Clinical Imaging Diagnosis

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Data-Driven Techniques, Analytical Frameworks and Practical Applications

Edited by

Parita Oza, Smita Agrawal,
Sudeep Tanwar and
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CHAPTER 1

IMAGING MODALITIES IN CLINICAL PRACTICE

MANNA DEBNATH[1*] AND SANTOSH OJHA[2]
[1,2]ASSISTANT PROFESSOR, DEPARTMENT OF MEDICAL IMAGING TECHNOLOGY, BAPUBHAI DESAIBHAI PATEL INSTITUTE OF PARAMEDICAL SCIENCES, CHAROTAR UNIVERSITY OF SCIENCE AND TECHNOLOGY, GUJARAT, INDIA

Abstract

Medical imaging modalities are crucial to diagnosing, planning, and monitoring many medical conditions in modern clinical practice. X-ray imaging, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography (USG), interventional radiology, nuclear medicine, and hybrid imaging are the most common imaging modalities used in healthcare settings. X-ray Imaging is the foundation of medical imaging. The most common applications of X-rays are for diagnosing chest and bone fractures, as well as for fluoroscopy, which allows real-time monitoring of the individual's body. Although CT is also based on X-rays, it creates three-dimensional images of the body part; However, MRI uses non-ionizing radiation to acquire images, unlike CT. While it is used for soft tissue and musculoskeletal imaging, CT has the advantages of assessing tumor detection and trauma assessment. USG is frequently employed as the imaging technique of choice for image-guided procedures like biopsy and fine needle aspiration cytology. Interventional Radiology employs single and bi-plane C-arms mounted with an image intensifier and flat panel detector. Nuclear medicine and hybrid imaging have applications for cancer stage and myocardial perfusion imaging. Every single day, modern medicine is constantly developing new modalities and technologies to provide more tools for disease detection and treatment.

Keywords: X-ray, Computed Tomography, Magnetic Resonance Imaging, Ultrasonography, Interventional Radiology, Hybrid Imaging.

1 Introduction to Imaging Modalities

Imaging modalities are one of the most crucial tools used by modern medicine, to visualize the human body's internal structures and functions using non-invasive or minimally invasive techniques. These imaging modalities can be projection radiography or emission radiography in nature. The primary imaging modalities include X-ray Imaging, which utilizes ionizing radiation to acquire images using different technologies and techniques such as General Radiography, Mammography, Fluoroscopy, Dual-energy X-ray absorptiometry (DEXA), Computed Tomography (CT). Advanced imaging modalities such as Magnetic Resonance Imaging (MRI) and Ultrasonography use non-ionizing radiation to acquire images of the human body.

Apart from these, nuclear medicine relies on the radiations emitted by the radioisotopes injected into the human body to generate the images and advanced techniques such as Hybrid imaging and interventional radiology techniques. These modalities provide specific solutions for medical specialties such as Cardiology, Neurology, Oncology, Orthopaedics, Gastroenterology, Obstetrics, Gynaecology etc. These imaging modalities are different according to the method to provide the medical images and working principle varies with various advantages and limitations. These modalities ultimately acquire the medical images called radiographs. Once acquired, these medical images from each of the modalities can be introduced to a variety of processing techniques, which further enhance these medical images thereby increasing the applicability of imaging modalities. This chapter summarizes the basic introduction to different imaging modalities used by modern medicine for the diagnosis of various conditions of patients.

2 X-ray Imaging

On November 8, 1895, German physicist Sir Wilhelm Conrad Roentgen discovered X-rays. Immediately after the discovery, X-rays were used to investigate human bones and other organs, laying the foundation for radiology. X-rays are ionizing electromagnetic radiations characterized by wavelengths in the range of 0.01 nm to 10 nm and energy spanning from 100 eV to 100 keV. The energy of X-ray photons is sufficient to release electrons from the intended atoms or molecules, hence exhibiting ionizing properties. X-ray photons upon interaction with the patient's body undergo absorption, transmission, or scattering. The degree of X-ray attenuation is dependent on the density of various materials. Generally, dense materials like bones absorb a greater amount of X-ray energy compared to less dense materials like soft tissues or fat. The tissue-specific absorption of X-ray photons causes the variable energy of X-ray photons transmitted through patient's body, which is captured by the photosensitive detectors and produces variable densities in the radiograph. The different tissues present in the patient's body absorb roughly two-thirds energy of the X-ray photons produced by the X-ray tubes. Approximately one-third of the X-ray photons are scattered, with less than 1% transmitted to the detectors to produce a radiograph (Mowery and Singh 2024).

Most of the modalities in medical imaging rely on X-ray attenuation and tissue-specific absorption to produce a radiograph. In this chapter the basic principles and working of diagnostic imaging equipment will be explained.

3 X-ray production

The production of X-rays involves bombarding a matter with energized electrons inside the vacuum tube. Modern imaging modalities use these vacuum tubes, commonly called X-ray tubes made up of Pyrex or borosilicate glass. These X-ray tubes have two electrodes made up of Tungsten (W) i.e., a spiral filament acting as the cathode (negatively charged electrode), which provides the free electrons, and a target anode (positively charged electrode) for bombarding the electrons. Tungsten has a high melting point (3370ºC) and atomic number (Z=74) making it ideal for manufacturing the cathode filament and anode block of the X-ray tubes. The tungsten filament is enclosed by a focusing cup with a negative potential, which concentrates electrons into a beam and directs them toward the target anode. The X-ray generator is responsible for providing the required electrical energy to tube assembly for X-ray production. The X-ray generator consists of transformers and rectifiers, with a separate control mechanism that adjusts the potential difference across the electrodes and the current in the tube, determining the contrast and brightness of a radiograph (Curry, Dowdey, and Murry 1990).

High-frequency generators are used in new radiographic equipment. X-ray circuit consists of two major parts: A high voltage circuit (High-kV circuit) and a low-voltage circuit (filament circuit).

The low-voltage filament circuit contains a step-down transformer connected to the tungsten filament in the X-ray tube. This low-voltage circuit (10 volts) provides current (3-5 Ampere) to the filament, which in turn will heat the coiled filament and release the electrons, called thermal electrons, and the whole process is called thermionic emission. The high kV circuit consists of an autotransformer, timer selection, kV meter, mA meter, step-up transformers, and a rectifier assembly. The function of a high-kV circuit is to provide adequate kinetic energy to the electrons by maintaining a high potential difference (40-150 kV) between the electrodes i.e., cathode and anode. The autotransformer is the kVp selector; the voltage across the circuit is increased by the step-up transformer, which is essential for the X-ray production, and finally rectifier assembly converts the Alternating current into Direct current providing the constant potential across the electrodes (Harisinghani, Chen, and Weissleder 2018).

When the exposure begins, current flows through the filament, and thermal electrons are released generating an electron cloud around the tungsten filament. A High voltage is applied between the cathode and anode, causing the electrons to accelerate towards the positively charged anode, thereby briefly completing the high kV circuit. These electrons with high kinetic energy strike the target atom, losing their energy through processes such as excitation, ionization, and radiation The excitation produces heat energy (99%), the ionization produces the characteristic x-rays (0.1%) and through the process of radiation, bremsstrahlung x-rays (0.9%) are produced (McCollough 1997; Harisinghani, Chen, and Weissleder 2018).

The characteristic radiations are produced when a sufficiently energized thermal electron from the cathode (energy exceeding the target electron's binding energy) collides with and ejects these inner shell electrons, creating a vacancy in the shell. The electron from the outer shell fills this vacancy, and the extra energy is transformed into electromagnetic radiation known as X-rays or radiation. The energy of the emitted X-rays is equals the difference between the binding energy of the destination shell and the binding energy of the origination shell (McCollough 1997). The energy levels of characteristic radiations vary because the difference in binding energy of electrons across all shells are constant for each element.
Bremsstrahlung radiations are also referred to as braking radiation. The bremsstrahlung radiations are produced when energized thermal electrons are directed towards the target gets deaccelerated as they are attracted towards the positively charged nucleus. This loss of kinetic energy by the accelerated electrons is released in form of bremsstrahlung radiation. Most interactions between thermal electrons and targets produce bremsstrahlung radiations (McCollough 1997).

4 General Radiography Unit

General radiography or projection radiography, utilizes x-rays to generate two-dimensional radiographs of the patient's body. The modality utilizes X-ray tubes (as explained earlier) as a radiation source and different types of detectors that absorb the residual attenuated X-rays coming from the patient's body, ultimately providing various densities and contrast in the radiograph. Creating radiographs using modern equipment is essentially the same as with traditional methods; the only difference is the detectors used to capture and process the images.

4.1 Film-Screen Radiography

These general radiology devices initially processed and captured images using films as the detector for over a century. A lightproof cassette houses the light-sensitive films typically sandwiched between the intensifying screens. These intensifying screens convert the X-ray photons into light photons during the exposure, which affects the film's sensitive layer (emulsion) and forms a latent image. The use of an intensifying screen would expose the films more effectively than if, they were directly exposed to X-rays, and would lower the patient's absorbed dose. Once the exposure had been done, these films were processed in a special room called a darkroom using different chemicals; these chemicals would convert the captured latent image into the visible image on a radiograph (Curry, Dowdey, and Murry 1990). The exposure factors predominantly control the film density and contrast in the case of conventional radiography. The product of milliampere and exposure time (mAs) affects the density of the films, whereas the kilovoltage peak (kVp) controls the radiographic contrast.

Radiography has evolved ever since the discovery of X-ray from the use of conventional radiography utilizing the film-screen combination to recent imaging techniques as digital radiography where digital radiographs are acquired by using modern detectors.

4.2 Computed Radiography (CR)

Computed radiography (CR) was the first method of digital radiography to be introduced. CR system used the Photostimulable phosphor (PSP) plates to capture the incident X-ray photons producing a latent image, which could be further processed using the readout laser. These plates were called CR plates and had a thin coating of Europium-activated Barium Fluorohalide [BaFX: Eu^{2+}] (Schaefer-Prokop et al. 2009). The CR cassette is used the same as the conventional cassette during the exposure and the exposed cassette is processed using the CR reader.

4.3 Direct Digital Radiography (DDR)

Another type of digital radiography is Direct digital radiography is another type of digital radiography system, in which the radiographs are captured directly by the detectors without any intermediate processing steps such as cassette readout in computed radiography. The Thin-film transistors (TFT) utilized in the DDR flat panel detectors are coated with a thin layer of amorphous silicon and an X-ray absorption medium to transform X-ray photons into electrical signals. Depending on the types of medium used, DDR detectors are classified as:

(a) Indirect conversion TFT detectors: The X-ray photons are converted into light photons by these detectors using scintillation crystals (Caesium Iodide), and these light photons are further converted into a charge and a digital image by the Si-photodiode. Indirect conversion detectors are commonly used for routine radiography and real-time imaging as well.

(b) Direct conversion TFT detectors: These detectors contain a deposition of amorphous selenium on the TFT array, which directly converts the absorbed X-ray photons into charge. Direct conversion detectors are used commonly in the mammography unit.

4.4 Clinical Applications

Skeletal Imaging is one of the crucial applications of general radiography, primarily used for the diagnosis of fractures and dislocations, and different bone pathology such as osteoporosis, osteoarthritis, etc. Thoracic imaging, including chest X-rays, is essential for monitoring heart problems and implants as well as for the diagnosis and follow-up of disorders such as lung cancer, pneumonia, pleural effusions, and chronic obstructive pulmonary disease (COPD). On the other hand, urological disorders, abdominal mass evaluation, and various gastrointestinal tract ailments all rely upon abdominal imaging for diagnosis. Dental imaging is a further specialized use of general radiography that not only evaluates abnormalities in the teeth and jaw but also is essential for organizing and overseeing orthodontic treatments. Paediatric Imaging is crucial to monitor bone growth and development and for diagnosing congenital abnormalities. Emergency and Trauma Imaging is essential for promptly detecting acute injuries like fractures, dislocations, and internal injuries. Routine health screening: General radiography plays a crucial role during the health check-up to diagnose the signs of chronic diseases, ensuring timely intervention and management. General radiography, or X-ray, is essential for diagnosing a variety of diseases, especially in emergency and routine clinical settings. It is particularly effective at detecting skeletal anomalies such fractures, joint dislocations, and bone infections (osteomyelitis) (Baker, Hillen, and Demertzis 2014). Chest imaging is essential for diagnosing pneumonia, chronic obstructive pulmonary disease (COPD), TB, and lung cancer. It is also beneficial for abdominal imaging, which can detect intestinal obstruction or perforation, foreign materials, and kidney stones (Wallace et al. 2009; Boermeester et al. 2012). Radiography is a rapid, cost-effective, and widely available imaging technique, making it the first choice in many clinical circumstances. Although it is less comprehensive compared to modern imaging modalities like CT or MRI.

4.5 Advantages of Digital radiography over Film-screen radiography

Digital radiography has a higher radiation dosage efficiency than film-screen radiography. It has a high dynamic range in greyscale, allowing the CR system to capture and display a wide range of X-ray intensity. Additionally, digital radiography allows for improved image processing, which aids in the diagnosis of many illnesses. The integration of the Radiology Information System (RIS) with the Hospital Information System (HIS) for radiograph processing improves workflow dramatically. Furthermore, digital radiography enables the adoption of Teleradiology in real time, minimising waiting times. Digital radiography allows for efficient digital image storage and retrieval via PACS.

5 Mammography

Mammography is a specific type of X-ray imaging that examines breast tissue using low-energy radiation, mainly employed for the early identification of breast cancer and various other conditions. Since the fatty and fibro-glandular tissue constitutes the majority of the breast tissue, the mammography unit uses lower energy X-rays compared to the conventional radiography unit. A typical mammography unit operates between 20 – 40 kVp, thus providing us the better image contrast, which is crucial for the examination of the breast tissue (Mann 2022; Ebrahimi 2019). The mammography unit uses the target anode made up of Molybdenum (Mb) and Rhodium (Rd) for the emission of low-energy X-rays. The filter, which is usually composed of the same material as the target anode, is employed to reduce undesirable high- and low-energy radiations (Bushong 1980). Initially, film-screen combinations were used for mammography, until recently, after digital radiography techniques were introduced; digital detectors have now become popular. In addition to the tube assembly, high-frequency generator, and imaging detectors, the mammography unit utilizes a compression device made up of a radiolucent plate, parallel to the detector surface to compress the breast tissue before exposure. Automatic Exposure Control (AEC) is used in mammography units to improve image quality while reducing the patient's radiation exposure.

5.1 Clinical Applications

Screening Mammography is a routine mammography that has to be performed (every 2 years) for asymptomatic women after the age of 35-40 years for the early detection of cancer. Routine screening mammography consists of four views – craniocaudal and Medio lateral oblique view for each breast. Another application is Diagnostic mammography conducted for patients showing clinical signs like a palpable mass or nipple discharge, among other symptoms. In addition to the standard views, the clinicians conduct a comprehensive clinical assessment and, if necessary, perform additional views or procedures. Application like Digital Breast Tomosynthesis (DBT) is an advancement in mammography techniques where a three-dimensional image of breast tissue is acquired using a moving X-ray source utilizing digital detectors. These acquired images can be further post-processed and reconstructed into different planes. DBT is particularly advantageous for the diagnosis of dense breasts and improves the cancer detection rate (Sardanelli et al. 2017). Moreover, Mammograms play a crucial role in monitoring patients with known lesions or abnormalities and patients after treatment of breast cancer to detect early recurrence.

Mammography is the most effective method for early identification of breast cancer, especially in asymptomatic women. It can detect breast tumours before they become palpable, hence boosting treatment outcomes and survival rates. Mammograms reveal tiny calcifications, lumps, and morphological abnormalities in breast tissue, which may indicate malignancy. The method is particularly effective at detecting ductal carcinoma in situ (DCIS), an early stage of breast cancer. Diagnostic mammography, on the other hand, is utilised for individuals who have symptoms such as lumps or nipple discharge and produces detailed images of the breast tissue (Shetty 2021). Advances in digital mammography have increased detection rates, particularly in women with thick breast tissue.

5.2 Advantages

Mammography is considered as the gold standard for breast cancer screening because of its superior soft tissue characterisation. It enables early diagnosis of breast lesions or diseases, resulting in more effective treatment options. Mammography equipment is commonly available in many healthcare settings. Any abnormal mammography results may necessitate additional testing, such as MRI or ultrasonography, or therapies such as biopsy, which will aid in the diagnosis of the illness.

5.3 Disadvantages

Mammography, while extremely effective, might result in overdiagnosis and overtreatment due to its sensitivity in identifying even minute abnormalities that may not be clinically visible during a woman's lifetime. This may lead to unneeded therapy. Furthermore, false positive results can occur, particularly in women with thick breasts, causing worry and extra radiation exposure from subsequent mammograms. Although the radiation dose in mammography is low (3.0 mGy per projection), there is still a tiny risk of radiation harm. However, the benefits of mammography for early diagnosis far outweigh the slight radiation risk (Grimm et al. 2022).

6 Dual-energy X-ray absorptiometry (DEXA)

Dual-energy X-ray absorptiometry, commonly abbreviated as DEXA is a low-dose X-ray imaging technique that assesses the bone mineral content (g) and area of bone (cm^2). It allows for the estimation of bone mineral density (BMD) (g/cm^2), as well as body composition. It involves the emission of two different X-ray photon energies, which are absorbed at different rates by bone and soft tissue. DXA can accurately estimate bone mineral density by measuring differential absorption (Di Iorgi et al. 2018).

A DEXA utilizes a dual-energy X-ray source, typically 70 and 140 kV with a specialized filter and detector system. The T-score and Z-score are the most important measures for assessing bone density. The Z-score contrasts the patient's BMD with that of healthy people of the same age, gender, and ethicality; the T-score compares the patient's BMD to that of a healthy young adult of the same sex, expressed in standard deviation (Blake and Fogelman 2007). T-score and Z-score together provide clinicians with critical information for assessing fracture risk, guiding treatment strategies, and monitoring bone health over time, resulting in proactive management of musculoskeletal conditions across various demographic groups.

6.1 Clinical Applications

Bone Mineral Density (BMD) is used to diagnose bone diseases such osteoporosis and osteopenia. The T-scores of the patients are compared to the usual reference level to measure their bone health. The WHO's Fracture Risk Assessment Tool (FRAX) is used to estimate the risk of osteoporosis or fractures over a ten-year period (Krugh and Langaker 2024). A DEXA scan also allows for body composition analysis, which provides precise assessments of body fat, muscle mass, and bone mass. This assists clinicians in identifying and treating problems such as obesity and sarcopenia (Shepherd et al. 2017). Furthermore, monitoring and managing bone health is critical for cancer patients and those with endocrine diseases such hyperparathyroidism or hyperthyroidism.

DEXA is primarily used to assess bone mineral density (BMD), making it the gold standard for diagnosing osteoporosis. This is especially relevant for postmenopausal women and the elderly, who are more susceptible to osteoporosis-related fractures. DEXA scans detect early bone loss accurately, enabling for earlier intervention to avoid fractures. In addition to osteoporosis, DEXA can detect osteopenia, a condition of low bone density that occurs before osteoporosis. The scan is also used to determine body composition, which provides information on fat and muscle distribution that might be useful in metabolic diseases and obesity (Dalili et al. 2020).

6.2 Advantages

DEXA provides quick data acquisition with a low radiation exposure. It performs thorough body assessments, including bone density and body composition measurements like lean body mass and fat distribution. DEXA is also useful for predicting which patients are more susceptible to fracture.

6.3 Disadvantages

DEXA has some drawbacks, including a lack of consistency in soft tissue and bone measurements. Its regional assessment of body composition is inferior to more modern techniques. DEXA is likewise relatively expensive and in limited availability. Additionally, if the patient is not properly positioned or if an artefact is present, the results may be falsely positive.

7 Computed Tomography (CT)

Computed Tomography (CT) scan is a high-tech imaging modality that generates cross-sectional images of the patient's body using X-rays and advanced computing. The first CT scan was developed by South African scientist Allan Cormack and British engineer Sir Godfrey Hounsfield. The CT scan has revolutionized modern medicine by its ability to provide precise and detailed images of the patient's body. CT scanner has a gantry with an X-ray tube, a high-frequency generator as the source of energy, a detector assembly to capture the attenuated X-ray photon, and a processing system. The CT scanner uses different advanced types of detectors i.e., Scintillation detectors, Gas ionization detectors, or flat panel detectors. The patient lies on a motorized CT couch that moves across the gantry during a scan. The detector assembly and X-ray tube spin continuously around the patient, producing X-rays from various angles. The detector assembly present on the gantry captures these attenuated X-rays (Fig. 1-1). The intensity of these attenuated X-rays provides the attenuation property of various tissues, which are then expressed in terms of Hounsfield unit (HU) by reconstruction algorithms, finally producing the cross-sectional images.

These acquired cross-sectional images can be reconstructed in different planes into axial, coronal, sagittal, or oblique, and further be post-processed using special algorithms as per the user's requirement. The post-processing techniques include Volume Rendering (VR), Surface Rendering, Maximum, and Minimum Intensity Projection, etc. Using these algorithms, the CT images are further enhanced minimizing the artifacts (Seeram 2015).

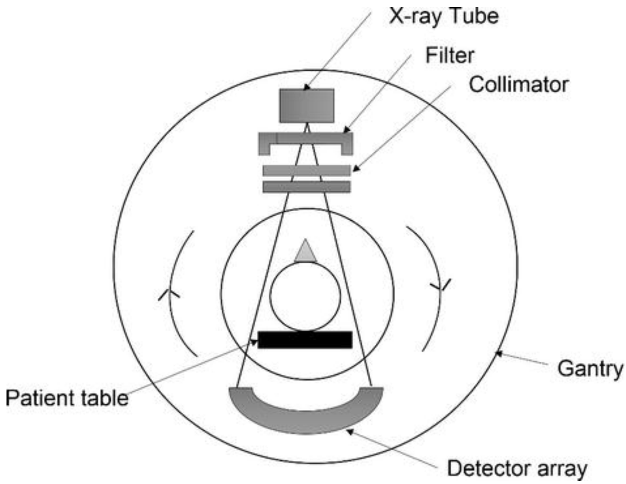

Fig. 1-1 Illustrative diagram showing the working principle of CT scanner (R. Gharieb 2022)

7.1 Clinical Applications

CT imaging is frequently employed in many disciplines of medicine because to its versatility and accuracy. CT is considered the first-line imaging modality in emergency situations, particularly for neurological disorders, acute head injuries, fractures, strokes, and cerebral haemorrhages. Cardiac imaging has evolved with the introduction of Multi-Slice CT scanners (MSCT) and Electron Beam Computed Tomography (EBCT), allowing for complete examinations of coronary artery calcifications and pulmonary veins while maintaining contrast and spatial resolution. CT is an important tool for diagnosing abdominal and thoracic illnesses, and it is utilised for both contrast and CT angiographic examinations. Iodinated contrast media are administered intravenously during CT angiography, and Helical CT is used to scan the area of interest and view fully opacified arteries. CT endoscopy generates non-invasive three-dimensional images of the colon's interior by using volume data from the CT scanner to build a virtual reality environment. CT scans play a crucial role in oncologic research for cancer diagnosis, staging, follow-up, and therapy planning and monitoring. Additionally, CT is widely utilised in operations like CT-guided biopsies, where it aids in precisely guiding the needle to the location, and in the successful drainage of abscess cavities by guiding drainage catheters into them.

Computed Tomography (CT) is particularly useful in detecting malignancies such as lung, liver, and pancreatic tumours, as well as metastases. CT scans are crucial in trauma care because they enable for the immediate examination of interior injuries such as organ lacerations, haemorrhages, and fractures that would otherwise be invisible on traditional X-rays. CT angiography is used in cardiovascular imaging to diagnose coronary artery disease, pulmonary embolisms, and aortic aneurysms. CT is also useful in diagnosing neurological diseases such as stroke, brain tumours, and traumatic brain injuries. It is used in abdominal imaging to help diagnose appendicitis, diverticulitis, and other gastrointestinal diseases (Schena et al. 2015).

7.2 Advantages

The excellent spatial resolution provided by CT imaging makes it possible to see inside structures in great detail. Because of its short acquisition time, it is perfect for emergency situations where prompt diagnosis is essential. Furthermore, CT is a non-invasive technique that produces sharp images of inside structures without requiring surgery.

7.3 Disadvantages

The radiation exposure from a CT scan is higher than that from other imaging modalities. In contrast-enhanced CT, there is a chance of developing a contrast allergy. Compared to MRI, it lacks superior soft tissue differentiation (contrast resolution). The procedure in CT is expensive as compared to X-ray.

8 Magnetic Resonance Imaging

MRI works on the spinning movement of certain nuclei within the human body. MR active nuclei are defined by their inclination to line up their axis of rotation with an applied magnetic field. Protium, an isotope of the hydrogen nucleus, is employed as an MR active nucleus in MRI. MRI scanners exist in a variety of field strengths, ranging from 0.5 to 3.0 Tesla. The radio-frequency pulse causing the hydrogen nuclei to resonate is determined by both the hydrogen and the magnetic field strength. In the transverse plane, resonance produces in-phase magnetization at the Larmor frequency. Coherent (in-phase) magnetization produces an MR signal. Coherent transverse magnetization causes magnetic field variations inside the coil, resulting in an electrical voltage (Westbrook and Talbot 2018;

Berger 2002). The components of the MRI system include a magnet for nuclear synchronization, a radio-frequency source for RF excitation, a magnetic field gradient used for spatial encoding and gradient echo, a computer system for image creation and user interface design and an image processor that converts signals into visuals (Fig. 1-2).

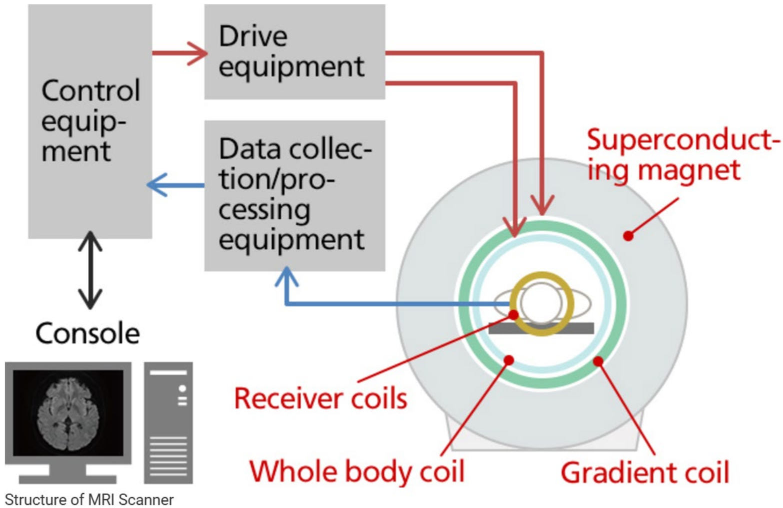

Fig. 1-2 Instrumentation of MRI scanner (Image courtesy: Canon Inc.)

8.1 Clinical Applications

Magnetic resonance imaging (MRI) is a non-invasive technology that generates comprehensive images of the body's different organs and tissues. It is commonly used in medical diagnosis and research. MRI has numerous clinical applications in an extensive spectrum of clinical fields.

The clinical applications of MRI include functional MRI, one of the best choices for brain mapping and dementia, providing valuable insights into brain activity. White matter tract abnormalities and other diseases can be diagnosed with the help of diffusion tensor imaging and diffusion kurtosis imaging. A non-invasive method for measuring tissue stiffness, MRI elastography yields valuable information for a range of disorders. Techniques for mapping articular cartilage, including T2 mapping, T2* mapping, and T1 mapping, are essential for assessing the human body's articular cartilage. When evaluating spinal problems, bone and soft tissue tumors, and muscle-related disease, MRI is the preferred method. A variety of brain tumors, stroke, multiple sclerosis, aneurysms, vascular malformations, and epilepsy can also be detected by MRI. MRI is best suitable for fetal imaging because of its non-ionizing radiation.

Magnetic Resonance Imaging (MRI) is highly effective in diagnosing neurological, musculoskeletal, and oncological diseases. MRI can identify tumors, strokes, multiple sclerosis, and degenerative disorders such as Alzheimer's. Its excellent soft tissue contrast makes it appropriate for spinal cord injuries, herniated discs, and joint diseases such meniscus tears or ligament damage. MRI is also commonly used in oncology to detect soft tissue tumors, liver masses, and metastases. In cardiovascular imaging, MRI can detect congenital heart disease, cardiomyopathies, and myocardial infarctions (Armstrong and Keevil 1991).

8.2 Advantages of MRI

MRI is a safe imaging method for patients because it is noninvasive and uses non-ionizing radiation. Because it produces high-resolution pictures that are essential for a precise diagnosis, it is the recommended modality for imaging soft tissues. Furthermore, multi-planar imaging produced by MRI enables thorough views of the region of interest. Neurology, cardiology, and other specialties can benefit from MRI's versatility, which makes it a vital tool in many medical specialties.

8.3 Disadvantages of MRI

One of MRI's drawbacks is its high price, which makes it costly to purchase. Furthermore, MRI takes a lot longer to acquire data than CT and other imaging modalities. Because MRI is expensive and requires infrastructure, it might not be offered in remote healthcare facilities. Additionally, individuals with potentially hazardous equipment, such as aneurysm clips and pacemakers that are not compatible with MR, should not use it. Because of the enclosed design of the scanner, MRI is not recommended for claustrophobic patients. Additionally, MRI is extremely sensitive to patient movements, which may compromise image quality.

9 Ultrasonography

Ultrasonography (USG) is an imaging technique that uses high-frequency ultrasound waves to create an image of the patient's inner body structures. Ultrasound waves are longitudinal types of mechanical waves that are propagated by creating a disturbance in the medium. The energy of the ultrasound waves is transmitted by collisions with adjacent particles.

Ultrasound waves are produced by the vibration of the piezoelectric crystals housed inside the transducer assembly of the ultrasonography unit. When an AC is supplied to these crystals, due to the constant change in the polarity of the AC, the crystals vibrate violently and Ultrasound waves are produced. The produced ultrasound waves are directed toward the patient's body. These echoes are reflected, either refracted, attenuated, or transmitted through the different tissues of the patient. These reflected echoes when reached by the sonography transducer, build mechanical force on the surface of crystals that produces the electrical signal, which is later, converted into the digital image. The ultrasound machine operates in three basic modes – Amplitude-Mode, Brightness-Mode, and Motion-Mode depending upon the requirement of the user (Powles et al. 2018).

9.1 Clinical Application

Doppler scan is one of the major applications of ultrasonography, allowing the visualization of blood vessels and providing information about the velocity and direction of blood flow. Atherosclerosis, deep vein thrombosis, aneurysms, peripheral artery disease, and arteriovenous malformations are among the blood vessel conditions that are frequently diagnosed by Doppler scanning. Ultrasonography is used in obstetrics and gynaecology to measure the amount of amniotic fluid, evaluate foetal growth, and monitor the course of pregnancy. Additionally, it is used to help in the diagnosis of abdominal pain, distension, bleeding, and mass evaluation (Recker et al. 2021). Echocardiography is a specialised technology that uses ultrasonic waves to study how the heart works. It provides both 2D and 3D visualisation of the structure and function of the heart. Ultrasonography is one of the most commonly used studies in abdominal imaging, and it is essential for assessing and describing tissue and lesions in a variety of organ-specific illnesses as well as urological disorders. Ultrasonography is also a crucial tool in emergency medicine for quick diagnosis and decision-making; in emergency situations, procedures like Focused Assessment with Sonography for Trauma (FAST) and point-of-care ultrasound (PCOUS) are frequently employed.

Ultrasonography is extremely beneficial for monitoring foetal development and detecting ectopic pregnancies or foetal abnormalities. Gallstones, conditions of the liver, and kidney stones are all easily detected using abdominal imaging (Lyons 1982). Ultrasonography is also used extensively in cardiac imaging (echocardiography) to evaluate heart function and detect valvular heart disease and pericardial effusions. Doppler ultrasound is used to assess blood flow in arteries and veins, allowing doctors to diagnose problems such as deep vein thrombosis (DVT) and peripheral artery disease. Its real-time imaging capacity is extremely useful for guiding needle biopsies, catheter insertion, and draining fluid collections.

9.2 Advantages

Ultrasonography is a safer imaging method because it doesn't use any ionising radiation, especially for children and pregnant women. In addition to helping guide biopsy needles, fluid aspirations, and other minimally invasive treatments, it offers real-time imaging of organs, blood flow, and the foetus' heartbeat. Ultrasonography is widely utilised as a cost-effective imaging technology for a variety of applications, such as musculoskeletal imaging, cardiology, urology, and obstetrics.

9.3 Disadvantages

The operator's expertise and experience greatly affect the quality and accuracy of examination outcomes. There are limitations when examining deeper structures, structures behind bones, or gas-filled organs, which may not be clearly visible. Furthermore, compared to other diagnostic techniques like magnetic resonance imaging (MRI) or computed tomography (CT) scans, ultrasonography has a smaller field of view. Furthermore, it requires significant training and experience to effectively acquire and interpret USG images.

10 Interventional Radiology

Interventional radiology is a medical specialty that uses real-time imaging guidance during treatments. Angiography is a radiological procedure for visualizing blood vessels following an intravenous infusion of contrast material. Angiography procedures are used to detect functional morphological vascular changes. Shortly after Wilhelm Conrad Rontgen discovered the X-ray, the first angiography was carried out. In 1896, E. Haschek and O. Lindenthal performed the first X-ray angiography with an amputated hand, utilizing bismuth, lead, and barium salts as a contrast medium (Feezor et al. 2011). In Interventional radiology, there are two types of angiography: conventional subtraction angiography and digital subtraction angiography.

Conventional subtraction angiography: Conventional subtraction technique requires a film without contrast i.e. initial radiograph and another film with contrast i.e. angiographic film. The position of the patient must be identical in both positions. Once the radiographs are taken subtraction is performed photographically.

Digital subtraction angiography: Digital subtraction angiography is an electronic subtraction method for showing contrast-filled vessels without interfering with background. Image intensifiers and other data acquisition facilities are used to obtain rapid digital information as the contrast passes through the vessels, subtracting bones and soft tissues and leaving behind only the contrast-filled blood vessels.

Digital subtraction angiography has some advantages over conventional angiography which include less traumatic compared to conventional angiography, safe procedure, less amount of contrast medium is required, small catheter, reduced procedure time, and immediate visualization of the image in the monitor i.e. cine viewing. The limitations of digital subtraction angiography are motion artifacts, decreased spatial resolution compared to conventional angiography and IV DSA causes superimposition of vessels however it can be overcome using tube angulations (Magalhães 2001).

Further classification of Interventional Radiology includes (Fig. 1-3):

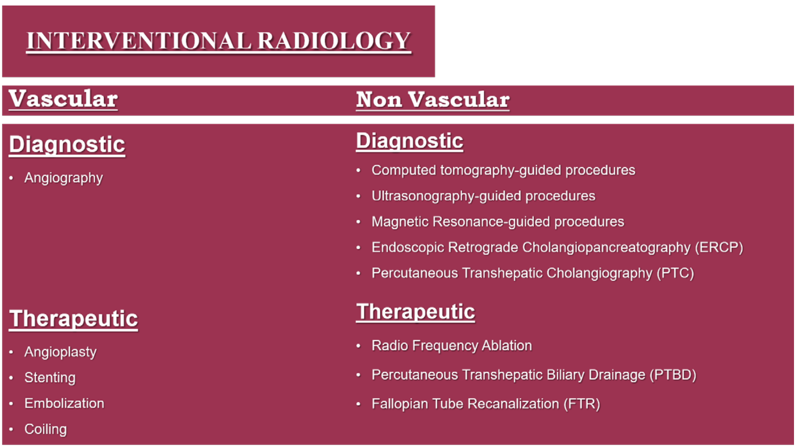

Fig. 1-3 The above figure shows the vascular and non-vascular classification of Interventional Radiology

11 Instrumentation

These days, single- and biplane C-arms are made expressly to hold the complex instruments and accessories needed to carry out interventional treatments including angiography. An angiographic table, generators, X-ray tubes, image intensifiers, cathode-ray tubes, and lighting are the main pieces of equipment in the interventional radiology room.

High Voltage Generators: The three-phase generator is used in interventional radiology. It can provide repeatable exposure i.e. 8 exposures per second, which ultimately reduces the exposure time to 0.001s.

X-ray Tubes: Anode X-ray tube revolving at a high speed is employed. The best features of the structure are produced with a tiny 0.3 mm focal point.

11.1 Image Intensifier

An image intensifier may transform a low-intensity X-ray into a visible light output, allowing for brighter picture amplification. The following are the different parts of the Image Intensifier: Input phosphor, Photocathode, evacuated vacuum tube, electron optics lens, and output phosphor.

Input phosphor: The image intensifier's input phosphor is made of sodium (Na) activated caesium iodide (CsI), which is placed on an aluminum (Al) substrate. The thickness of the Al substrate is roughly 0.5mm. Typically, the input phosphor has a diameter of 15–40 mm. X-ray photons are changed into light photons using an input phosphor.

Photocathode: The 2 nm-thick layer of the image intensifier is called the photocathode. Usually, the photocathode is made of an antimony and cesium alloy. The photocathode has a thin layer of aluminum (Al) covering it. The photocathode absorbs light photons released by the input phosphor, releasing photoelectrons in the process.

Evacuated vacuum tube: For the electrons to flow freely like in the x-ray tube situations, a vacuum is necessary. The voltage used to accelerate the electrons is between 25 and 35 kVp.

Electron optics lens: Several positively charged electrodes comprise the lens. They are focused on the output phosphor using electron optics.

Output phosphor: The image intensifier's output phosphor, which is placed on the output window, is made of zinc cadmium sulfide that has been activated by silver (Ag). When this output phosphor absorbs the accelerated electrons, it produces a green light. The typical dimensions of this output phosphor are 25 to 35 mm in diameter and 0.005 mm in thickness.

Cathode ray tube: It is a picture tube, which controls for regulating brightness and contrast.

Angiographic Table: Angiographic table is stationary with a floating or moveable tabletop. Tabletop is capable of moving longitudinally and laterally. The control for moving the table should be located on the side of the table and on a remote control foot switch. The foot switch enables the angiographer or interventional radiologist to control the table movement.

Lighting: Angiographic procedures require intermittent fluoroscopy, the room should contain both fluorescent lights and incandescent. Fluorescent lights are used during vessel puncture and patient preparation. The fluorescent lights should be connected to the fluoroscopic control so that when the fluoroscope is on, fluorescent lights go off, and vice versa. Incandescent lights should be on all the time.

The accessories equipment used in the interventional radiology room are as follows: Catheters, Guidewires, Needles, stent, Foot Pedals, Monitors, Sheath, Dilators, ECG Monitors, Defibrillators, Oxygen Supply, Pressure Injector, Sink, Air conditioning system and Emergency Crash Cart.

11.2 Clinical Applications

A variety of medical disorders are diagnosed and treated by interventional radiology procedures. The following are some clinical uses for interventional radiology:

11.3 Vascular Interventions

Angioplasty and stenting: This is used to treat stenosis and blocked blood vessels due to atherosclerosis or plaque deposition. Stenting can also be used to treat aneurysm in the blood vessels. Example: Percutaneous transluminal coronary angioplasty and Endovascular placement of stent in aortic aneurysm of the abdomen (Byrne et al. 2017).

Embolization: It is the non-surgical, therapeutic insertion of multiple substances into the bloodstream to occlude vessels to prevent haemorrhage, or to devitalize a structure, tumor, or organ by occluding its blood supply. Example: Procedures such as uterine artery embolization (UAE) for fibroids or trans arterial chemoembolization (TACE) for liver tumors (Gupta et al. 2014; Lau et al. 2006).

11.4 Oncologic Interventions

Radiofrequency ablation (RFA) and microwave ablation (MWA): Radiofrequency ablation is a minimally invasive cancer treatment method. RFA is an image-guided technique where an electrode is injected into the tumor site, after that a high-frequency alternating current is applied, which produces heat due to agitation of the ions around the electrode and destroys cancer cells. Although the fundamental characteristics of the RFA and MWA are similar, the only difference is the phenomenon of generating heat. MWA provides several advantages over RFA, including a superior convection profile, greater consistent intratumoral temperatures, shorter ablation periods, and the possibility to treat several lesions at the same time with different probes (Izzo et al. 2019).

Example: Destroy cancer cells in the liver, lungs and kidneys

Cryoablation: Percutaneous cryoablation involves putting cryoprobes into malignant tissue while under imaging supervision. Cryoablation damages cells, kills them, and produces tissue necrosis (Erinjeri and Clark 2010).

Example: Cryoablation in liver, lung, renal, and adrenal tumors (Tatli et al. 2010).

11.5 Other Interventions

Vertebroplasty and Kyphoplasty: These are minimally invasive interventions that include injecting bone cement through a small hole in the skin into a damaged vertebra to stabilize it and prevent further fracture. Although the fundamentals of both procedures are similar, there is a minute difference. In vertebroplasty, bone cement is introduced into the broken bone to stabilize the vertebrae, whereas, in kyphoplasty, a balloon is inserted into the vertebral body and gradually expanded to restore shape and height to the fractures. The balloon is then withdrawn and bone cement is injected. This will keep the corrected height and form in place.

Example: Osteoporotic fracture, neoplasm, and pain relief, etc. (Mathis, Ortiz, and Zoarski 2004).

Nephrostomy: Nephrostomy is an interventional procedure in which a drainage catheter is inserted to drain an obstructed kidney or ureter. Examples: Obstructive Uropathy, Pyonephrosis, and before Percutaneous Nephrolithotomy, etc. (Aitchison 2009).

Interventional radiography (IR) uses image guidance and minimally invasive methods to diagnose and treat a wide range of diseases. Under fluoroscopic or CT guidance, IR is utilized for vascular treatments such as angioplasty, stent implantation, and aneurysm or tumor embolization. It is especially effective for treating vascular obstructions (such as peripheral artery disease) and performing biopsies or drain placements in difficult-to-reach regions. Interventional radiologists use image-guided ablation to treat liver, kidney, and lung tumors. IR techniques reduce the need for open surgery, resulting in shorter recovery times and lower patient morbidity. The combination of diagnostic and therapeutic capabilities, combined with the precision provided by real-time imaging, make IR an important modality for managing both acute and chronic illnesses (Sabharwal, Fotiadis, and Adam 2007; Kulkarni et al. 2024).

11.6 Advantages

Interventional Radiology is an integral part of modern medicine due to its good advantages. The advantages of Interventional radiology are as follows: All interventional radiology techniques are minimally invasive, lowering the risk of infection and consequences. Patients endure less discomfort than those who have open operations because they have shorter hospital stays and recover faster. Interventional radiology employs real-time imaging guidance, allowing for accurate targeting of the region of interest, resulting in better outcomes and less harm to the surrounding tissues. This procedure has a wide range of uses, including biopsies, angioplasties, stent placement, and embolization. Many interventional radiology procedures are conducted as outpatients, which allows patients to return home the same day. Furthermore, the majority of these treatments only require local anesthesia, which minimizes the hazards associated with general anesthesia.

11.7 Disadvantages

All the imaging modalities come with a few disadvantages, which include:

Interventional procedures require highly skilled and experienced doctors, who are not available in half of the regions. Additionally, equipment availability is extremely limited. The High radiation dose to the patient due to repeated multiple cumulative exposure. Interventional radiology is much safer than open surgeries however; it still carries risks such as infection, bleeding, hematoma formation in the puncture site, contrast complications, guidewire fracture, local or surrounding tissue damage, etc.

Interventional radiology provides numerous benefits, including less invasiveness, quick recovery, economic effectiveness, and many others. However, it includes a few risks, which have already been discussed. The choice to use interventional radiology should be based on available resources, patient needs, and the skill of the interventional radiology team.

12 Nuclear Medicine Imaging

Nuclear medicine Imaging is a branch of medicine that treats and diagnoses patients using radioactive tracers or radiopharmaceuticals. Gamma ray or positron-emitting radionuclide injections into the body are a part of nuclear medicine imaging. This substance is usually referred to as radiotracer. When radionuclides decay or photons are emitted, the gamma camera detects them and creates an image of the radionuclide distribution.

The field of nuclear medicine emerged between 1910 and 1945. In 1913, George de Hevesy discovered the absorption and transport of radioactive lead nitrate. He also developed the concept of the tracer technique, which was later applied to plants in 1923. The very first human investigation involving the intravenous administration of radiotracer took place in 1927. Lawrence invented the cyclotron in 1930. In the 1950s, technological advancements enabled the acquisition of images of radionuclides distribution in the human body. Wrenn and his team define the advantages of positron emitters, which were introduced in 1951. In the 1960s, I131 was first implemented to diagnose thyroid disorders. The final evolution occurs when a 3D image replaces the 2D image. The current era of nuclear medicine was introduced by the invention of PET by Phelps and colleagues and SPECT by Kuhl and colleagues as a result of this significant advancement (Cherry, Sorenson, and Phelps 2012).

Single photon emission tomography (SPECT) and positron emission tomography (PET) are the two main categories of nuclear medicine imaging.

12.1 Single Photon Emission Tomography (SPECT)

Utilizing radionuclides that decay by emitting gamma rays, single photon imaging is possible. The distribution of radionuclides in the patient from a single angle forms the basis of the image. This provides slightly less detailed information but is nonetheless diagnostically relevant (e.g., bone scan). However, in the tomographic mode of SPECT, data is obtained from different angles of the subjects. This enables a cross-sectional view of the distribution's sagittal, coronal and oblique view and provides in-depth information missing from the SPECT normal mode image. Filter back projection and iterative reconstruction are used for image reconstruction (Cherry, Sorenson, and Phelps 2012).

12.2 Gamma Camera

Hal O. Anger developed the gamma camera in 1950. Tc-99m gamma rays and characteristics X-rays are used to produce images. The gamma camera detects gamma rays emitted by Tc-99m that is given intravenously. The four most frequent types of collimators used in nuclear medicine are parallel holes, pinholes, converging, and diverging collimators. Collimators are built of materials with a high density and atomic number. Gamma cameras frequently use pinholes and parallel holes' collimators (Thayalan 2014).

12.3 Positron Emission Tomography (PET)

PET is a nuclear medicine system with improved detection of metabolic and biochemical functions of human tissues and organs. Positron imaging uses radionuclides that decay by emitting positrons. The positrons emitted have a relatively short lifespan. Two high-energy photons are produced by the subsequent annihilation with the electron, and PET images are obtained by detecting these photons using an imaging camera. Because annihilation coincidence detection is more powerful, there is no need for an additional collimator, making the PET more efficient than the SPECT (Cherry, Sorenson, and Phelps 2012).

The radiopharmaceuticals that are most frequently used in nuclear medicine are Tc^{99m}-MDP, Tc^{99m}-sestamibi, Tc^{99m}-DTPA, I^{131}-Sodium iodide, and F^{18}– fluorodeoxyglucose, etc.