ACCSCIENCE PUBLISHING

INNOSC Theranostics and Pharmacological Sciences

REVIEW ARTICLE

Medical imaging technology: Principles and systems

Bin Zhang[1,2], Liang Liu[3], Deyue Meng[4], and Chin Siang Kue[5]*

[1]Department of Human Resource, The Fourth Hospital of Hebei Medical University, Shijiazhuang, China

[2]Postgraduate Center, School of Graduate Studies, Management and Science University, Shah Alam, Selangor, Malaysia

[3]Department of Oncology, The Fourth Hospital of Hebei Medical University, Shijiazhuang, China

[4]Department of Obstetrics and Gynecology, The Fourth Hospital of Hebei Medical University, Shijiazhuang, China

[5]Department of Diagnostic and Allied Health Sciences, Management and Science University, Shah Alam, Selangor, Malaysia

Abstract

Medical imaging technology is an important course in biomedical engineering. It is a multidisciplinary field integrating advanced technologies from physics, electronic engineering, computer science, engineering mathematics, material science, and fine processing. This course lays the foundation for the implementation of imaging diagnostics essential for medical automation. It enables participants to systematically grasp the fundamental knowledge in medical imaging principles, equipment, and system analysis, as well as to understand the direction of the latest developments in this field. This paper discusses the basic principles and performance of various basic imaging devices, such as X-ray imaging, magnetic resonance imaging, nuclear medicine imaging, and ultrasound imaging. In addition, it explores the systems involved and the future prospects of medical imaging technology.

Keywords: Medical imaging; Human security; X-ray; Magnetic resonance imaging; Ultrasound

***Corresponding author:**
Chin Siang Kue
(cskue@msu.edu.my)

Citation: Zhang B, Liu L, Meng D, Kue CS. Medical imaging technology: Principles and systems. *INNOSC Theranostics and Pharmacological Sciences.* 2024;7(3):3360.
doi: 10.36922/itps.3360

Received: April 4, 2024

Accepted: July 15, 2024

Published Online: July 29, 2024

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1. Introduction

With the advancement of science and technology, medical imaging technology has made significant progress. Medical imaging refers to the process of creating medical image data and the technology or devices used to form these images (modern medical imaging). It is a science that relies on the interaction between specific energy and living organisms to extract information about the shape, structure, and certain physiological functions of tissues or organs, providing essential imaging information for biological tissue research and clinical diagnosis. The convergence of medical imaging technology with artificial intelligence (AI) has sparked transformative changes in the field, fostering mutual advancements and driving innovation. AI applications in medical imaging aim to streamline image recognition and analysis processes, ultimately bolstering diagnostic accuracy, efficiency, and reliability. Therefore, medical imaging occupies an important position in clinical diagnosis,[1] representing the intersection of high-tech and medicine.

The future development of medical imaging will primarily depend on advancements in computer-led high technology, which will subsequently enable modern medical imaging to progress rapidly. Modern medical imaging has evolved beyond traditional single ordinary X-ray and angiography examinations to include ultrasound, radionuclide imaging, X-ray computed tomography (CT), digital subtraction angiography, magnetic resonance imaging (MRI), digital imaging (computed radiography and digital radiography) of conventional X-ray examinations, and image storage and transmission of medical imaging system composed of multiple technologies such as picture archiving and communication systems. Overall, understanding the strengths and limitations of medical imaging technology is essential for health-care professionals to effectively utilize these modalities in clinical practice, ensuring optimal patient care and outcomes.

2. Common characteristics and types of medical imaging equipment

Medical imaging equipment is primarily composed of an energy emission source, effect tissue, detector, processor, display, and other components. As shown in Figure 1, the main types of medical imaging technology include: (i) X-ray imaging, (ii) MRI, (iii) nuclear imaging (nuclear medicine imaging technology), (iv) ultrasound imaging, (v) impedance imaging, (vi) thermal-microwave imaging, and (vii) optical imaging.[2] Among these technologies, the first four are the most widely used and easily popularized. Different types of medical imaging have complementary advantages, as detailed in Table 1.

3. Principles of medical imaging

In recent years, the advent of new imaging methodologies such as high-field MRI, spectral CT, and hybrid equipment has revolutionized medical imaging practices, offering enhanced diagnostic capabilities and clinical insights. High-field MRI, characterized by magnetic fields exceeding 3 Tesla, has enabled unprecedented spatial resolution and tissue contrast, which is particularly beneficial for neurological and musculoskeletal imaging. The improved signal-to-noise ratio provided by high-field MRI has facilitated enhanced anatomical detail and heightened sensitivity to pathological changes, advancing the detection and characterization of various diseases. Similarly, spectral CT, which utilizes energy-sensitive detectors to capture photon energy information, has emerged as a promising technology for spectral imaging and material differentiation. By discerning subtle differences in tissue composition and molecular properties, spectral CT enhances diagnostic accuracy and enables personalized treatment strategies, particularly in oncology and cardiovascular imaging. Moreover, the integration of hybrid imaging systems, such as positron emission tomography (PET)/CT and PET/MRI, synergistically combines the functional information from PET with the anatomical detail provided by CT or MRI.

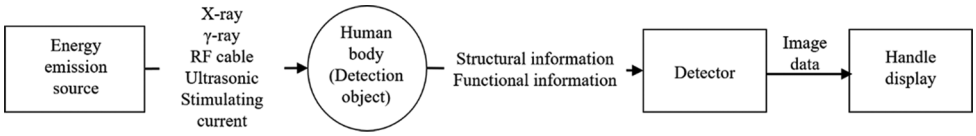


Figure 1. Medical imaging process
Abbreviation: RF: Radiofrequency.

Table 1. Types of medical imaging technologies

Medical image classification	Dominant form	Description content
Structure image: Describe the physiological anatomy of the human body	X-ray, CT	Tissue density distribution
	UI	Changes in tissue acoustic impedance
	MRI	Magnetic resonance density distribution and relaxation characteristics
Functional images: Describe the functional activities of human body tissues and organs in different states	RI (SPECT, PET)	Physiological and metabolic functions of tissues and organs
	fMRI	The functional activity of the human brain
	DFI	Blood flow imaging
Other types of imaging	EIT	Internal impedance or change in impedance
	Thermal and microwave imaging	Infrared signal on the body surface and microwave radiation signal in the body
	Optical imaging	Using optical and television technology to observe the shape of some human organs

Abbreviations: CT: Computed tomography; DFI: Detective flow imaging; EIT: Electrical impedance tomography; fMRI: Functional magnetic resonance imaging; MRI: Magnetic resonance imaging; PET: Positron emission tomography; RI: Radioisotope; SPECT: Single-photon emission computed tomography; UI: Ultrasonic imaging.

This integration offers comprehensive insights into disease processes and treatment responses. These advancements in imaging methodologies hold immense potential for optimizing patient care, guiding therapeutic interventions, and advancing our understanding of complex diseases. However, challenges concerning cost, accessibility, and standardization must be addressed to fully realize the clinical benefits of these innovative technologies. Future research efforts should focus on refining imaging protocols, validating diagnostic accuracy, and expanding the clinical utility of these cutting-edge imaging modalities across diverse medical specialties.

3.1. X-ray imaging

Roentgen discovered X-rays in 1895, which was the greatest discovery in medical diagnostics in the 19th century.[3] X-ray fluoroscopy and photography technology, as the earliest forms of medical imaging technology, remain among the most commonly used medical diagnostic methods today, holding considerable clinical value. The signal detected by the X-ray imaging system is the intensity of X-rays after they penetrate the tissue, reflecting differences in the X-ray absorption coefficients of various human tissues. This difference is due to variations in tissue thickness and density, which the image captures, showing the shape of tissues, organs, and diseased areas. For more than half a century, medical imaging science progressed steadily but slowly alongside advancements in X-ray technology.[4] In the early 1970s, the introduction of computerized X-ray tomography (XCT) marked a period of rapid development in medical imaging. CT involves taking thousands of X-rays from different angles. The substantial amount of data collected is processed by computers to form a three-dimensional image of any part of the body.[5] Doctors can instruct the computer to display a two-dimensional cross-section at any depth from any direction. CT scanning has brought revolutionary changes to medical diagnosis, allowing doctors to detect brain bleeding in head injuries or visualize the shape and extent of tumors in cancer patients.[4]

CT uses a digital signal input to the computer for processing. The processing of image formation involves dividing the selected layer into several cuboids of equal volume, called voxels.[6] The information obtained through scanning is used to calculate the X-ray attenuation coefficient or absorption coefficient of each voxel, which is then arranged into a digital matrix. Digital matrices can be stored on magnetic or optical disks. A digital-to-analog converter transforms each number in the digital matrix into small squares of grayscale, ranging from black to white, called pixels. These pixels are arranged in a matrix to form a CT image.

The emergence of XCT introduced a new concept in medical imaging. XCT uses extensive X-ray absorption data obtained from scanning around the body's organs to reconstruct tomographic images. When a beam of thin (fan-shaped) X-rays passes through a section of the body's organs, the total attenuation coefficient along the X-ray path is the line integral of the voxel attenuation coefficients, which can be measured with a detector.[4] Detectors convert the intensity of the rays into electrical signals, which are digitized and processed by computers. By conducting multiple measurements at different angles around the organs, the absorption coefficient related to each voxel at a specific level is calculated. The resulting two-dimensional absorption coefficient matrix is stored in the computer, using different gray scales.[7] This matrix information is then displayed as an image. The grayscale of each pixel on the displayed image corresponds to the absorption coefficient of the respective voxel, thereby providing information on the distribution of the attenuation coefficient on the fault plane. XCT technology is called tomography because it obtains a cross-sectional image of the body's organs.

This digital imaging technology has evolved from the first generation to the fifth generation. At present, the third and fourth generations are commonly used. The continued development of these two generations of CT technology has primarily focused on improving speed, enhancing image quality, developing new functions, expanding the scope of applications, and facilitating operations. For example, spiral scanning can reduce the time needed to scan the same coverage length by one-quarter to one-fifth or increase the scanning coverage length by 25 – 33% in the same amount of time. Another manifestation of increased speed is the shortened image reconstruction time. Some CT products adopt new image reconstruction technology, increasing the reconstruction time to one second, thus speeding up the scanning cycle. High-end CTs with continuous imaging or fluoroscopy functions can display six to eight images per second. CT fluoroscopy is very important for interventional radiology, as it reduces the number of scanning layers and the patient's X-ray exposure dose. Some products can achieve a 512 × 512 matrix image with a scanning dose of only 15 mA. Further studies are ongoing on CT fluoroscopy technology using an X-ray exposure dose of 10 mA. In terms of image quality, the spatial resolution of high-end, low-voltage spiral CT machines has reached 20 lp/cm, with high low-contrast resolution, significantly improving the ability to differentiate soft tissues.

The new generation of CT is called electron beam CT (EBCT). In EBCT, an electron beam is emitted by an electron gun, and a deflection coil changes the direction

of the electron beam to hit a set of semicircular target rings, producing X-rays. When the X-rays pass through the subject's body, they are received by the detector group arranged on the opposite side. Since there is no mechanical movement, the scanning speed can be as high as 50 ms/layer. While the temporal resolution is excellent, the spatial resolution is not as high as that of high-end third- and fourth-generation machines. Further, the development of EBCT is anticipated. Some hospitals in China have officially launched EBCT, which, due to its imaging speed being 20–40 times faster than ordinary CT, can provide exceptionally clear images of moving organs such as the heart. After many generations of development, XCT has been widely used in medicine. At present, it is primarily used in diagnosing spinal and head injuries, intracranial tumors, brain–blood clots, early heart disease prevention and treatment, soft-tissue injuries, gastrointestinal diseases, and malignant lesions of the waist and pelvis.

3.2. MRI

Since the 1980s, nuclear magnetic resonance technology has been applied to clinical medicine. The strong magnetic field interacts with the nuclei of the body tissue in the imaged part of the human body. The nuclei and their physiological conditions resonate under the magnetic field's influence and change their positions. The images generated by the magnetic field not only avoid the damage caused by CT machines to human tissue cells but also detect small physiological changes before pathological changes occur. Consequently, MRI has become a new branch of medical imaging diagnosis.

MRI is currently one of the most advanced imaging examination methods. It is an emerging imaging diagnostic technology that non-invasively displays the internal structure of the human body. Although this technology has been developed for <20 years, it has rapidly advanced, with equipment manufacturing technology and diagnostic theory continually improving. At present, MRI equipment is widely used in hospitals in large- and medium-sized cities. Its high-resolution images of human tissues and organs provide more intuitive image information about the internal structure of the human body, offering richer and more meaningful diagnostic and treatment information for clinical use.[8]

According to the principle of MRI, atomic nuclei are positively charged, and the nuclei of many elements, such as hydrogen-1, fluorine-19, and phosphorus-31, undergo spin motion. Normally, the arrangement of nuclear spin axes is irregular, but when placed in an external magnetic field, the spatial orientation of the nuclear spins transitions from disorder to order. The magnetization vector of the spin system gradually increases from zero, and when the system reaches equilibrium, the magnetization intensity stabilizes. If the nuclear spin system is affected by external influences, such as radiofrequency excitation of the nucleus at a certain frequency, a resonance effect occurs. After the radiofrequency pulse stops, the excited atomic nuclei cannot maintain this state and return to their original arrangement in the magnetic field. During this process, they release weak energy, which becomes radio signals. When these signals are detected and spatially resolved, an image of the distribution of atomic nuclei in motion can be obtained. The process of returning atomic nuclei from an excited state to an equilibrium arrangement is called a relaxation process, and the time it takes is called relaxation time. There are two types of relaxation times: T1 and T2. T1 is known as spin-lattice or longitudinal relaxation time, and T2 is known as spin-spin or transverse relaxation time.

Although MRI images are also displayed in different grayscales, they reflect differences in magnetic resonance signal intensity or the length of relaxation times T1 and T2, unlike CT images, where grayscales reflect tissue density. MRI images can generally be divided into three basic images: T1-weighted image, T2-weighted image, and proton density image. Fat appears as a high signal in these images, while muscles, liver, pancreas, and other tissues and organs show a medium signal on T1-weighted images and a low signal on T2-weighted images. Lung tissue, large blood vessels, and calcification generally appear as low signals in these images. In contrast, tissues and organs such as the kidneys and spleen have lower signals on T1-weighted images and higher signals on proton density and T2-weighted images. The contrast of CT images depends on the X-ray attenuation properties of the tissue. Fat has low density, calcifications have high density, and large blood vessels have a density similar to that of the liver and kidneys. Tumors often have a density similar to soft tissue, and contrast agent injection is generally required for better visualization and characterization.

The amount of information provided by MRI is not only greater than many other medical imaging techniques but also fundamentally different. Therefore, it has significant advantages in the diagnosis of diseases. MRI can directly produce tomographic images of cross-sections, sagittal planes, coronal planes, and various oblique planes without producing artifacts common in CT scans. MRI does not require the injection of contrast agents, exposes the patient to no ionizing radiation, and has no adverse effects on the body. Compared to CT, MRI has no radiation damage or bone artifacts, can perform multi-faceted and multi-parameter imaging, offers high soft-tissue resolution, and is suitable for diagnosing various diseases across different

body systems, such as tumors, inflammation, trauma, and degenerative conditions. MRI is particularly effective for examining sexual lesions and various congenital diseases. Its imaging of the brain, spine, and myelopathy is superior to that of CT. MRI can display the structure of blood vessels without using vascular contrast agents, making it unique in distinguishing between blood vessels, masses, lymph nodes, and vascular structures. Its soft-tissue resolution is several times higher than that of CT, allowing it to sensitively detect changes in water content in tissue components. Therefore, MRI often detects lesions earlier and more effectively than CT.

MRI can clearly and comprehensively display the cardiac chambers, myocardium, pericardium, and other small structures in the heart. It is a reliable method for diagnosing various heart diseases and assessing cardiac function. The images obtained using MRI are exceptionally clear and detailed, greatly improving diagnostic efficiency and reducing the need for exploratory surgeries such as thoracotomy or laparotomy. Since MRI does not use X-rays, which are harmful to the human body, or contrast agents that can often cause allergic reactions, it is considered safe. MRI can image various parts of the human body from multiple angles and planes with high resolution, providing detailed views of anatomical structures and their relationships, and better localizing and characterizing lesions. It is of great value in diagnosing diseases in various body systems, especially in detecting early-stage tumors.

3.3. Ultrasound imaging

Ultrasound is one of the best non-invasive and painless examination methods for human lesions today. In the 1960s, ultrasonic technology was applied to clinical diagnosis, leading to the development of type A, M, B, and C ultrasonic diagnostic machines. These machines can be used to observe the internal structure of the human body, diagnose tumors and cysts, and check the normality of organs, fetuses, and more. Long-term use, observation, and analysis have shown that the frequency and intensity of ultrasound imaging equipment are harmless to human health. Type A (amplitude modulation type) uses amplitude to indicate the strength of the reflected signal, displaying an "echogram." M type (photoelectric scanning type) uses the vertical direction to represent the spatial position from shallow to deep and the horizontal direction to represent time, displaying a graph of photoelectric movement over time. Both of these machine types are one-dimensional displays with limited application ranges. Type B (intensity modulation type) is an ultrasonic section imager, commonly referred to as "B-ultrasound." It uses photoelectric signals of varying brightness to represent the strength of the received signal. As the probe moves horizontally, the light point on the display screen moves synchronously, creating a two-dimensional cross-section image scanned by the ultrasonic sound beam. B-mode ultrasound is the most important diagnostic method in clinical applications. D-type ultrasound is based on the Doppler principle.

The working principle of ultrasonic diagnosis relies on the good directivity of ultrasonic waves and physical properties such as reflection, refraction, and attenuation, similar to light. Using an ultrasonic instrument and various scanning methods, ultrasonic waves are emitted into the body and spread through tissues. When there is a difference in acoustic impedance between normal and pathological tissue, the echo signal is received and processed to form a two-dimensional cross-sectional sonogram. Due to the different interface morphology, motion status, and degree of ultrasound absorption of various tissues, their echoes have specific commonalities and characteristics. By combining physiological, pathological, and clinical knowledge with a series of human body section sonograms, the location, nature, or function of the lesion can be determined, allowing for an accurate diagnosis.

During ultrasound imaging, ultrasound beams are used to scan the human body, and images of internal organs are obtained by receiving and processing reflected signals. Ultrasound diagnostic technology is non-damaging, painless, and can be performed repeatedly. It is particularly suitable for examining soft tissues, obtaining dynamic information, and conducting dynamic research. It has high sensitivity and resolution, is small in size, and is highly automated. Recent advancements in ultrasound imaging technology include grayscale and color display, real-time imaging, ultrasound holography, and intrabody cavity ultrasound imaging. Ultrasound imaging methods are often used to determine the location, size, and shape of organs; delineate the scope and physical properties of lesions; provide anatomical diagrams of glandular tissues; and identify normal and abnormal fetuses. It is widely used in ophthalmology, obstetrics and gynecology, the cardiovascular system, digestive system, and urinary system.[9]

Color Doppler ultrasound imaging (color Doppler ultrasound) is an advanced imaging examination method that adds Doppler blood imaging technology to B-ultrasound. Known as "non-invasive angiography," it uses three frequency probes: high, medium, and low. During the examination, the probe is in contact with the skin of the relevant part through an adhesive, and the scanning results form a two-dimensional cross-sectional sonogram on the monitor, which can be saved in the form of color photographs. This method is used to examine the heart, great blood vessels, cerebral arteries, liver, spleen, kidneys,

uterus, appendages, prostate, testicles, and other organs, accurately measuring blood flow, and the size, texture, and boundaries of stones and masses. In addition, it can be used in clinical interventional examination and treatment.

3.4. Nuclear medicine imaging

The nuclear medicine imaging system, also known as the radionuclide imaging system, detects rays emitted by radionuclides in the human body. The image signal reflects the concentration distribution of the radionuclide and displays both morphological and functional information. Nuclear medicine imaging is essentially different from other imaging modalities. Its images depend on factors such as blood flow, cell function, cell number, metabolic activity, and excretion and drainage of organs or tissues, rather than changes in tissue density. It is a functional image, and the clarity of the image mainly depends on the functional status of the organ or tissue. Since changes in functional metabolism during disease processes often occur before morphological changes, nuclear medicine imaging is considered one of the earliest diagnostic methods of significant value.

Nuclear medicine imaging technology is an imaging method that captures the radioactive differences between normal and diseased tissues within and outside the organ. Nuclear medicine imaging examination first involves selectively administrating certain radioactive drugs (trace, accurately targeted, safe, and harmless enhanced tracers) to the human body. These drugs accumulate in specific organs or participate in certain bodily processes. During these metabolic processes, radionuclides emit gamma rays, which then photographed by nuclear medicine imaging instruments photograph to get images on the concentration distribution and metabolic process of these radionuclides in organ tissues. Nuclear medicine imaging examination methods are widely used in medicine. The primary difference between it and XCT is that the ray source of XCT is outside the body, while the ray source of nuclear medicine imaging is inside the body. Nuclear medicine imaging technology can obtain not only anatomical images of human organs but also physiological, biochemical, pathological processes, and functional images. Using mathematical algorithms, a three-dimensional "transparent human body" image showing the density distribution of radioactive elements in the body can be reconstructed in a computer.

At present, the main technologies for nuclear medicine imaging include gamma photography, single-photon emission computed tomography (SPECT), and PET. The latter two are collectively called emission CT, with PET also becoming a primary technical means for studying brain function.

The gamma camera consists of three parts: a probe, an electronic circuit, and a display device. The gamma camera can observe all parts of an entire organ image simultaneously in a short period of time. It has high sensitivity, can image at 1 time, and can conduct continuous and dynamic observation of the organ. Cameras equipped with electronic computers are most suitable for quantitative analysis and rapid continuous dynamic analysis of organ and tissue imaging, significantly improving the diagnostic effect of *in vitro* imaging and being valuable for diagnosing cardiovascular diseases, tumors, and other conditions.

The SPECT probe is a gamma camera that rotates 360° around an organ of the patient. During rotation, it collects a frame of images at specific angles. After computer processing, the images are superimposed, and the filtered back-projection method is used to reconstruct cross-sectional images from a series of projections. From the three-dimensional information of transverse tomographic images, sagittal, coronal, and arbitrary oblique tomographic images can be obtained through image recombination. SPECT combines the characteristics of both gamma cameras and CT, allowing for stereotaxic positioning and dynamic observation of changes in local function and metabolism of organs. The detection rate of lesions and the clarity of imaging are better than those of gamma cameras.

PET[10] is a relatively advanced clinical examination imaging technology in the field of nuclear medicine. The general method involves labeling a substance necessary for the metabolism of biological life, such as glucose, protein, nucleic acid, or fatty acid, with a short-lived radionuclide (such as fluorine-18 or carbon-11), and then injecting it into the human body. The accumulation of this substance in metabolism reflects the metabolic activities of life, thereby achieving the purpose of diagnosis. The main substance used in hospitals is fluorodeoxyglucose, commonly abbreviated as FDG. Its detection mechanism relies on the fact that the metabolic status of different tissues varies. In high-metabolizing malignant tumor tissues, glucose metabolism is strong, and there is greater accumulation. These characteristics can be reflected through images, enabling the diagnosis and analysis of lesions.

3.5. Near-infrared imaging

The infrared thermal imaging device uses an infrared detector to detect infrared rays radiated from the surface of the human body and convert them into electrical signals. The infrared camera acquires the video signal, which is then amplified, filtered, and sent to a computer for imaging. This technology can be used to diagnose temperature-related diseases, such as superficial tumors,

early-stage breast cancer, peripheral vascular diseases, the viability of replanted limbs, and skin conditions. Medical infrared thermal imaging cameras display the temperature distribution of the human body (thermal image) to indicate changes in the temperature distribution, location, and extent. Various inflammations and malignant tumors cause higher temperatures in the affected areas on the heat map, while embolisms, decreased microcirculation, and effusions show lower temperatures. Near-infrared thermal imaging diagnoses diseases based on the difference in thermal radiation between normal and abnormal tissue areas. By receiving infrared thermal radiation during the metabolism of body cells, it measures the depth, shape, and intensity of the thermal radiation source. Based on the thermal radiation of the whole body, after sorting and quantifying the corresponding relationship between the distribution status and each tissue and disease, the image reconstruction algorithm is used to obtain the temperature image and then cross-sectioned. By analyzing the relationship between the thermal radiation differences in the body's cell metabolism and the health status, the location and nature of the body's lesions can be determined, providing a basis for diagnosis. Near-infrared thermography is non-invasive and can estimate the physiological and molecular processes of intact tissues of the body, providing corresponding chemical and physical information.[11] Near-infrared thermal imaging can effectively evaluate tumor markers and can be used clinically for diagnosing tumors, cardiovascular and cerebrovascular diseases, respiratory system diseases, digestive system diseases, and more. It can detect lesions earlier than other examination methods, making it especially valuable for the differential diagnosis of tumors.

3.6. Medical endoscopic imaging

A medical endoscope is a diagnostic instrument that is directly inserted into the inner cavity of human organs to observe the surface shape of the inner cavity in real time. The images it obtains are realistic and intuitive. There are more types of endoscopes, each designed for specific cavities of the human body, such as the esophagoscope, gastroscope, enteroscope, colonoscope, choledochoscope, mediastinoscope, bronchoscope, urethroscope, cystoscope, renal pelvis endoscope, colposcope, hysteroscope, laparoscope, and arthroscope. Recently, thin-diameter endoscopes with diameters as small as 0.07 mm have been introduced. An endoscope can be used for multiple purposes, including examining coronary arteries. Laser endoscopy and three-dimensional endoscopy are also under development. Laser endoscopy is a new generation of endoscope that combines diagnostic and treatment functions. Three-dimensional endoscopes can provide three-dimensional images, enabling difficult operations to be performed smoothly and significantly improving the safety of surgeries.

The invention of laser technology in the 1960s was one of the major scientific and technological achievements of the 20th century. The high directionality, brightness, monochromaticity, coherence, and biological effects of lasers have been widely used in medicine. Medical lasers are often used for surgical cutting, tissue cauterization, coagulation and hemostasis, light needle acupoint irradiation, laser blood cell counting, laser microspectroscopy analysis, laser holography diagnosis, and laser Doppler blood flow velocity measurement. Consequently, "laser medicine" has become an important branch of medicine.

3.7. Comparison of the medical imaging technology

The comparative analysis of CT, MRI, and endoscopy highlights the distinct advantages and limitations of each modality in medical imaging. CT imaging, with its high spatial resolution and rapid acquisition, is well suited for visualizing bone structures and detecting traumatic injuries, making it invaluable in emergency settings. However, its use is constrained by ionizing radiation exposure, which poses risks, particularly in sensitive populations.[5] In contrast, MRI offers superior soft-tissue contrast and multiplanar imaging capabilities, making it indispensable for evaluating neurological, musculoskeletal, and cardiovascular conditions without the use of ionizing radiation. Nonetheless, MRI is associated with longer acquisition times, higher costs, and contraindications in patients with certain metallic implants or claustrophobia. Endoscopy provides direct visualization and intervention capabilities, enabling real-time examination and tissue sampling for accurate diagnosis and targeted interventions in gastrointestinal and respiratory disorders. However, its invasive nature carries inherent risks such as perforation, bleeding, and infection and may require sedation or anesthesia, leading to patient discomfort and procedural complexity. Overall, understanding the strengths and limitations of CT, MRI, and endoscopy is essential for health-care professionals to effectively utilize these modalities in clinical practice, ensuring optimal patient care and outcomes.

4. Safety of the medical imaging technology

When evaluating medical imaging systems, the safety of the human body is a critical concern. The damage caused by ionizing radiation to the human body primarily includes both direct damage (such as local redness, hair loss, and a possible increase in the incidence of certain diseases) and indirect damage, mainly genetic damage (such as genetic mutations and deformities). In general speaking, CT scans account for about 2% of radiological examinations, but the radiation dose released exceeds the radiological average

and accounts for about 20% of the population's radiation exposure. The annual number of head CT examinations accounts for about 60% of total examinations. In addition, nearly half of the head CT examinations include both plain and enhanced scans, doubling the radiation dose. Therefore, the potential radioactive hazards of CT cannot be ignored. For example, if a pregnant woman is exposed to radioactive lead during the 3rd month of pregnancy, it may cause serious consequences such as fetal hydrocephalus, hematopoietic system defects, and skull defects. Therefore, when pregnant women undergo CT examination, they need to place an X-ray protection device on the abdomen to avoid and reduce the risk of fetal malformations.

During operation, the MRI instruments can generate strong static magnetic fields, ultra-low-frequency and highly variable electromagnetic fields, and radiofrequency fields. Radiofrequency fields are not an important part of MRI protection. At present, MRI protection mainly relies on shielding from static magnetic fields and ultra-low-frequency high-variable magnetic fields, especially static magnetic fields. In addition, MRI is an expensive and sophisticated equipment that usually requires an air-conditioning system, resulting in higher indoor radon concentrations.[12] To prevent the impact of magnetic fields on the human body, magnetic field shielding is commonly used, and methods such as copper mesh are used for degaussing. However, MRI is generally much less harmful to the human body than CT.

Nuclear medicine imaging, also known as radioisotope imaging, also causes ionizing radiation exposure in the human body. In X-ray photography, although the intensity of radiation is relatively high, the patient is only exposed for a short period of time. In contrast, the concentration of radioactive materials used in radioisotope imaging is very low, but the exposure of radiopharmaceuticals to the human body continues for a period of time until they are excreted from the body or decay. Therefore, an important factor to consider when selecting a radioactive material formula is the requirement for a short half-life.

When evaluating the ionizing radiation damage caused by X-ray and radioisotope imaging in the human body, attention should be given to both the intensity and duration of exposure. In X-ray imaging, the radiation intensity is relatively high, but the exposure time is short. Conversely, although the concentration of radioactive isotope materials is low, the exposure to the human body lasts for a longer period until it is excreted or decays. Therefore, during X-ray examinations, the dose to the human body should be minimized as much as possible. When selecting radioactive materials, their short half-life should be considered to reduce prolonged exposure.

Available statistics indicate that the levels of ultrasound exposure used in diagnosis do not cause harm to the human body. Due to its non-destructive and non-invasive nature, ultrasound imaging has been increasingly used in clinical practice. This is especially true for sensitive areas, such as fetal and eye examinations, where ultrasound is much safer than X-ray. However, even ultrasound imaging should be used with caution for embryos in the early stages of development.

5. Development trends in medical imaging technology

The future development trend of modern medical imaging aims to improve information transmission methods, improve information transmission efficiency, create new methods of information expression, and improve image display quality on the premise of ensuring personnel safety. The ultimate medical significance is to more accurately detect initial pathological changes in human tissues, providing a basis for early diagnosis and treatment. Medical imaging technology is evolving from analog to digital images; from two-dimensional images to three-dimensional images; from local images to overall images; from macro images to micro images; from static images to dynamic images; from morphological to functional images; and from single to integrated images.[3] This includes acquiring multi-temporal (dynamic) images, multi-dimensional images, multi-parameter images, multi-modal images, and multiple clinical indicators (including lesion examination, characterization, organ function assessment, and blood flow estimation), as well as treatment aspects (including three-dimensional positioning, volume calculation, and surgical planning) and multi-regional display observation. Improvements can be made from the following aspects:

(i) Developing ultra-high-resolution phenomenon systems
(ii) Enhancing the performance of imaging equipment and adding new functions. For instance:
    - MRI: Incorporating magnetic resonance spectroscopy imaging[13]
    - Ultrasound: Implementing color blood flow imaging, intracavity ultrasound imaging, digital processing for three-dimensional image display, and ultrasound CT
    - CT: Continuing to improve spatial resolution and scanning speed, focusing on studying changes in disease metabolism, and reducing costs.

Medical images can intuitively display the anatomical structure, form, and functions of various tissues and organs inside the body, making them indispensable in clinical diagnosis. However, existing imaging examinations cannot yet fully meet clinical diagnostic needs, as any single

imaging method can only obtain partial information about the body and cannot provide a sufficient basis for accurate diagnosis. At present, no imaging results can completely replace clinical examinations, and imaging needs to be combined with other examination methods to achieve accurate diagnosis.

In recent years, advancements in medical imaging technology have significantly enhanced its role in clinical diagnosis. However, several challenges remain, such as avoiding interference from various factors during the imaging process and improving imaging quality. In multi-modal imaging, there is a need for better integration of images from different sources after certain transformations to obtain comprehensive information about the anatomy and function of the body from a single image. Some imaging methods still require improvement. For instance, MRI primarily relies on hydrogen molecular imaging, which poses challenges for imaging areas like the alveoli, which are mainly gas filled and contain almost no water. From a safety perspective, although the concentration of radioactive tracers used in nuclear medicine imaging is very low, these radioactive tracers cause radiation exposure in the patient's body until they are eliminated or decay. Therefore, when selecting a radioactive tracer, its half-life and radiation dose should be considered.[14]

In medical image analysis, convolutional neural networks (CNNs) achieve over 90% accuracy, aiding in lesion identification.[15] They efficiently extract features, expediting diagnosis and reducing physician workload, thereby improving diagnostic consistency. CNNs find broad applications, revolutionizing medical imaging across domains such as radiology and pathology.[16] CNNs distinguish themselves from other artificial neural networks primarily through their incorporation of convolutional layers. This addition significantly enhances the performance of neural networks, spurring the creation of numerous convolutional models and techniques aimed at further optimization and innovation.[15] A novel approach, termed the differential CNN, coupled with simultaneous multidimensional filter implementation, has enhanced the performance of CNNs while mitigating the computational cost associated with conventional methods.[17] Techniques such as deep learning and machine learning algorithms, including CNNs, have demonstrated remarkable success in tasks such as tumor detection, lesion localization, and disease classification, substantially augmenting the precision and effectiveness of image interpretation. Furthermore, AI leverages extensive data analysis and pattern recognition capabilities to unveil intricate patterns and features within images, aiding in disease risk assessment and prediction.[18] By analyzing vast repositories of image data alongside clinical information, AI facilitates the identification of disease risk factors, enabling proactive interventions and personalized medical management. Moreover, AI-driven image reconstruction and enhancement methodologies refine image quality and resolution, empowering physicians with clearer and more informative visuals for precise diagnostic and therapeutic decision-making.[19,20] In essence, the fusion of medical imaging technology and AI signifies a paradigm shift in medical practice, underpinning enhanced diagnostic accuracy, personalized care, and elevated standards of health-care delivery.[21]

6. Conclusion

The development of medical imaging technology will accelerate, with applications becoming more mature, image quality becoming clearer, and the advantages of imaging increasingly integrated. This progress brings new hope to countless patients and will contribute significantly to the prevention, early diagnosis, and treatment of diseases.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Bin Zhang, Chin Siang Kue
Writing – original draft: Bin Zhang
Writing – review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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