides the necessary operational visibility for IT staff to perform rapid manual interventions



Figure 8. 11. Redundant temperature and humidity monitoring via wired IP and wireless RF sensors



8.1.5 Fire Safety and Environmental Monitoring

Fire safety in a hospital data center requires a dual objective: protecting human life and protecting irreplaceable electronic equipment and data. These objectives are not always served by the same suppression technology, necessitating a layered, multi-method approach that complies with NFPA 75 [15].

Detection

A fire detection system in a data center must be capable of detecting a developing fire before visible flames or noticeable smoke appear. Integration with the building's fire alarm panel ensures that, in the event of a smoke incident in the data center, building-wide evacuation procedures are triggered, and fire-suppression measures are initiated simultaneously.

Suppression Agents

Although water-based sprinkler systems are effective for standard building fires, they are not suitable for data centers. Instead, non-conductive systems that leave no residue are preferred to protect sensitive electronic equipment in server rooms. For this reason, gas-based fire suppression systems are the most used solution [19]:

- CO₂ (Carbon Dioxide): Effective oxygen-displacement agent has life-safety risks and requires evacuation procedures
- Novec 1230 (FK-5-1-12): A fluorinated ketone clean agent that suppresses fire primarily by absorbing heat. Its atmospheric lifetime is approximately 5 days making it the environmentally preferred option [20]. It minimizes damage to sensitive IT equipment.
- FM-200 (HFC-227ea): A clean chemical suppression agent that extinguishes fire mainly through heat absorption.

The other gas-based suppression systems are Inergen (IG-542), Argonite (IG-55) and Nitrogen based systems [19].

The safety and operational continuity of the data center infrastructure depend heavily on an integrated approach to fire protection and environmental monitoring (Figure 8.12).

Parallel to environmental tracking, the facility implements a specialized clean-agent fire suppression system. The setup utilizes two Novec 1230 gas extinguishers, which are deployed on top of Rack Cabinets.

The system is fully integrated with the Facility Fire Alarm System. When smoke or thermal anomalies are detected, the system triggers localized audio-visual alarms, including a high-decibel siren and strobe light. Simultaneously, a dedicated CCTV camera monitors the entire server room area in real time, allowing remote security personnel to visually confirm fire alerts.

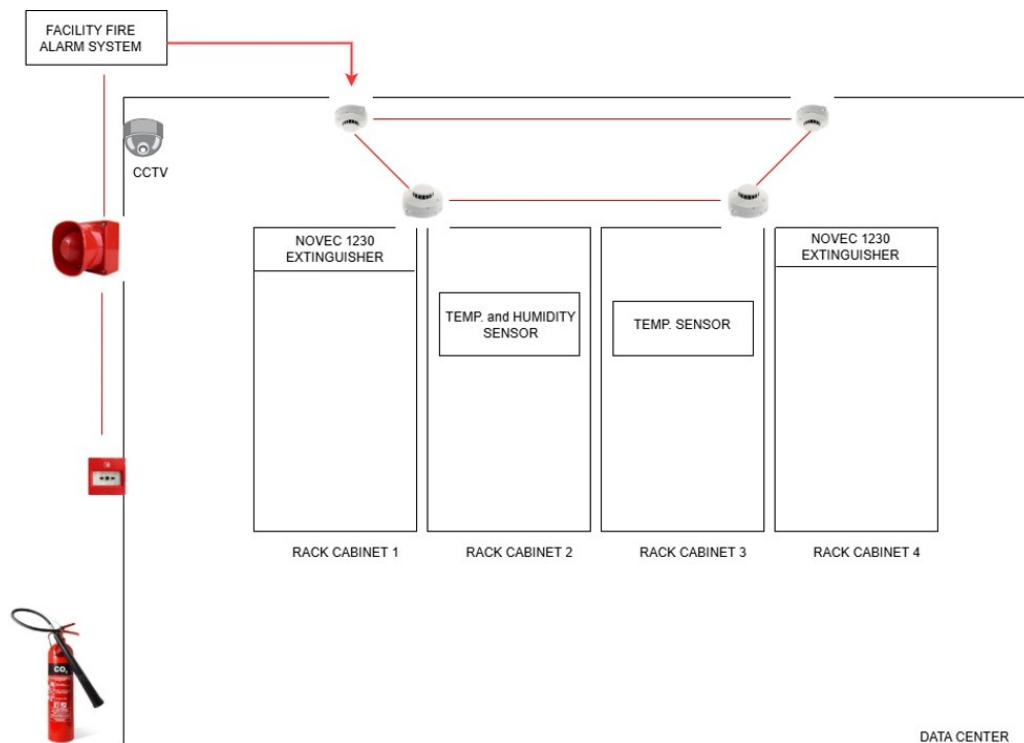


Figure 8.12. Schematic layout of the integrated fire suppression and environmental monitoring infrastructure.



8.1.6 Physical Security: Access Control and Surveillance

Physical security controls are a foundational component of information security management systems (ISMS) under ISO/IEC 27001:2022. Access controls used as software such as firewalls, authentication systems, encryption are ineffective if an unauthorised individual can physically access servers, network switches, or storage arrays [21].

Access Control Systems

Hospital data centers deploy multi-factor physical access control combining biometric authentication (typically fingerprint scanning) with credential-based mechanisms (RFID smart cards or proximity badges).

Access events are logged with timestamped entries associating the individual's identity with time of entry or exit. These logs are retained for a minimum period defined by the hospital's security policy and are reviewed periodically or on demand following security incidents.

CCTV Surveillance

IP-based closed-circuit television (CCTV) cameras provide 24/7 recording of the data center. Network Video Recorders (NVRs) store video data on dedicated storage with configurable retention periods. Motion-detection algorithms within the NVR generate alerts for unexpected movement during off-hours, with notifications delivered to on-call staff.

Camera placement follows the principle of no blind spots: every rack row, power distribution zone, and access corridor must be within camera field of view.

Flood Detection

Water leaks, which can occur for any number of reasons, pose a serious threat to electrical infrastructure. Wireless water leak detection sensors detect the



presence of water and send instant notifications to IT staff's mobile devices via Wi-Fi. Their key features are as follows:

- High-sensitivity sensing that detects thin water films before pooling occurs.
- Battery-level monitoring and low-battery alerts to ensure sensor availability.
- Mobile application providing sensor status dashboard, historical log review, and threshold configuration.
- Easy installation without specialised cabling—critical in environments where cable routing is constrained.

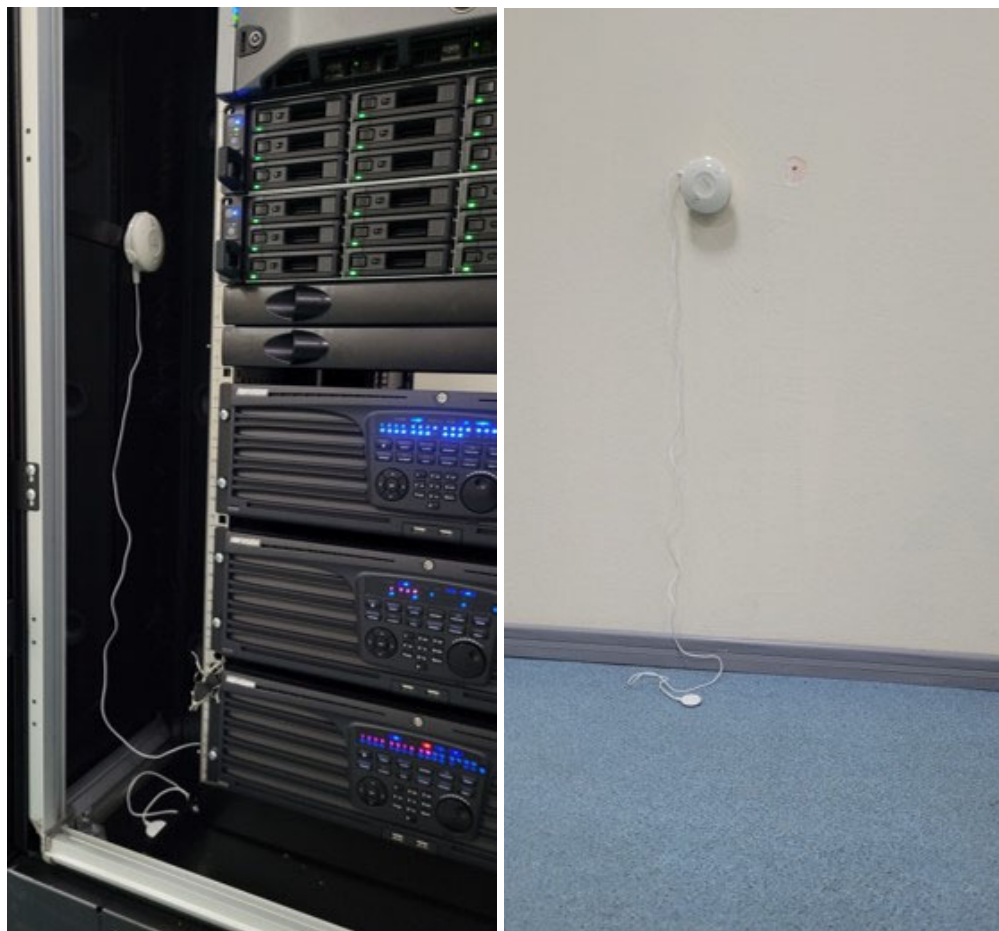


Figure 8.13. Flood detection sensor and devices



8.1.7 Monitoring, Alerts, and Notification Infrastructure

The operational objective of a hospital data center is to ensure uninterrupted IT operations [1]. To achieve this objective, a complete, multi-layered monitoring infrastructure is required to detect anomalies before they escalate into incidents that impact services. Modern data center monitoring requires an incident-driven model. When predefined threshold values are exceeded or faults occur, infrastructure components generate autonomously configured alerts.

It is possible to use centralized monitoring platforms such as Nagios, Zabbix, Prometheus, or vendor-specific DCIM solutions to aggregate alerts from all infrastructure layers. Additionally, many systems can send e-mail notifications over SNMP and SMS alerts through GSM operators using web services.

 Infrastructure Layer	 Monitored Parameters	 Alert Examples
 Servers & Virtualisation	<ul style="list-style-type: none"> CPU/memory/disk utilisation Hardware faults OS/hypervisor errors 	<ul style="list-style-type: none"> CPU > 90% for 10 min RAID degraded VM snapshot failed
 Backup Systems	<ul style="list-style-type: none"> Job completion status Storage capacity Replication lag 	<ul style="list-style-type: none"> Backup job failed Backup volume > 85% capacity
 Storage (SAN/NAS/RAID)	<ul style="list-style-type: none"> Disk health Capacity thresholds I/O latency 	<ul style="list-style-type: none"> Disk predictive failure (SMART) Volume > 80% full
 Network Equipment	<ul style="list-style-type: none"> Link status Latency Packet loss Security events 	<ul style="list-style-type: none"> Uplink down Interface error rate > 0.01%
 UPS & Power	<ul style="list-style-type: none"> Battery charge/health Load % Input/output voltage 	<ul style="list-style-type: none"> Battery < 20% remaining Input voltage out of range
 Environmental Sensors	<ul style="list-style-type: none"> Temperature Humidity Smoke Water presence 	<ul style="list-style-type: none"> Inlet temperature > 27 °C Water detected

Figure 8.14. Hospital data center monitoring matrix by infrastructure layer.

8.1.8 Server-Network Architecture and High Availability Framework

The network topology of the hospital data center is engineered around the core principles of fault tolerance and high availability to prevent single points of failure across clinical workflows (Figure 8.15). External connectivity is managed via a central Router that bridges traffic between the Internet, the Local Area Network (LAN), and the internal data center infrastructure. Core switching operations are governed by a redundant dual-switch configuration comprising Data Center Backbone Switch 1 (Active) and Data Center Backbone Switch 2 (Passive-BACKUP-Same Configuration). This active-passive clustering ensures that if the primary backbone switch experiences a hardware or link failure, the secondary switch can immediately assume the routing load without interrupting hospital-wide operations. This operation is a manually coordinated job by system and network administrators.

Under the core switching layer, the hospital's core software infrastructure is driven by a dual-server layout: Hospital Information Management System (HIMS) SERVER 1 and SERVER 2. To optimize performance and prevent system bottlenecks during peak operational hours, a dynamic Load Balancing mechanism is deployed between these two HIMS servers. Furthermore, severe hardware-level precautions are implemented on each server to maximize uptime. Each server is equipped with dual Power Supply Units (2 PSUs) and four Network Interface Cards (4 NICs). Within this network layout, NIC 1 and NIC 2 are combined using a Bounded NIC configuration (link aggregation). This bounded framework merges physical connections into a single logical link, providing both increased bandwidth and automatic failover capabilities if one physical network cable or port fails.

At the foundational storage layer, data persistence and security are guaranteed through a centralized Storage (HIMS Data) array connected via high-speed fiber



optics. Data paths between the HIMS servers and the storage units are fully redundant, utilizing Fiber 1 and Fiber 2 topologies to safeguard against cable damage. The storage array itself integrates critical enterprise-grade safeguards, including two Power Supply Units (2 PSUs), two independent Control Units, and two Host Bus Adapter (HBA) Fiber Channel Cards featuring 4 ports. To protect critical electronic patient records against physical drive failures, the data layout is structured using RAID 6 and hot spare disk configurations. This storage architecture allows the system to survive the simultaneous failure of one or two hard drives without any data loss or service disruption, ensuring continuous access to vital healthcare data.

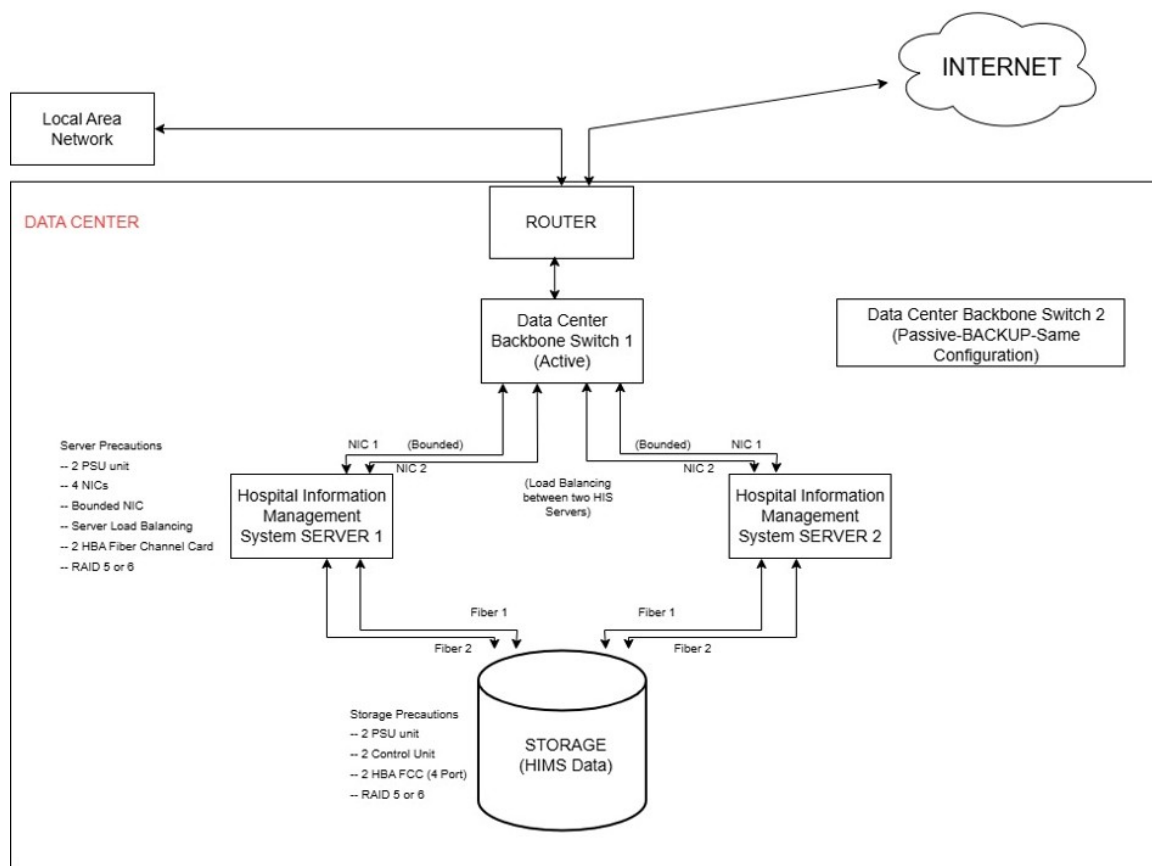


Figure 8.15. Network topology and server-storage redundancy architecture for the hospital information management system (HIMS).

8.1.9 Data Security and Backup Strategy

Data security in a hospital environment is simultaneously a clinical necessity, a legal obligation, and an ethical responsibility. Patient health records are classified as sensitive personal data and require explicit consent for processing, purpose limitation, and technical/organizational measures proportionate to the risk [3]. Failure to protect this data exposes the institution to administrative sanctions, civil liability, and reputational damage.

The data security architecture encompasses multiple concentric layers;

- **Firewall Management:** Next-Generation Firewalls (NGFW) inspect traffic at the application layer, enforcing policies based on identity, application type, and content in addition to traditional port/protocol filtering. Separate DMZ zones isolate externally accessible services (patient portals, integration APIs) from internal clinical networks.
- **Antivirus / Antimalware:** Centralised management consoles deploy and update endpoint protection agents across all servers and clinical workstations simultaneously. In large hospital networks, centralised management is essential—manual agent management at scale is operationally unviable.
- **Log Management and Periodic Analysis:** Centralised Security Information and Event Management (SIEM) systems collect, normalise, and correlate logs from all infrastructure components. Periodic log analysis—ideally with automated anomaly detection—identifies suspicious patterns such as unusual login hours, privilege escalation attempts, or data exfiltration indicators.
- **Update and Patching:** A structured patch management programme applies OS, firmware, and application security updates to servers and

client workstations within defined timescales. Healthcare environments face the challenge of clinical application vendor certification requirements, which may delay patch deployment pending vendor testing.

The hospital's data center employs a multi-layered architecture for data backup and business continuity. This helps prevent data loss and ensures that the IT infrastructure does not cause any disruption to the healthcare services provided. In this architecture, the storage space used is separate from the backup storage. Furthermore, a scalable and sustainable architecture has been established using virtualisation architectures. Hospital Information Management System SERVER 1 and SERVER 2 write data to primary storage.

The planned backup policy includes a daily full backup, which decreases the risk of data loss and corruption. This backup is transferred from the server to the Network Attached Storage (NAS). In addition, incremental backups are automatically taken every 15 minutes to ensure a low point of data loss. This approach minimizes the Recovery Point Objective (RPO).

This Virtualization Pool is composed of three physical hosts (Virtualization Server 1, 2, 3) and in this pool system runs many of virtual machines. To store data for this virtual system we use a different storage array from HIMS storage.

This means that a second data storage unit can also be kept as a backup. Virtualization system takes snapshots for the virtual machines regularly and these snapshots are also archived in Network Attached Storage (NAS).

The multi-layered internal replication strategy ensures that individual server failures or software-level errors are resolved almost instantly. To further minimise the risks associated with this local architecture and to ensure that a

disaster recovery option is also considered, this architecture includes a remote backup structure.

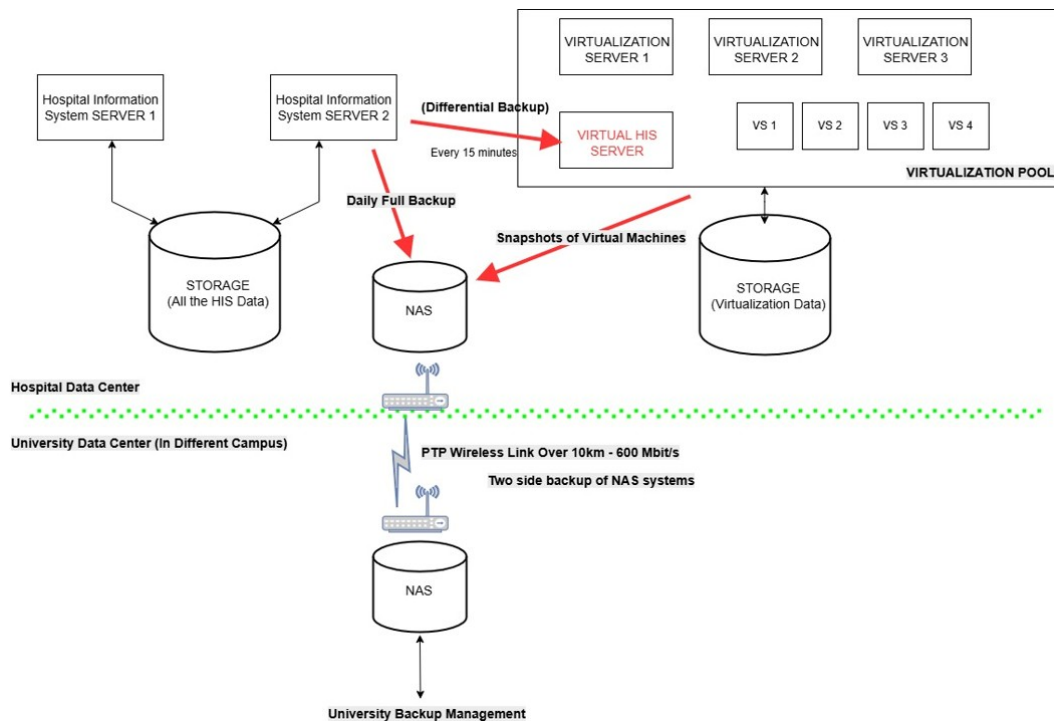


Figure 8.16. Data backup, virtualization, and off-site disaster recovery architecture via point-to-point (PTP) wireless link.

The hospital data center has a point-to-point wireless link between University Data Center located on a completely different campus. We route backup data traffic to this link to prevent bandwidth congestion with daily hospital operations data traffic. The distance between the two data centers is around 10 kilometres. Also, this 600 Mbit/s wireless bridge operates as a redundant connection parallel to the existing fiber optic line used for metro ethernet circuit. This structure provides an independent secondary channel for disaster recovery. With this wireless bridge, data from the hospital data center is stored in the university data center, and similarly, data from the university data center is stored in the hospital data center, thereby establishing a disaster recovery solution for both data centers.



8.1.10 Organizational and Governance Elements

Technology alone cannot keep a hospital IT environment running and reliable. The human and process sides of the organization like access rules, training, helpdesk workflows, and written policies are necessary for daily HIMS operations. Operational experience shows that managing users and processes is just as critical as the technology itself to prevent disruptions in healthcare services. [1].

For this architecture to function effectively, there are four further key elements that must not be overlooked within the hospital. The first of these is Role-Based Access Control, which ensures that staff are authorised to access the HIMS modules they require to perform their duties. Secondly, training services must be provided to ensure all staff can use the HIMS software correctly. To this end, learning management systems are implemented. Thirdly, helpdesk and maintenance processes establish a standard framework for reporting and resolving software errors or hardware issues. This ensures that technical issues are resolved before they impact hospital operations. Finally, formal policies and procedures regulate daily workflows. With these elements and a well-planned data center architecture, a HIMS system capable of delivering uninterrupted healthcare services is established.

8.1.11 Integration and Interoperability Standards

A hospital HIMS does not operate in isolation. It must exchange information with external systems, including national health registries, insurance and billing systems, partner hospitals, and public health authorities. It must also enable good communication between its own internal modules. Achieving this interoperability requires data exchange standards, the most important of which in healthcare are HL7 and DICOM.

Health Level Seven (HL7) standards serve as the foundational framework for exchanging clinical and administrative data between disparate healthcare software applications. Specifically, HL7 defines the protocols, data types, and structural formats required to transmit textual patient records, such as admission details, laboratory results, and electronic prescriptions [7]. HL7 messaging ensures that when any transaction is made on HIMS, this information is instantly and accurately transmitted to the relevant external systems, including the national health record system. Modern healthcare infrastructures increasingly adopt the HL7 FHIR (Fast Healthcare Interoperability Resources) standard, which uses RESTful web-based APIs to support secure and interoperable real-time data exchange across distributed healthcare systems [22].

Parallel to textual data integration, the **Digital Imaging and Communications in Medicine (DICOM)** standard governs the handling, storage, and transmission of medical imaging data. In a typical hospital workflow, radiological procedures, such as X-rays, MRI, and CT scans generate large, high-resolution binary datasets that traditional database systems cannot process efficiently. The DICOM standard addresses this by encapsulating both the visual pixel data and the patient's metadata into a single, standardized file format [8]. Furthermore, DICOM protocols enable smooth interoperability between the HIMS and the Picture Archiving and Communication System (PACS). The imaging systems allow large clinical images to be transmitted securely through the hospital network to public health platforms or remote teleradiology specialists without loss of image quality or data integrity.

To show how these communication standards and web services work in a real hospital, Figure 8.17 explains the complete integration process during a patient's visit. At the beginning, the HIMS uses secure web services to check



patient details with the National Identity System and verify insurance coverage through the National Social Security System. After the medical treatment or operation is complete, the infrastructure uses the HL7 and DICOM standards mentioned above to safely format and send the patient's health records and medical images to the National Health System. Finally, an automatic system compares the medical data with the financial invoice. This shows how data standards directly help both medical care and administrative workflows.

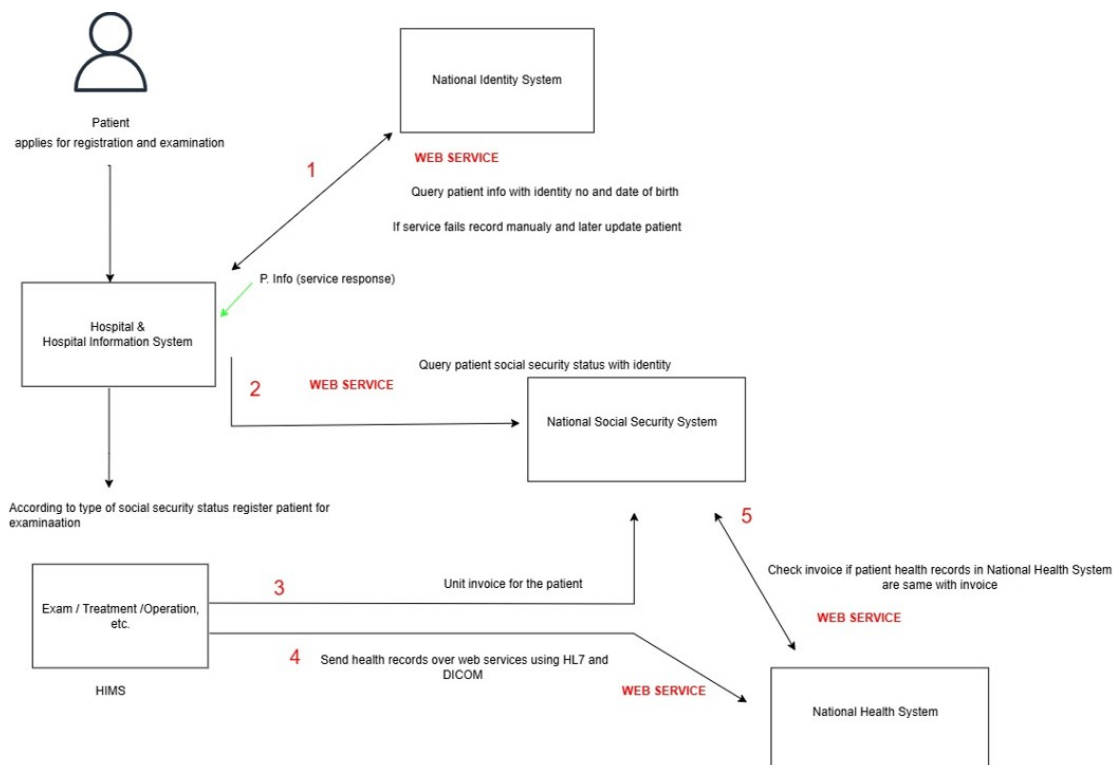


Figure 8.17. Step-by-step integration workflow of HIMS with national identity, health, and social security systems.

From the perspective of engineering students, working with hospitals' information technology infrastructure includes different disciplines. An engineer should possess good skills in network management, power systems, cybersecurity and data protection. As healthcare organizations are complicated in terms of their infrastructure, an engineer should constantly acquire new

knowledge and skills, keep documentation updated and cooperate with other experts, namely clinicians, healthcare managers and technical specialists.

Summarizing the findings about IT management in hospitals one can state the following points: design for failure, monitor everything, test your assumptions. The first statement means that every piece of equipment can fail at some point, but infrastructure architecture is designed to protect patients from failures; the second one relates to infrastructure monitoring as every anomaly is an important indicator; the last statement means that testing is crucial as untested recovery can only be assumed to work.

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CHAPTER 9

THE DECARBONISATION OF HEALTHCARE SYSTEMS: A STRATEGY THAT BEGINS AT INSTITUTIONAL LEVEL AND EXTENDS TO HOSPITAL ENGINEERS

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The section addresses to the Canary Islands Health Service strategy for mitigating the carbon footprint of healthcare facilities.

9.1. HUMAN HEALTH IN THE CONTEXT OF ENVIRONMENTAL TRANSFORMATION

Human health cannot be considered in isolation from the environment in which people live. Access to safe drinking water, air quality, food security, climate stability, housing conditions and the functioning of ecosystems all directly influence the onset, distribution and severity of numerous diseases. For much of the development of modern healthcare systems, healthcare policy and



environmental policy progressed along separate paths. The former focused primarily on diagnosis, treatment and disease prevention, while the latter addressed pollution, the use of natural resources, ecosystem conservation and the control of impacts arising from human activity.

That separation is now difficult to sustain. Environmental changes are altering fundamental determinants of health and placing new pressures on healthcare services. Rising temperatures, the intensification of certain weather events, declining air quality, changes in the distribution of disease vectors and growing water and food insecurity are creating a context in which environmental protection and health protection form part of the same public policy.

The World Health Organization has identified climate change as one of the main health threats of our time. Its consequences are not limited to isolated events or exceptional disasters. They also develop gradually, worsening pre-existing diseases, increasing exposure to certain risks and widening inequalities between populations and territories.

This reality requires a broader understanding of traditional healthcare action. Providing appropriate care to a person who is ill remains at the core of healthcare delivery, but it is no longer sufficient. It is also necessary to act upon the environmental conditions that contribute to disease, compromise quality of life or increase population vulnerability.

In this context, energy efficiency, emissions reduction, sustainable mobility, the circular economy, responsible water management and infrastructure resilience should not be regarded as policies external to the healthcare system. They are instruments of prevention, public health and collective protection.

At the same time, healthcare services themselves generate significant environmental impacts. Hospitals and health centres consume energy, water,

medicines, materials, food, chemicals and equipment. They require complex logistics networks, produce waste and depend on global supply chains. The healthcare system therefore occupies a dual position: it must respond to the effects of climate change, while also reducing its own contribution to that process.

This dual responsibility places decarbonisation at the centre of the transformation of contemporary healthcare.

9.1.1. The Environmental Footprint of Healthcare Activity

A hospital is one of the most technically complex forms of public infrastructure. It operates continuously and is subject to exceptionally demanding requirements in terms of safety, availability and continuity of service.

Within a single building there may be heating, ventilation and air-conditioning systems, hot-water production, high-availability electrical installations, standby generators, energy centres, medical gas networks, electromedical equipment, laboratories, sterilisation facilities, diagnostic imaging, kitchens, laundries, information systems and numerous support services.

This complexity has a direct consequence: healthcare delivery requires intensive resource consumption. Energy demand depends not only on the size of buildings, but also on the required indoor environmental conditions, the need to control air quality, the continuous operation of certain equipment and the obligation to maintain essential services even in the event of external failures.

According to the global study produced by Health Care Without Harm and Arup, healthcare activity accounts for approximately 4.4% [1] of global net greenhouse gas emissions. This estimate illustrates the sector's climatic significance and demonstrates that healthcare does not occupy a marginal position within the global emissions economy.

However, most of the healthcare climate footprint does not arise exclusively within hospitals. A very significant proportion comes from the value chain: the manufacture and transport of medicines, medical products, medical equipment, construction materials, textiles, food products, chemicals and other goods and services purchased by healthcare organisations.

This considerably broadens the scope of any decarbonisation strategy. Improving the efficiency of an energy centre, installing renewable energy or reducing electricity consumption forms a necessary part of the response, but does not address the entire problem. Action is also required in relation to procurement, logistics, mobility, product use, models of care and waste management.

From a carbon-accounting perspective, healthcare emissions can be grouped into three broad areas.

The first comprises emissions generated directly by the organisation, including those from boilers, standby generators, owned vehicles, fuels used in facilities and certain clinical gases.

The second comprises emissions associated with electricity, heat or other forms of energy purchased from third parties.

The third includes indirect emissions arising from the supply chain and from all activities linked to healthcare delivery, even where those emissions occur outside the physical boundaries of healthcare facilities.

This classification demonstrates that decarbonisation cannot be assigned solely to maintenance departments. It requires the participation of procurement, pharmacy, logistics, finance, occupational risk prevention, quality, human resources, clinical services and infrastructure planning.

Certain gases used in clinical practice merit specific consideration. Some inhaled anaesthetics and nitrous oxide have a high global-warming potential. Their overall impact depends on patterns of use, the technologies employed, the condition of distribution networks and the existence of leaks. Their management must therefore combine clinical, technical and environmental criteria without compromising patient safety.

Waste is another visible expression of healthcare's environmental impact. Healthcare facilities generate domestic-type waste, paper, cardboard, packaging, organic matter, plastics, infectious waste, pharmaceutical products, chemicals and other waste streams requiring differentiated treatment.

The expansion of single-use products has contributed to improvements in certain standards of safety and hygiene, but has also intensified raw-material consumption and waste generation. The appropriate response is not the indiscriminate replacement of all disposable products, but the assessment of each application according to its clinical risk, life cycle, potential for reuse and overall environmental impact.

Water is also a strategic resource for healthcare activity. It is used in sanitary facilities, cleaning, sterilisation, laundry, catering, air-conditioning, thermal production, laboratories and numerous support processes. In regions affected by water scarcity or with high energy dependence on desalination, every cubic metre consumed also carries a significant energy and climate footprint.

Leak reduction, consumption sub-metering, monitoring, the selection of efficient equipment and technically viable reuse should form part of routine management. The objective is not to restrict essential consumption, but to eliminate inefficiency and match water quality to the actual requirements of each use.

Mobility adds a further component to the healthcare footprint. Travel by patients, staff, suppliers and healthcare vehicles generates energy consumption, atmospheric emissions and congestion. The design of more localised care networks, shared transport, fleet electrification, telemedicine and improved accessibility can reduce this impact without diminishing quality of care. The environmental footprint of healthcare is therefore multidimensional. It is not limited to the energy consumed by buildings, but extends to all decisions associated with the organisation of service delivery.

9.1.2. The effects of climate change on health

Climate change affects health through both direct and indirect mechanisms. Direct effects arise as the immediate consequence of physical events such as heatwaves, flooding, wildfires or extreme storms. Indirect effects occur through changes in ecosystems, water, food, the economy, working conditions or the distribution of disease.

Extreme heat is one of the most evident risks. High temperatures impair the body's ability to regulate its temperature and may cause dehydration, heat exhaustion, heatstroke and the worsening of cardiovascular, respiratory, renal and metabolic conditions.

Vulnerability is not distributed equally across the population. Older people, children, pregnant women, patients with chronic illnesses, outdoor workers and people living in poorly adapted housing face greater exposure. This therefore reveals an issue that directly affects equity across the global population.

The 2025 *Lancet Countdown* report estimated that the rate of heat-related deaths increased by 23% since the 1990s, reaching about 546,000 deaths per year [2]. Indicators of this kind demonstrate that the health impact of global warming is already measurable and is not confined to future scenarios.

Rising temperatures may also alter the geographical range and periods of activity of mosquitoes, ticks and other vectors. As a result, some infectious diseases may spread into new regions or maintain transmission over longer periods. Changes in rainfall patterns also affect health. Prolonged droughts reduce water availability, impair agricultural production and may increase the concentration of certain pollutants. At the opposite extreme, intense rainfall and flooding can damage sewerage infrastructure, contaminate water supplies and facilitate disease transmission.

Wildfires also generate a substantial burden of air pollution. Fine particulate matter and other pollutants produced by combustion can travel considerable distances and worsen respiratory and cardiovascular disease, including among populations located far from the source of the fire.

Air pollution and climate change partly share a common origin: the use of fossil fuels. For this reason, decarbonisation policies deliver immediate health benefits. Reducing emissions not only limits future warming, but also reduces current exposure to harmful pollutants.

The effects on mental health should not be underestimated. The loss of homes, destruction of livelihoods, exposure to emergencies, economic uncertainty and fear of future extreme events may cause anxiety, depression, post-traumatic stress and a deterioration in social wellbeing [3].

Climate change also alters working conditions. Heat reduces physical capacity, increases the risk of accidents and may make certain tasks impracticable during parts of the day. These effects are particularly relevant in agriculture, construction, industry, transport and other sectors involving high environmental exposure. The social dimension is inseparable from the health dimension. Climate impacts fall most heavily on those with the fewest resources to adapt.



Poorly insulated housing, lack of access to cooling, insecure employment and distance from healthcare services all increase the risk of serious consequences.

Climate change therefore not only increases the overall burden of disease. It also amplifies existing inequalities [4].

Healthcare systems will have to respond to increased demand for care, changing epidemiological patterns and a greater frequency of emergency situations. At the same time, their own infrastructure may be affected by flooding, extreme temperatures, wildfires, electricity failures, water scarcity or disruption to supplies of medicines and materials [5,6].

Adaptation of the healthcare system is therefore no longer optional. It is a condition for ensuring continuity of care.

9.1.3. Integrating Sustainability and Health

The institutional response must be structured around two mutually reinforcing lines of action: mitigation and adaptation.

Mitigation seeks to reduce the emissions and environmental impacts generated by healthcare activity. It includes energy efficiency, the replacement of fossil fuels, the use of renewable energy, low-emission mobility, waste reduction, water optimisation and the incorporation of environmental criteria into purchasing and contracts. Adaptation seeks to prepare the system to operate under more adverse climatic conditions. It requires risk assessment, strengthened infrastructure, security of critical supplies, revision of emergency plans and adaptation of care capacity to emerging threats.

Both approaches must be addressed together. A healthcare facility that is energy efficient and less dependent on fossil fuels is generally more robust in the face of energy crises. A more diversified and local supply chain may reduce emissions while also improving the availability of essential products. Efficient

water management reduces consumption and increases the capacity to respond to periods of scarcity. Sustainability should therefore not be confined to isolated measures, temporary campaigns or projects promoted by individual professionals. It must be incorporated into governance, planning, budgeting, procurement, infrastructure design and performance evaluation.

Integrating sustainability and health means recognising that emissions reduction, responsible resource use and the resilience of healthcare facilities form part of the healthcare mission itself.

Decarbonisation is not an objective external to healthcare. It is a means of preventing disease, protecting the population and preserving the future capacity of the system. Hospital engineering plays a central role in this process. Its function can no longer be limited to maintaining installations or resolving technical incidents. It must participate in strategic planning, innovation, life-cycle assessment, risk management and the technological transformation of healthcare facilities.

The challenge is to reduce environmental impact without compromising safety, quality or continuity of care. Dispersed initiatives are insufficient. An institutional strategy is required to define objectives, responsibilities, indicators and monitoring arrangements.

Only through this approach can sustainability become a structural dimension of healthcare systems.

9.2. THE CARBON FOOTPRINT OF A HOSPITAL: MEASUREMENT AND THE SCOPE FOR ENGINEERING ACTION

The decarbonisation of a healthcare system must begin with a basic question: where are its emissions actually generated? Without a quantified answer, decisions tend to focus on visible measures, such as installing photovoltaic

panels or replacing lighting, without understanding their relative significance within the total footprint. Measurement makes it possible to establish a baseline, identify the principal sources, prioritise investment and subsequently verify whether the measures adopted have delivered an effective reduction.

A carbon footprint represents the total greenhouse gas emissions generated directly or indirectly by an organisation, activity or product. To facilitate comparison, these gases are converted into a common unit: the tonne of carbon dioxide equivalent, expressed as tCO₂e. This unit accounts not only for carbon dioxide, but also for methane, nitrous oxide, refrigerant gases and other compounds, weighted according to their contribution to global warming.

In a hospital, the inventory must cover far more than the energy consumed by the building. Healthcare delivery depends on industrial installations, electromedical equipment, clinical gases, medicines, single-use products, food, water, transport, waste, construction works, outsourced services and an extensive logistics chain. The resulting footprint will be valid only if the organisational and operational boundaries are clearly defined and if the sources included remain consistent over successive reporting years.

For this reason, carbon-footprint calculation should not be regarded as an isolated administrative exercise. It should become a permanent instrument of technical management and institutional planning.

9.2.1. Direct and Indirect Emissions: The Three Scopes of the Footprint

Corporate greenhouse gas accounting classifies emissions into three scopes. This distinction makes it possible to differentiate sources directly controlled by the organisation from those occurring outside its facilities as a consequence of its consumption or activity.

Scope 1 covers direct emissions from sources owned or controlled by the organisation. In a hospital setting, these include, among others, the combustion of diesel, natural gas or other fuels in boilers and thermal equipment; fuel consumption by owned vehicles; the operation of certain standby generators; and fugitive emissions caused by refrigerant-gas leakage. Certain gases used in clinical practice may also be included where they are released within the healthcare facility.

Scope 2 covers indirect emissions associated with the generation of electricity, heat or other energy purchased from third parties. Although these emissions physically occur at generating plants, they are attributed to the organisation that demands and consumes the energy. In a hospital located within an electricity system with a high proportion of fossil-fuel generation, electricity consumption may represent a particularly significant source of emissions.

Scope 3 covers all other indirect emissions arising from the value chain. It includes the manufacture and transport of medicines, medical products, equipment, food and materials; travel by staff, patients and visitors; services provided by contractors; construction works; logistics; external waste treatment; business travel; and other activities required to deliver care, even where the emission sources are owned by third parties.

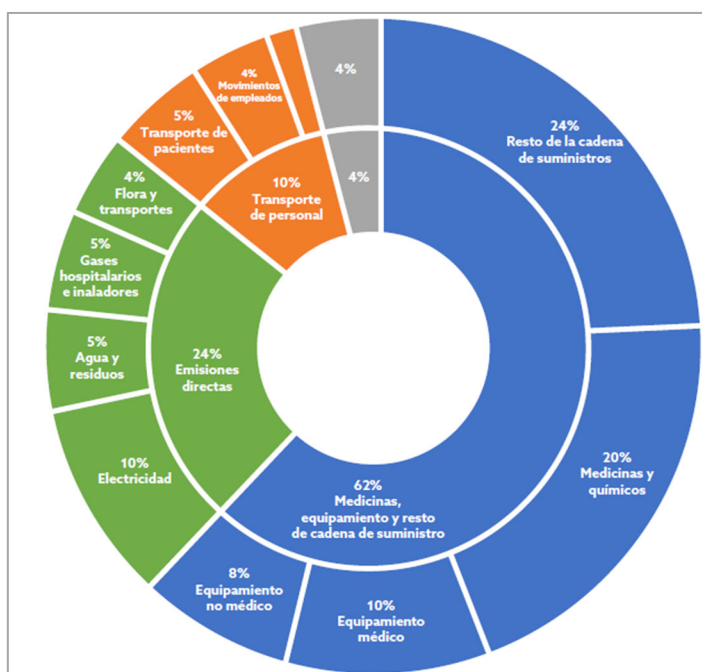
This classification is essential, but it should not be confused with the distribution of the footprint by activity. The scopes describe the relationship of control between the organisation and the emission source. Functional categories, by contrast, explain which clinical, logistical or technical process generates the emissions. The same activity may produce emissions across more than one scope. Mobility, for example, falls within Scope 1 when it involves owned vehicles and Scope 3 when it relates to staff, visitors, hauliers or contracted services.



9.2.2. Distribution of the Healthcare Carbon Footprint

International experience shows that most of the healthcare carbon footprint is not necessarily generated within buildings. The distribution initially used as a reference by the Canary Islands Health Service's Salud Zer0 Net Emissions 2030 Strategy, based on the British National Health Service model, assigns 24% to emissions directly associated with healthcare operations [7]. Within this block, electricity accounts for approximately 10%; water and waste for 5%; hospital gases and inhalers for a further 5%; and owned fleets and transport for 4%.

In the same model, mobility by patients, staff and visitors accounts for a further 10%. Healthcare services delivered by external companies represent approximately 4%. The remaining 62% arises from medicines, chemicals, equipment and other components of the supply



chain. Within this block, medicines and chemicals account for 20%, medical equipment for 10%, non-medical equipment for 8% and the remainder of the supply chain for 24%. These percentages should not be applied automatically to every hospital. The actual distribution will depend on the electricity system, the range of services provided, the age of the building, the climate, surgical activity, the logistics model, the level of outsourcing, mobility patterns and the criteria used to calculate supply-chain emissions. Nevertheless, this reference is useful for understanding a fundamental point: energy use within the building is

strategically important, but it does not represent the entirety of the healthcare system's footprint. It also explains why responsibility for decarbonisation cannot rest exclusively with technical services. Action on the supply chain requires the involvement of pharmacy, procurement, purchasing, logistics, clinical departments and executive management. Hospital engineering nevertheless retains a cross-cutting role because it contributes to the technical specification of equipment, installations, construction works, maintenance contracts, energy consumption and operating conditions.

9.2.3. A Quantitative Approach: The Experience of The Canary Islands Health Service

The quantification undertaken by the Canary Islands Health Service provides an indication of the scale of the problem within a real healthcare system. Verified reports for the public hospitals of the Canary Islands calculated a combined footprint of 701,188 tCO₂e for 2021. This value was equivalent to approximately 5.69% of the Canary Islands' total greenhouse gas emissions and 15.34% of the emissions associated with the archipelago's electricity-generating stations, based on the energy data used in the study.

Analysis by hospital also showed a strong concentration of emissions in the most complex facilities. Four major hospital complexes recorded individual footprints close to or above 140,000 tCO₂e, whereas smaller island hospitals recorded considerably lower figures. This difference cannot be explained solely by built floor area. It is also influenced by the number of beds, healthcare activity, technological intensity, the presence of specialist referral services, purchasing volumes and the complexity of the logistics chain.

A subsequent analysis of one hospital within the Canary Islands Health Service, covering the 2024 reporting year, quantified a total verified footprint of 157,404



tCO₂e. Within the complete inventory, imported electricity accounted for 14,223.43 tCO₂e, equivalent to 9.04% of the footprint, while stationary combustion contributed 1,081.55 tCO₂e, approximately 0.69%. Together, electricity and stationary fuel combustion therefore represented around 9.72% of total emissions.

This result could lead to an incorrect conclusion: that hospital engineering can act on only a small proportion of the footprint. The interpretation changes when the analysis focuses on the emissions that the organisation can effectively manage. In the case studied, the footprint identified as manageable amounted to 27,550.86 tCO₂e. Within that boundary, imported electricity represented 51.63% and stationary fuel combustion 3.93%. Taken together, these two components accounted for 55.55% of the emissions considered manageable.

The difference between 9.72% of the total footprint and 55.55% of the manageable footprint is significant. The first value describes the weight of energy within the hospital's complete inventory, which is dominated by indirect value chain emissions. The second (55.55%) demonstrates the importance of energy within the area in which the organisation can intervene with the greatest capacity and speed.

The concept of a manageable footprint does not constitute a new scope within carbon accounting. It is a prioritisation tool. It makes it possible to distinguish between emissions over which the hospital has direct decision-making authority and those whose reduction depends mainly on suppliers, manufacturers, national policies or wider market transformations.

9.2.4. Part of the Footprint that Hospital Engineering Can Influence

The scope for action by hospital engineers can be considered at three levels: direct control, technical influence and strategic intervention.

Direct control is concentrated mainly on Scope 1 and Scope 2 emissions. Engineering services manage or supervise energy centres, heating, ventilation and air-conditioning installations, domestic hot-water production, electrical systems, lighting, pumping systems, standby generators, distribution networks, control systems and, in many cases, owned fleets and refrigerant gases.

Within these areas, it is possible to modify the technology, fuel, equipment efficiency, operating schedules, setpoints, maintenance arrangements and source of energy. This is the area in which the relationship between a technical decision and a quantifiable reduction in emissions is most immediate.

Technical influence extends to certain Scope 3 categories. Engineers participate in the drafting of projects and specifications, advise on equipment procurement, establish maintenance requirements, define durability conditions, assess consumption, contribute to water and waste management and may introduce life-cycle criteria into construction works and supplies. Although the final decision may not rest exclusively with the technical department, its specifications influence the environmental performance of acquired assets for many years.

Finally, strategic intervention consists of converting dispersed data into useful information for management. This includes establishing baselines, identifying significant energy uses, normalising consumption according to activity, evaluating investments, calculating payback periods, verifying savings and anticipating risks to operational continuity.

Hospital engineering therefore ceases to be an exclusively reactive function. It is not limited to repairing faults or maintaining installations, but contributes to defining the hospital's energy and environmental model.

Energy Consumption Within the Hospital

Once the energy component has been isolated, it is necessary to understand how it is distributed internally. Based on the experience of organisations such as the Canary Islands Health Service, a general estimate is that heating, ventilation and air-conditioning may account for around 35% of energy consumption; heating and domestic hot-water production for 20%; lighting for 12%; and hospital equipment and processes for the remaining 33%.

These proportions are not universal. In warmer climates, cooling may account for a larger share. In hospitals with sterilisation facilities, kitchens, laundries, diagnostic imaging or other energy-intensive equipment, process loads may alter the distribution significantly. Sectoral percentages should therefore be used only as an initial indication.

Planning must be based on measured consumption. A hospital needs to know not only how much energy it uses, but also when, where and for what purpose it is used. Monthly utility bills make it possible to monitor the overall cost, but they do not identify specific inefficiencies. This requires sub-metering by building, energy centre, end use and critical area.

Monitoring should combine energy variables with activity data. Consumption per square metre is useful for comparing buildings, but may be insufficient when comparing hospitals with different service portfolios. Other indicators, such as consumption per bed, inpatient stay, procedure, consultation or unit of output, allow trends to be interpreted more accurately and prevent a reduction in activity from being mistaken for a genuine improvement in efficiency.

Actions Available to Hospital Engineers

The first action is measurement. The installation of sub-meters, power-quality analysers, sensors, flow meters and monitoring platforms makes it possible to

identify abnormal consumption, unjustified night-time loads, losses, simultaneous heating and cooling, and deviations from expected patterns. Measurement should be integrated into the building management system and supported by indicators, alarms and review procedures.

In heating, ventilation and air-conditioning, measures may include replacing chillers and heat-generation equipment, installing variable-speed drives, regulating flow rates, recovering heat, optimising setpoints, reducing distribution losses and aligning operating schedules with actual occupancy. In a hospital, any reduction must respect requirements relating to ventilation, air quality, pressure differentials, temperature, humidity and infection control. Efficiency cannot be achieved by degrading clinical conditions.

Electrification of heat production through heat pumps can reduce fossil-fuel use, particularly when combined with renewable electricity. Its feasibility must be assessed according to the required temperatures, simultaneous heating and cooling demand, available electrical capacity, circuit configuration and opportunities for energy recovery.

On-site renewable generation reduces imported electricity and exposure to market volatility. However, it must be designed on the basis of actual load profiles, available space, structural capacity, shading, operating patterns and connection constraints. In some facilities, energy storage may improve renewable energy utilisation and strengthen resilience, although its justification should not be based solely on emissions reduction.

Lighting offers relatively mature measures: replacement with LED technology, regulation, zoning, presence detection and the use of daylight. Nevertheless, its contribution is generally smaller than that of heating, ventilation, air-conditioning and hospital processes. It should therefore not displace

investments with greater reduction potential simply because it is a straightforward and visible measure.

The building envelope also affects demand. Improvements to windows and doors, solar shading, roofs, insulation and glazed openings can reduce heat gains and improve comfort. These measures are particularly effective when coordinated with the renewal of technical installations, thereby avoiding oversizing and reducing required capacity.

For refrigerant gases, an up-to-date inventory of equipment, refrigerant charges, gas types and leaks is essential. The loss of even a small quantity of a refrigerant with high global-warming potential can offset part of the benefit achieved through energy-efficiency improvements. Leak prevention, refrigerant recovery during maintenance and progressive replacement with lower-impact alternatives should be incorporated into maintenance contracts.

Water management also has an energy dimension. Pumping, hot-water production, treatment and, in island territories, desalination all involve energy consumption and emissions. Sub-metering, early leak detection, optimisation of cooling towers and water circuits, and technically acceptable reuse can reduce both water and energy consumption.

In waste management, engineering can contribute to the design of spaces, internal routes and treatment technologies. Incorrect segregation can cause waste comparable to municipal waste to be classified as healthcare waste, requiring more energy-intensive and costly treatment. Solutions should be evaluated across the complete cycle: generation, storage, transport, treatment, safety and final destination.

Owned fleets can be addressed through low-emission vehicles, charging infrastructure, shared management and route optimisation. By contrast, the

mobility of staff, patients and visitors requires coordination with human resources, healthcare planning and the public authorities responsible for transport.

Finally, procurement is one of the most powerful instruments available. Technical specifications may include requirements relating to efficiency, durability, repairability, spare-parts availability, refrigerant recovery, monitoring, maximum consumption, life-cycle costing and environmental reporting obligations. The Salud Zer0 Net Emissions 2030 Strategy explicitly incorporates the modernisation of procurement procedures, the integration of green clauses and sustainable supply-chain management as structural elements of decarbonization [7].

From Inventory to Action

Calculating the footprint is not the end of the process. Its value lies in enabling decisions on which measure should be implemented first, which investment delivers the greatest reduction, which action produces additional benefits and how the result will be verified.

Each project should begin with a measurable baseline, define the expected energy or material saving, convert that saving into avoided emissions and establish a monitoring procedure. Actions should have a defined timescale, an assigned responsible party and a quantified objective.

Not all of a hospital's footprint can be reduced by technical services. A large proportion depends on medicines, medical products, models of care and external industrial supply chains. Nevertheless, the proportion under the control or influence of engineering is sufficiently significant to determine the success of any institutional strategy.



Hospital engineering therefore occupies a central position between the emissions inventory and effective transformation. Its responsibility is to translate tonnes of carbon dioxide equivalent into decisions on installations, equipment, contracts and procedures. Measurement makes the problem visible; prioritisation ensures that resources are used appropriately; and verification demonstrates that decarbonisation is genuinely taking place.

9.3. THE IMPORTANCE OF DEVELOPING AN INSTITUTIONAL STRATEGY

The decarbonisation of healthcare systems cannot depend solely on isolated projects, the personal initiative of individual professionals or the occasional availability of funding. The complexity of the healthcare carbon footprint, its cross-cutting nature and the diversity of the stakeholders involved require an organised response at institutional level.

A hospital may replace a chiller, install photovoltaic panels or upgrade its lighting. However, although these measures are useful, they do not in themselves constitute a decarbonisation strategy. A strategy requires an understanding of the starting point, the establishment of shared objectives, the allocation of responsibilities, the definition of priorities, the provision of resources and the verification of the results achieved.

The difference between a collection of projects and an institutional strategy therefore lies in the existence of a shared direction. Projects address specific needs. A strategy determines why action is being taken, the areas in which it will be taken, the criteria to be applied, the order of priority and the system through which performance will be evaluated.

This distinction is particularly important in healthcare. Decisions relating to energy, infrastructure, medicines, medical products, mobility, waste, water,

procurement and the organisation of care are made by different departments. None of them controls the entire footprint on its own. Without a common framework, each area may act according to its own priorities, without the organisation as a whole necessarily progressing towards an effective and coherent reduction in emissions.

An institutional strategy makes it possible to integrate these decisions within a single healthcare policy.

9.3.1. From Technical Initiative to Organizational Commitment

Hospital engineering has the capacity to identify inefficiencies, design solutions and implement measures affecting buildings and technical installations. However, its scope for action is limited where there is no clear institutional support.

Many decarbonisation measures require initial investment, contractual amendments, coordination with clinical departments, adaptation of administrative procedures and acceptance of organisational change. Technical services may identify an opportunity, but they do not always have the budgetary authority or hierarchical competence required to convert it into an executive decision.

An institutional strategy provides that framework. It turns sustainability into a formal organisational objective rather than an issue dependent on the individual sensitivity of each manager. This allows technical proposals to be assessed not only in terms of their immediate cost, but also according to their contribution to energy, climate, economic and healthcare objectives.

Executive support is particularly important where measures affect several departments. Reducing air-conditioning consumption, for example, may require changes to operating hours, setpoints, operating protocols or occupancy



conditions. Sustainable waste management requires the participation of clinical services, occupational risk prevention, cleaning, logistics and procurement. Fleet electrification requires coordination between engineering, general services, purchasing and financial management.

Without institutional leadership, these measures tend to become fragmented or blocked by conflicts of responsibility. A clear example of institutional leadership is provided by the Canary Islands Health Service's Salud ZerO Net Emissions 2030 Strategy, which is based on the need for departments to act in a coordinated and consistent manner under executive leadership [7]. The Canary Islands Health Service proposes multidisciplinary working groups, infrastructure modernisation, procurement reform, training, renewable-energy integration, sustainable supply-chain management and support for innovation.

This approach demonstrates that decarbonisation is not the exclusive responsibility of engineering, but neither can it be achieved without engineering. The institution must set the direction and provide the means; engineering must translate that mandate into technically viable solutions.

Why an institutional strategy is necessary

The first function of a strategy is to establish a common objective. In the absence of a shared reference point, individual hospitals may select different measures, use incompatible indicators or apply calculation methodologies that cannot be compared. This prevents the progress of the system as a whole from being evaluated. A strategy must define a time horizon, a baseline and interim objectives. The final objective may be expressed in terms of climate neutrality, an absolute reduction in emissions or a reduction in carbon intensity. However, it must be translated into realistic and verifiable intermediate targets. The second function is to establish priorities. Not all measures offer the same

reduction potential, degree of complexity or cost. An institution needs criteria for deciding when priority should be given to efficiency, electrification, renewable generation, equipment replacement, mobility or supply-chain emissions reduction. This prioritisation should not depend solely on the simple financial payback period. Asset life, avoided emissions, resilience, technological risk, clinical criticality and replicability should also be assessed.

The third function is to ensure continuity. Decarbonisation processes take place over long periods and may extend beyond the tenure of management teams or individual budget cycles. A formal strategy reduces dependence on particular individuals and allows a stable direction to be maintained despite organisational change.

The fourth function is to mobilise resources. The existence of institutional objectives facilitates budget planning, access to funding, early project preparation and the integration of measures into multiannual investment plans.

The fifth function is to legitimise technical action. When sustainability is incorporated into organisational objectives, hospital engineers have a stronger basis for proposing efficiency requirements, introducing environmental indicators or demanding higher levels of performance in contracts.

Finally, a strategy enables accountability. The organisation must be able to explain what emissions it generates, what measures it has adopted, how much it has invested and what reductions it has achieved. Without measurement and monitoring, decarbonisation risks becoming a declaration without operational substance.

The strategy as a means of supporting hospital engineering

Hospital engineering occupies a distinctive position within the healthcare system. It understands the actual performance of technical installations, the



limitations of buildings and the conditions required to maintain healthcare activity. This knowledge is essential for the design of technically achievable policies. However, engineers should not be left as the sole parties responsible for sustainability. A significant proportion of the footprint lies outside the direct scope of technical installations. The institutional strategy must distribute responsibilities and prevent decarbonisation from being treated merely as an extension of maintenance. Institutional support for engineering must take several specific forms.

First, there must be a governance structure. A coordinating unit must be identified, responsible officers must be appointed in each hospital and mechanisms must be established for working with procurement, pharmacy, logistics, occupational risk prevention, quality, human resources and clinical management.

Second, data must be made available. Technical services require energy, financial, contractual and healthcare activity data in order to assess measures properly. The absence of measurement systems and access to data restricts analytical capacity.

Third, common criteria must be established. Projects should use consistent methodologies for calculating savings, avoided emissions, life-cycle costs and payback periods.

Fourth, investment capacity must be ensured. Identifying opportunities is of little value if there is no process for converting them into financeable projects.

Fifth, the strategic role of engineering must be recognised. Technical managers should participate in investment planning, contract preparation, equipment procurement and the design of new buildings. This change in position is essential. Hospital engineering should not become involved only after

infrastructure has already been designed or equipment has been purchased. Its participation should begin at the earliest decision-making stage.

9.3.2. Strategic Areas That Should Be Included in a Healthcare Decarbonisation Policy

An institutional strategy must be adapted to the characteristics of each healthcare system. Nevertheless, it should include at least the following areas.

Governance, leadership and coordination

The strategy must define who leads, who implements and who evaluates. Sustainability must have the support of the highest level of management and a stable technical structure. Governance must avoid two risks: excessive centralisation, which may overlook the particular characteristics of each hospital, and fragmentation, which leads to incompatible models. The central level should establish common objectives, methodologies and criteria, while individual hospitals should adapt measures to their operational circumstances.

Measurement, objectives and indicators

The first operational area should be footprint measurement. The organisational boundary, base year, emission factors and data sources must be defined.

The strategy should include both absolute and relative indicators. Total emissions make it possible to assess the overall contribution, while normalised indicators, such as emissions per square metre, bed, inpatient stay, procedure or unit of activity, help to interpret efficiency. Each line of action should have a defined timescale and an objective, quantifiable emissions-reduction forecast.

Energy efficiency and infrastructure modernisation

As a general principle, demand reduction should precede the replacement of energy sources. The strategy should include audits, sub-metering, equipment

renewal, heat recovery, automation, improvements to the building envelope and optimisation of operation.

Priority should be given to replacing obsolete and energy-intensive installations, particularly where they present a risk of failure or use refrigerants with a high climate impact.

Efficiency must not be approached as an indiscriminate reduction in consumption. Every measure must guarantee environmental quality, safety and continuity of care.

Renewable energy and electrification

The strategy should establish a plan for on-site generation, heat electrification and the progressive reduction of fossil-fuel use.

Renewable generation should be sized according to actual demand profiles. Electrification through heat pumps should be assessed together with electrical-network capacity, required operating temperatures and backup requirements.

Sustainable procurement and administrative procedures

Public procurement is a central instrument because it influences the environmental performance of buildings, equipment and services for many years.

The strategy should incorporate verifiable environmental criteria into construction works, supplies and services. These criteria may relate to efficiency, service life, repairability, spare-parts availability, refrigerant management, water consumption, recycled content, carbon footprint or life-cycle cost. Sustainability should not be confined to generic award criteria. It should also be integrated into technical specifications, contract-performance conditions and monitoring systems.

Sustainable supply-chain management

The supply chain accounts for the majority of the healthcare footprint. The strategy should therefore establish mechanisms for requesting information from suppliers, comparing alternatives and reducing emissions associated with medicines, medical products, food, textiles and equipment.

Selection decisions should consider clinical effectiveness, safety, availability, cost and environmental impact. Sustainability cannot replace clinical criteria, but it should be incorporated where technically equivalent alternatives are available.

Water, waste and the circular economy

The strategy should include objectives for reducing consumption, detecting leaks, improving process efficiency and introducing reuse where viable.

In waste management, the focus should be on prevention and correct segregation. The circular economy is not simply a matter of recycling more; it also means reducing material use, extending equipment life and avoiding the unnecessary classification of waste as hazardous.

Sustainable mobility

Healthcare mobility includes owned fleets, ambulances and travel by staff, patients, visitors and suppliers.

The strategy should distinguish between what the organisation controls directly and what requires agreements with other public authorities. Fleet electrification, charging infrastructure, logistics optimisation, shared transport and remote care may all form part of this area.

Digitalisation and data management

Digitalisation should be used to generate knowledge and improvement, not merely to accumulate information.



Building management systems, energy platforms, smart meters and dashboards make it possible to detect deviations and evaluate measures. Integrating these systems with healthcare activity variables improves the quality of performance indicators.

Training and organisational culture

Transformation cannot depend exclusively on technology. Professionals influence the use of equipment, installations, materials and resources.

Training should be adapted to each professional profile. Technical staff require expertise in energy and carbon; procurement teams require knowledge of sustainable purchasing criteria; and clinical professionals require information on products, waste and sustainable clinical practice. The aim should not be to transfer responsibility to individual behaviour, but to make everyday decisions consistent with the institutional framework.

Innovation, research and flagship projects

A strategy should reserve space for pilot solutions and innovation projects. Not all technologies will initially be mature, but healthcare systems can act as demonstration environments. These projects should be conceived not only in terms of their direct impact, but also their capacity to generate commitment, institutional positioning and innovation. This approach is valid provided that flagship projects do not replace fundamental efficiency and management measures. Innovation should complement, rather than obscure, the need to renew installations, measure consumption and correct inefficiencies.

Climate adaptation and resilience

A healthcare decarbonisation strategy must also incorporate adaptation. Hospitals are critical infrastructure and must continue operating during heatwaves, flooding, supply failures, water shortages and logistics disruption.



Climate-risk assessment should be integrated into projects, emergency plans and investment decisions. An efficient, diversified and properly monitored facility is generally also more resilient.

9.3.3. The Example of The Canary Islands Health Service's Salud ZeroO Net Emissions 2030 Strategy

The strategy developed by the Canary Islands Health Service provides an example of how a healthcare organisation can structure its climate response.

Its objective is not limited to reducing energy consumption. It seeks to reduce direct and indirect emissions throughout the value chain, demonstrate leadership from the healthcare sector, apply measures across the organisation and generate innovation, economic activity and employment.

The programme is structured around six areas: energy efficiency and infrastructure modernisation; sustainable administrative procedures; awareness and training; sustainable supply-chain management; digitalisation; and strategic sustainability projects [7]. This structure provides an important lesson. Decarbonisation is addressed simultaneously through infrastructure, organisational arrangements, procurement, professionals, data and innovation. None of these areas is sufficient on its own.

The principal value of this type of strategy lies not only in the projects it contains. Its importance lies in transforming sustainability into a recognisable policy with a defined identity, objectives and continuity.

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CHAPTER 10

PROJECT EXPERIENCE AND CLOSING REMARKS

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The last section presents details about the project Smart Healthcare Engineering during Intensive training sessions, hands on practice and the hospital technical visits.

10.1 FROM TECHNICAL KNOWLEDGE TO HOSPITAL PRACTICE

The Smart healthcare engineering project was built around a practical need. Engineering students learn many technical subjects, but many of them have limited contact with hospitals. Hospitals, at the same time, need engineers who understand infrastructure, maintenance, medical technology, digital systems, safety and sustainability. The project connected these two sides through

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training activities, hospital visits, teaching materials and cooperation between universities and healthcare institutions.

The project was implemented by partners from Romania, Spain and Türkiye. The cooperation included universities, hospital specialists and technical staff. This structure was important because healthcare engineering cannot be developed only from the university side. It needs real examples from hospitals, and it needs direct discussion with the people who operate, maintain and use technical systems every day.



Figure 9.1. Intensive training session with students
ULPGC, Las Palmas de Gran Canaria Spain, 2024

10.2 INTENSIVE TRAINING PROGRAMMES

The intensive training programmes were among the central activities of the project. They gave students the opportunity to learn in an international environment and to compare different ways of organizing healthcare engineering education. The training was not limited to classical lectures. It included practical exercises, discussions with specialists, technical examples and direct observation of hospital systems.

The first intensive training programme was organized in Las Palmas de Gran Canaria, Spain, between 08.07.2024 and 19.07.2024. Students from UNITBV, ULPGC and MCBU participated in a 12-day programme dedicated to healthcare engineering. This first mobility created the common practical framework of the project and prepared the basis for the following activities in Romania and Türkiye.

The second intensive training programme was organized in Braşov, Romania, between 07.07.2025 and 18.07.2025. It was addressed to students from the three partner universities and included one main teaching activity each day. The programme combined theoretical sessions, practical activities and hospital visits. The topics included hospital installations, energy efficiency, 3D printing, organization of healthcare staff, corrosion, specific hospital facilities, IT infrastructure, maintenance, medical equipment, psychrometry, Arduino-based monitoring and direct visits to healthcare facilities.

The third mobility was planned in Manisa, Türkiye, between 06.07.2026 and 17.07.2026. Its role was to complete the cycle of intensive training programmes and to continue the same educational concept in another institutional and cultural context. Each mobility helped the project to test and improve the teaching methodology. Students were exposed to different hospitals, technical



systems and working conditions, while teachers were able to compare methods and adapt the educational material for future use.



Figure 10.2. Practical training activities and group work during the intensive programmes.

An important element of the training methodology was the use of repeated assessment. Before each training activity, students completed an initial test. After the activity, they completed a final test on the same subject. This made it possible to evaluate the learning outcomes more clearly and to adapt the next teaching sessions according to the students' level of understanding. In this way, the training was not fixed, but adjusted step by step to the real needs of the group.

This approach had a positive effect on the learning process. The comparison between the initial and final tests showed an increase of at least 20% in the students' level of knowledge by the end of the training programme. This result confirms that the combination of lectures, practical work, hospital visits and continuous assessment can improve the understanding of healthcare engineering topics.

10.3 HOSPITAL VISITS AND LEARNING IN REAL ENVIRONMENTS

Hospital visits were essential for the project because they allowed students to see the technical systems discussed in the handbook in real operating conditions. The project benefited from the openness and cooperation of hospitals from Las Palmas de Gran Canaria, Spain, Braşov, Romania and Manisa, Türkiye. This cooperation was very important, because access to hospital infrastructure is not always easy. Technical areas inside hospitals may include sensitive data, internal procedures, critical installations and technologies that are not normally open to the public.

A hospital must be understood as a complex technical environment, not only as a place where medical activities are carried out. Behind clinical work there are air handling units, water systems, electrical installations, medical gases,



sterilization areas, diagnostic equipment, data systems and maintenance procedures. These systems remain mostly invisible for patients, but they are essential for safe and continuous care.

During the training programme in Spain, an important role was played by the Hospital Universitario de Gran Canaria Dr. Negrín, from Las Palmas de Gran Canaria. During the Romanian intensive training programme, the activities included presentations and visits related to Săcele Municipal Hospital, Clinicco Braşov Hospital and Sf. Constantin Hospital. These hospitals have different dimensions and functions compared with large university hospitals such as Dr. Negrín Hospital or Manisa Celal Bayar University Hafsa Sultan Hospital in Türkiye.

This variation was a real benefit for the project and for the hands-on activities. Students could compare different hospital scales, technical solutions and local ways of organizing healthcare infrastructure. They also understood that technical decisions cannot be separated from patient safety. A discussion about ventilation is also a discussion about infection prevention. A discussion about hot water systems is also a discussion about microbiological risk. A discussion about IT infrastructure is also a discussion about data continuity, confidentiality and hospital resilience.

The hospital visits changed the way students understood engineering. In a classroom, a pipe, a sensor, a surface or a power supply is usually treated as a technical object. In a hospital, the same object becomes part of a chain that can influence diagnosis, treatment, comfort and safety. This was one of the most important results of the project. Students learned to connect technical details with the real work of a hospital and to see healthcare engineering as a practical field with direct impact on people.

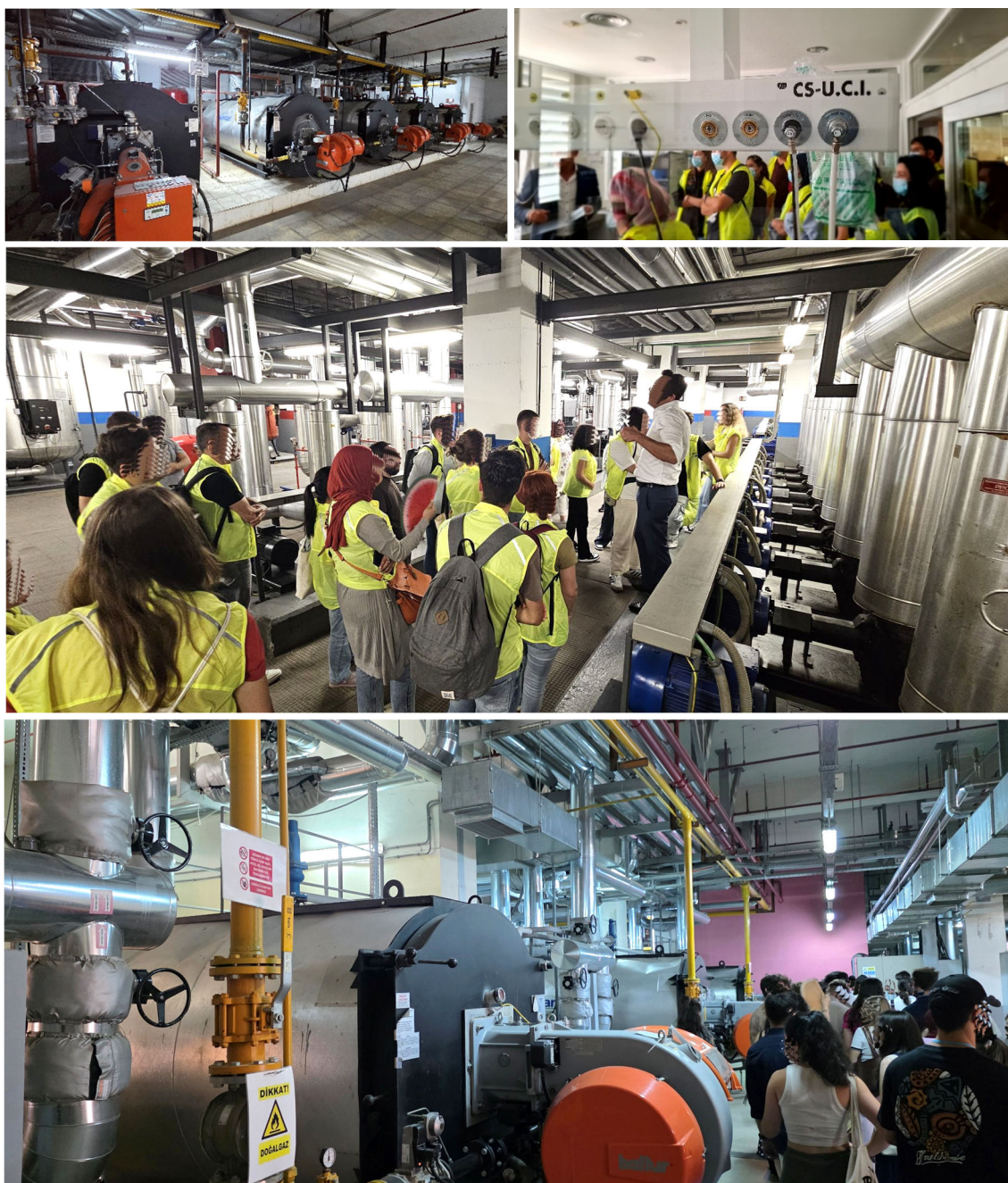


Figure 10.3. Hospital visit and technical explanations in a real healthcare environment.

The visits also supported communication between students and hospital staff. Engineers must be able to speak with medical personnel, administrative staff, maintenance teams and suppliers. The technical solution is useful only if it is understood, accepted and correctly used by the people working in the facility.



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10.4 TEACHING METHODOLOGY AND RESULTS OF THE PROJECT

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The teaching methodology developed within the project is illustrated through two applied topics: hospital air handling systems with psychrometric analysis and atmospheric corrosion in healthcare facilities [1,2]. The purpose of these training activities is to help students move beyond theoretical knowledge and understand how temperature, humidity, ventilation, indoor air quality and material degradation influence patient safety, comfort, maintenance and continuity of hospital services.

The methodology described in Smart Healthcare Engineering: A Data-Driven Educational Framework for Psychrometric Analysis and Air Handling Systems in Hospitals [1] and Smart healthcare engineering: transnational understanding of atmospheric corrosion processes in healthcare facilities [2] is based on practical work and contact with real technical problems.

Each training session starts with an initial test, used to identify previous knowledge and the concepts that require more attention. The theoretical explanations are then connected with hospital examples, especially air handling units, operating rooms, intensive care units and other areas where environmental control is essential. Students first work with manual instruments, such as psychrometers, to measure dry-bulb temperature, wet-bulb temperature and relative humidity (Figure 10.4).

These values are then used on the psychrometric chart to determine dew point, enthalpy and the behaviour of moist air.



Figure 10.4 Students working with the psychrometric chart.

The next step introduces digital monitoring. Students use Arduino boards, temperature and humidity sensors, and simple visual indicators to build a small environmental monitoring system. The digital values are compared with manual measurements, and sensor deviations are corrected by calibration (Figure 10.5).

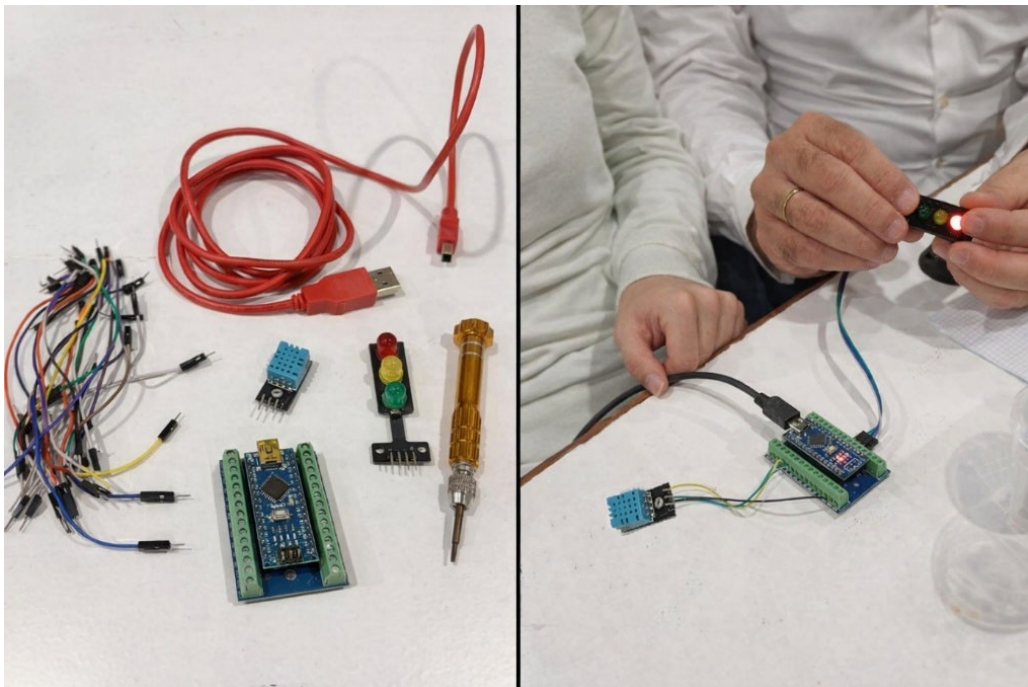


Figure 10.5 Basic Arduino kit used during the practical session.



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This stage shows students that digital systems are reliable only when their data are checked against physical measurements. In a hospital, an incorrect sensor value can affect ventilation control, comfort conditions and maintenance decisions. Therefore, the exercise connects programming, measurement, calibration and critical interpretation of data.

The teaching process is supported by teamwork, international cooperation and repeated assessment. Students work in mixed groups and compare technical solutions from different backgrounds. A final test is used to measure learning progress after the practical activities. In the analysed experience, student performance improved by an average of 36%, from an initial grade of 6.0 to a final grade of 8.1. The highest progress was observed among students with weaker initial results. This suggests that practical and collaborative learning can reduce differences between students and build a more uniform technical understanding.

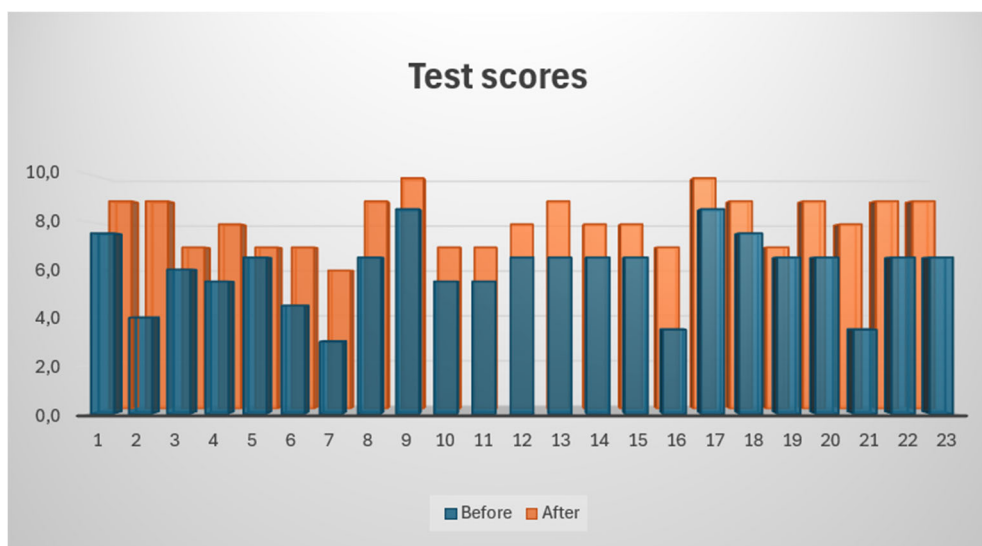


Figure 10.6 Student scores on the test

The same educational strategy is applied to the basic study of atmospheric corrosion. In hospitals, corrosion cannot be treated only as a classical materials

problem. The environment is more complex than in many other buildings. Metallic components may be exposed to humidity, condensation, temperature changes, disinfectants, sterilizing agents, cleaning products, volatile organic compounds and airborne pollutants. In areas such as operating rooms, intensive care units, sterilization units, HVAC rooms and water distribution systems, these factors may act together. Their combined action can damage protective oxide layers, increase the time of wetness and accelerate corrosion. For this reason, corrosion control must be included in hospital maintenance engineering as a preventive activity, rather than only as a corrective action after damage appears.

The objective is to help students and hospital staff identify corrosion risk factors, understand corrosion mechanisms, measure environmental variables and evaluate materials used in hospital infrastructure.

The methodology also connects corrosion with legal and managerial responsibility, because poor maintenance of technical systems can affect patient safety, regulatory compliance and the quality of healthcare services.

The methodology follows several practical stages. Representative hospital zones are selected to cover different environmental conditions, such as patient wards, operating rooms, sterilization units, HVAC rooms and intensive care units. Monitoring equipment is installed to record parameters relevant to corrosion, including temperature, relative humidity, airborne pollutants, particulate matter and other atmospheric variables. In parallel, metallic coupons made from common hospital materials are prepared and tested in the laboratory. The aim is to compare data recorded in the hospital with corrosion measurements performed under controlled or simulated conditions.

A pilot study was carried out at Dr. Negrin University Hospital in Spain, with participants from the University of Las Palmas de Gran Canaria, academic staff



and hospital professionals. The activity included hospital monitoring, theoretical training on corrosion and laboratory experiments on carbon steel, copper and zinc. Environmental monitoring equipment was installed in the hospital and operated for seven days. The recorded data showed an average temperature of 23.8 ± 0.7 °C, relative humidity between 47% and 65%, and an average PM2.5 concentration of $6.7 \mu\text{g}/\text{m}^3$, slightly lower than the outdoor reference value of $7.1 \mu\text{g}/\text{m}^3$. These values show that hospital areas can have specific microclimatic behaviour, influenced by human activity, cleaning operations and technical systems [2].

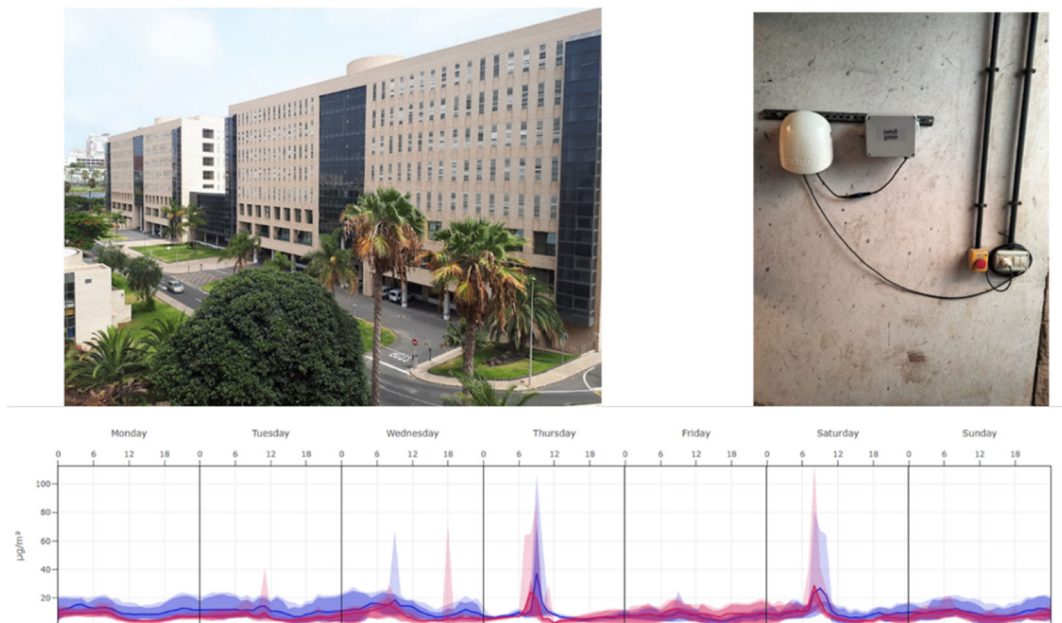


Figure 10.7 Installation in the hospital of environmental monitoring equipment and data recording.

The laboratory results confirmed that the tested materials behave differently under the same conditions. Electrochemical impedance spectroscopy showed that the corrosion process was mainly controlled by charge transfer, which is consistent with uniform corrosion. These results show that simple laboratory methods can provide useful information for understanding the durability of hospital materials. The laboratory tests under simulated environmental

conditions included measurements of the corrosion potential of copper, zinc and carbon steel.

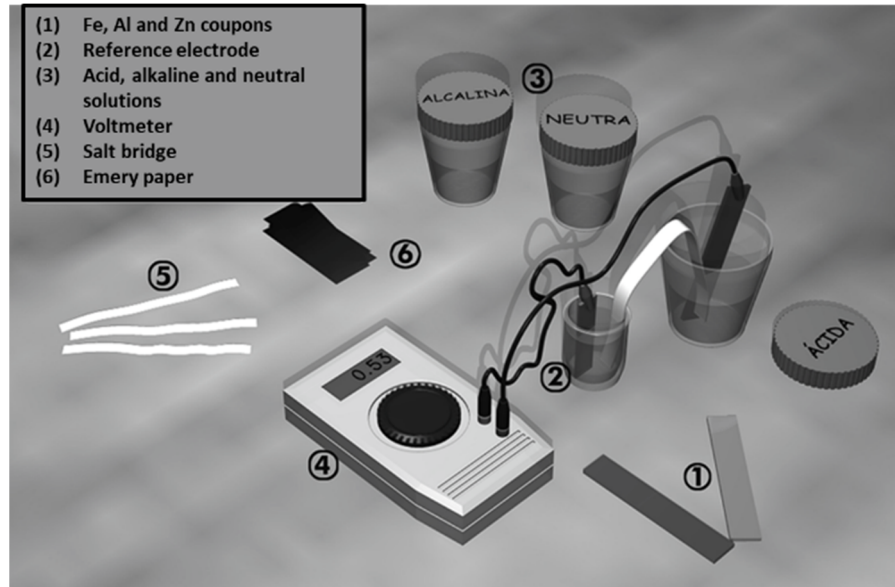


Figure 10.8 Corrosion potential measurements for materials used in healthcare environments.

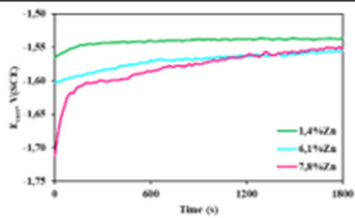
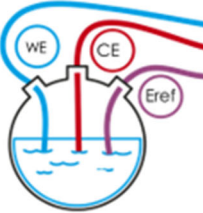
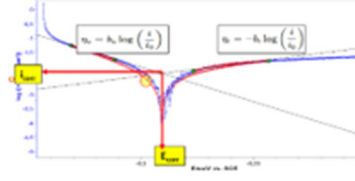
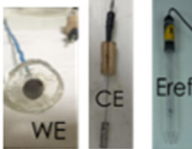
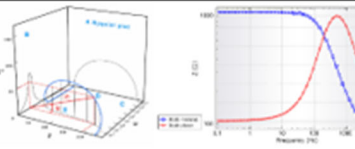
Equipment	Technique	Results
	Open circuit potential (OCP)	
	Linear polarization and corrosion rate	
	Electrochemical impedance spectroscopy (EIS)	

Figure 10.9 Electrochemical measurements of corrosion process parameters.



Students reported that direct exposure to field instrumentation and electrochemical testing improved their understanding of corrosion and their general knowledge of healthcare engineering. Hospital staff considered the measurements useful for preventive maintenance planning. This confirms that corrosion education should be connected with real hospital needs. When students observe how humidity, pollutants, cleaning agents and materials interact in practice, they better understand why preventive maintenance is essential.

This teaching methodology, used as a pilot study and during intensive training sessions, connects engineering knowledge with hospital reality. These examples show that psychrometry is more than a thermodynamic topic and corrosion is more than a materials science topic. Both become practical subjects linked with patient safety, infrastructure reliability, maintenance planning and sustainable hospital operation. The approach can also be adapted to other healthcare engineering topics where students need to understand the relation between technical data, real equipment and responsible decision making.

The full methodology and the case study data are available in the following published documents:



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Smart healthcare engineering: transnational understanding of atmospheric corrosion processes in healthcare facilities

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This work is a result of a pilot study integrated in an international project of collaboration and consists in the developing a comprehensive methodological framework to investigate the multifactorial nature of corrosion in hospitals across Spain, Romania and Turkey. By integrating multidisciplinary perspectives from engineering, materials science and law, the program prepares participants to address corrosion challenges through both technical competence and regulatory awareness. This pilot study conducted at Dr. Negrin Hospital (Spain) validated the methodology, involving 3 hospital professionals and 11 students with 3 academic staff from the University of Las Palmas de Gran Canaria. The study included environmental monitoring, laboratory experiments on electrochemical behavior and protective strategies against corrosion. Representative functional zones (including operating rooms, sterilization units, HVAC systems, intensive care units and patient wards) were instrumented with environmental monitoring devices to record pollutants, temperature, humidity and particulate matter. Metal coupons made of stainless steel, carbon steel, aluminum and zinc were exposed under simulated hospital conditions to assess corrosion rates. Data analysis combined quantitative and qualitative approaches to ensure methodological feasibility and reliability. The results emphasize that corrosion in healthcare settings has significant technical, economic and legal implications. Preventive strategies and continuous monitoring can reduce maintenance costs, enhance patient safety and ensure regulatory compliance. Ultimately, this work underscores the importance of multidisciplinary education and international collaboration in developing sustainable corrosion management practices for modern healthcare infrastructure.

KEYWORDS

collaborative learning, corrosion, educational training, smart healthcare, transnational engineering

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Article

Smart Healthcare Engineering: A Data-Driven Educational Framework for Psychrometric Analysis and Air Handling Systems in Hospitals

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Abstract

This paper presents a data-driven educational framework for teaching psychrometry and air quality control in hospitals, developed within an international pilot project involving universities and hospitals in Spain, Romania, and Turkey. The objective of this pilot study is to examine a multidisciplinary framework that equips engineering students with essential technical skills for managing hospital infrastructure, particularly in critical areas like operating rooms and intensive care units. The methodology integrates theoretical instruction, analogue instruments, and digital technologies, including Arduino-based sensing and AI tools, to facilitate data interpretation and critical thinking. By bridging manual measurements with digital monitoring, the framework aims to equalize proficiency among students from diverse engineering backgrounds. Quantitative results from 23 participants provide preliminary evidence of academic growth, consistent with the hypothesis that this integrated approach may facilitate conceptual mastery. This work offers preliminary insights into the advancement of data-driven modelling in engineering education, emphasizing the significance of multidisciplinary training and international collaboration in preparing future professionals for the oversight, operational management, and maintenance of modern healthcare facilities.

Keywords: psychrometry; indoor air quality; air handling units; engineering education; Arduino; pre-test/post-test assessment; healthcare HVAC; active learning

[2] Sánchez-Morales, C. J., & Mirza-Rosca, J. C. (2026). Smart Healthcare Engineering: A Data-Driven Educational Framework for Psychrometric Analysis and Air Handling Systems in Hospitals. *Technologies*, 14(8), 500. <https://doi.org/10.3390/technologies14080500>

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10.5 After the Project Activities

The handbook gives continuity to the training activities. A mobility programme has a limited duration, but the learning material remains available for students, teachers and hospital staff.

The project showed that healthcare engineering is a field where technical competence must be combined with responsibility. Innovation is useful only when it is introduced with attention to safety, maintenance, cost, cybersecurity and the real needs of healthcare facilities. Smart systems, artificial intelligence, IoT, monitoring tools and digital platforms can support hospitals, but they must be managed by people who understand both technology and healthcare constraints. This handbook is therefore more than a collection of chapters. It is a project that can support future teaching activities. It can be used in lectures, seminars, workshops, intensive training programmes and self-study. It can also help hospitals and universities continue the cooperation started during the project.

The final message is simple. **Healthcare engineering gives engineering students a new professional direction. It also gives hospitals access to future specialists who understand technical systems, patient safety and the responsibility of working in a healthcare environment.**



Declaration on the use of AI-assisted tools in the writing process.

AI-assisted tools were used during the preparation of this handbook only to support language editing, formatting and the improvement of tables and figures. These tools were not used to create scientific content, technical conclusions, interpretations or opinions presented in the handbook.

All scientific information, technical explanations, project descriptions and conclusions were provided, checked and approved by the authors. The authors take full responsibility for the accuracy, integrity and final form of the content included in this handbook.