Comprehensive Journal of Science
Volume (10), Issue (38), (Dec, 2025)
ISSN: 3014-6266

مجلة العلوم الشاملة
المجلد (10) ملحق العدد 38 ديسمبر 2025
ردمد: 3014-6266

How X-Rays Use High Energy Waves to Create Medical Images Inside the Body

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Received: 15-12-2025; Revised: 22-12-2025; Accepted: 2-1-2026; Published: 11-12-2026

Abstract:

An x-ray in regards to the electromagnetic spectrum, refers to a form of high-energy electromagnetic radiation, characterised by a short wavelength and it's ability to pass through opaque materials, which makes it ideal in medical imaging to view the internal structures of the human body. Their ability to penetrate soft tissue and while being absorbed by denser materials such as bones, allow contrast-based images to be produced as scans for medical research and diagnoses. There is a theoretical aspect of the role of x-rays in medical imaging, how they interact with matter within the human body, how the imaging process operates and is conducted and how this applies to the management of technological and safety systems to ensure efficiency in it's usage. Thoroughly, wave particle behaviour and attenuation is connected to detection of anomalies and structures in the human body, further reiterating how high energy waves are able to reveal internal anatomy in clinical contexts.

1-Introduction:

The discovery of x-ray radiation in 1895 by German experimental physicist Wilhelm Rontgen proved revolutionary to the development of medical practicing and imaging. It is different from visible light in that it is a highly penetrable source of radiation (due to it's higher concentration of energy) and can pass through the human body, where different tissues will absorb the radiation depending on their own density. Bones and other dense materials and tissues block a significantly larger amount of energy as compared to softer tissues, and hence, when they are visualised in the final image, they appear white, while the soft tissues will appear a more greyish colour. This creates a contrast in the x-ray image and is used in the diagnosis of various forms of medical anomalies, such as bone fractures and dislocations, and problems in the soft tissues such as pneumonia, lung cancers, and certain forms of tumours. Despite this discovery however, the detection of soft tissues is visualised poorly when imaging techniques are used and x-rays pose a threat as their ionising radiations can lead to the spread and contraction of cancers. Nevertheless, this idea has proven a significant contribution to fields of diagnostic and emergency medicine, orthopaedics, dentistry and numerous others. An understanding of the physics behind such development of high-energy radiation into medical practices allows an exploration of electromagnetic radiation, the interactions between waves and matter and energy interactions with the human body and their transformation into medical imaging.

2-Electromagnetic Waves and the Physics Behind X-Rays

On the electromagnetic spectrum, x-rays take up the place that is between ultraviolet light and gamma rays, with a higher frequency and lower wavelength with the former and a lower frequency and higher wavelength than the latter, yet is still included in the higher frequency section of the spectrum. The wavelengths of x-rays can span anywhere between 0.1 and 10 nanometres, while their frequencies can range from 3×10^{16} to 3×10^{19} Hz (Hughes, 2020). According to Maxwell's equations[1], EM waves consist of oscillating electric and magnetic fields perpendicular to each other that are self-propagating through space at the speed of light. When a dynamic electric field produces a similarly changing magnetic field, it in turn creates another electric field, stimulating a consistent process of respective electric and magnetic field creations that goes on indefinitely (Massachusetts Institute of Technology, 2024).

[1] Maxwell's equations describe are a set of fundamental equations explaining the behaviour of electric and magnetic fields and their interactions with each other, relating to their respective charges and currents

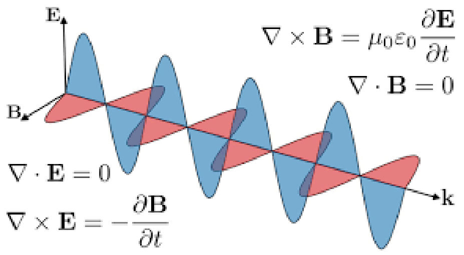


Figure 1. Maxwell's equations pertaining to electromagnetism

The energy of a single electromagnetic photon is determined by Planck's relation that E= *hf*, where 'E' is energy, 'h' as Planck's designated constant (6.626×10^{-34} J·s) and 'f' as the frequency (Chinese Physics B, 2017). What this relates is because x-rays are more inclined towards the high frequency section of the EM spectrum, they possess high energy photons, which enables stronger reactions with matter.

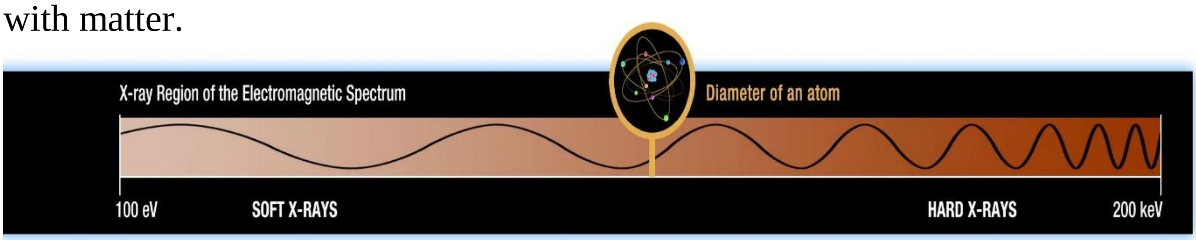


Figure 2. X-Rays in the Electromagnetic Spectrum

Because of this nature of x-ray radiation, they can be categorised as either soft x-rays or hard x-rays, distinguished by their energy capacities. Essentially, soft x-rays have lower energy to interact with softer materials and in the case of the human body, tissues, while hard x-rays have higher energy in comparison, to interact with materials of more denser structure, such as bones and other thick materials. The overall high energy of x-rays allows them to more easily penetrate tissue and undergo reactions such as photoelectric absorption, whereby an x-ray photon is completely absorbed by an inner shell electron in an atom, so the electron will be ejected as a photoelectron. For this to happen, the energy of the photon needs to be greater than the binding energy of the electron, so the photoelectron will carry the excess kinetic energy. Because it depends so heavily on the mass on the atomic material (hence more common occurrence in denser materials), there is evident contrast in x-ray imaging when differentiating between hard and soft tissue (Cleveland Clinic, 2023).

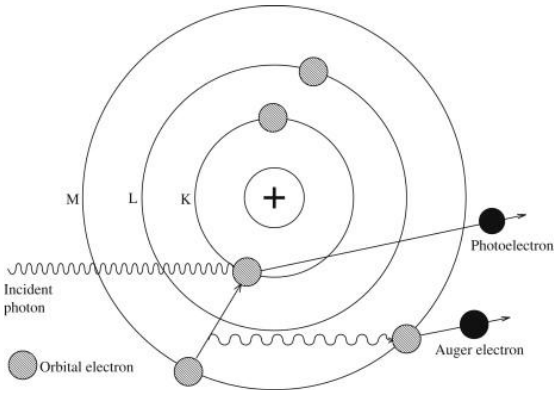


Figure 3. The structure of an atom undergoing photoelectric absorption (also known as the photoelectric effect)

The high energy of x-rays also allows them to undergo a process known as Compton Scattering, an interaction where a high energy photon (like an x-ray), collides with a charged particle (such as an electron, though not necessarily an inner shell electron like in photoelectric absorption) and causes the photon to scatter at a lower angle with a lower wavelength, and, subsequently, lower energy. When the electron recoils, the photon transfers some of it's energy and momentum towards it (Bushberg and Boone, 2011). In x-ray imaging, Compton scattering is the primary interaction between x-ray radiation and matter, decreasing the contrast in the final image and it's quality by adding noise to the detecting machine. (*Nondestructive Evaluation Physics : X-Ray*, 2025).

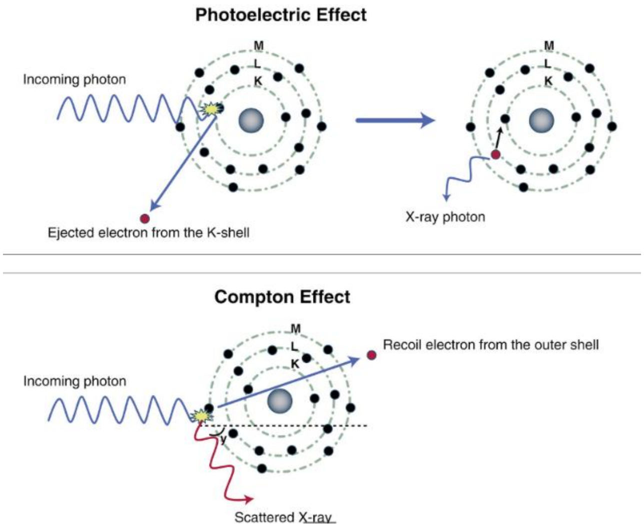


Figure 4. A comparison between the effects of photoelectric absorption and Compton scattering on X-ray radiation particles

3-Production of X-Rays in an X-Ray tube

For X-rays to be used in the case of imaging for medical processes, they are first generated in an evacuated X-ray tube. Inside the tube, an electrode called a cathode, an electrode where a reduction reaction takes place, (meaning it gains electrons and a conventional current flows into an external circuit), has a metal target (which is, in most cases a tungsten filament) that is heated to a temperature high enough for the electrons to be released in a process known as thermal emission. The electrons are then accelerated through a high voltage applied between the cathode and the anode (an electrode where an oxidation reaction occurs, losing electrons and the conventional current flows into the anode from the external circuit). The speed at which the electrons accelerate is usually around 30–150 kVp (Dawood Tafti & Maani, 2023). When the accelerated electrons collide with the metal target, their energy is converted into X-rays through two major processes, known as Bremsstrahlung Radiation (or braking radiation) and Characteristic Radiation. Only about 1% of this radiation, however, is actually useful energy. The rest of it becomes heat (Seibert, 2016), which calls for the specialised need of rotating anodes and cooling systems to be built into diagnostic machines in order to accommodate this heat requirement.

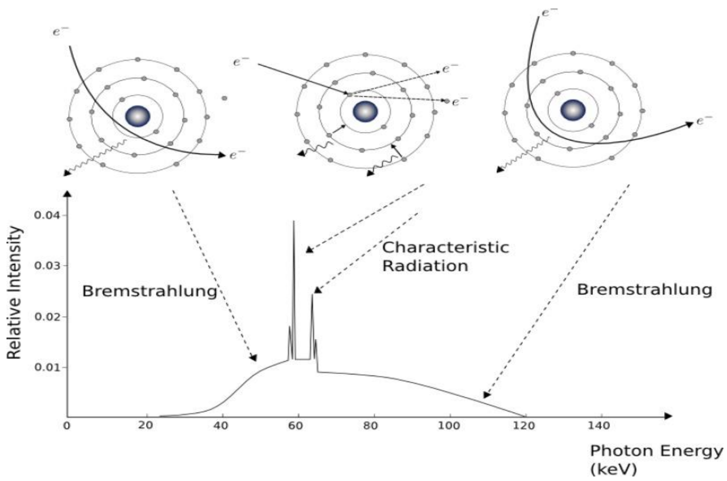


Figure 5. Diagram of the components within an X-ray tube, working to produce x-ray radiation for medical imaging

3.1 Bremsstrahlung Radiation

'Bremsstrahlung' is the German word for braking radiation. This in itself is a reference to the action of electrons during this form of electromagnetic radiation, wherein after charged particles (which, again, is typically an electron) hit the metal target in the X-ray tube, they begin to rapidly decelerate through their interaction with an electric field (and an atomic nuclei). As it's kinetic energy decreases, it loses energy in the form of a photon, or the radiation. Because it's deceleration can vary by certain amounts, instead of a singular wavelength, it creates a spectrum of X-rays (Swinburne University of Technology, 2025). It is this spectrum that creates the X-rays used in the medical imaging devices to create the visualised depictions of internal human anatomy and systems.

3.2 Characteristic Radiation

While in Bremsstrahlung radiation, the charged particles decelerate, in the case of characteristic radiation, the electron from the X-ray tube collides with the inner shells of the tungsten atoms. If this electron's incoming energy proves to be greater than the binding energy of the inner shell's electron, then this inner shell electron is ejected from the atom, leaving a vacancy or a hole where it once was, leaving the atom now unstable. Because of this, in order to regain stability, an atom from the outer shells will fall to fill this vacancy and as it drops to a lower energy level, it releases any excess energy in the form of a photon. (The energy emitted by the photon is equal to the difference in energy between the two energy shells, and it is this quality of characteristic radiation which makes it ideal for material analysis, as the energy of the photon is characteristic of the specific element from which it is emitted from. Additionally, unlike the continuous spectrum of radiation emitted by Bremsstrahlung radiation, the energy levels emitted by characteristic radiation are more specific and discrete, conveyed as sharp, distinct lines on the spectrum.

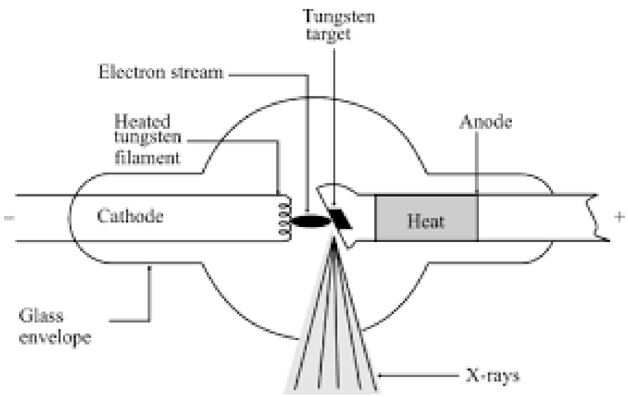


Figure 6. The relative intensity of photon energy emitted by a spectrum of X-ray radiation as either Bremsstrahlung or characteristic energy

4-Interactions of X-Rays with Biological Tissue

The ways in which x-rays can react with material within the body depends on the ability of individual tissues in absorbing radiation. In this case, the two most relevant interactions in diagnostic radiology are the photoelectric effect and Compton scattering. As explained before, each refers to how charged particles such as electrons react with atoms at the metal target of tungsten within the X-ray tube (John Hopkins Medicine, 2025). With the photoelectric effect, it is more prevalent in materials with higher atomic numbers (meaning materials with a higher number of protons in their atoms' nucleus, and, subsequently, electrons in the outer shell of those atoms), such as calcium, a mineral in bones that provides the strength and structure of these tissues. After the X-ray photon is absorbed in photoelectric absorption into an inner shell electron, in medical images, the bones will appear a whiter colour as a result of this effect. And, with the scattering of the photon in the case of Compton scattering, it mostly occurs in the incidence of softer tissues, and is the most common interaction with human tissue in X-ray imaging (Dawood Tafti & Maani, 2023).

However, alongside the photoelectric effect and Compton scattering, there also exists other ways in which X-ray radiation interacts with biological tissue, however, act minimally compared to the previously named interactions. Coherent scattering is one of them, and occurs when an X-ray photon of low energy interacts with an orbital electron, however, because it doesn't have as much energy, it cannot eject it as would be in the case of Compton scattering, and be absorbed. The photon will then be deflected and changes direction, however, it does not cause nor contribute to ionisation, which means it will only contribute a small amount to the dose and final generated image. Because of it's insignificant value to the final result, it doesn't exist as a major interaction between X-ray radiation and biological tissue when compared to the photoelectric effect and Compton scattering (ICRP, 2021).

During interactions between human tissue and X-ray radiation, there is a need to reduce the intensity of the radiation as it passes through a material. The existence of the photoelectric effect and Compton scattering allow this to occur, a process called X-ray attenuation. X-ray attenuation follows Beer-Lambert's law[2]:

$$I = I_0 e^{-\mu x}$$

Where I is the transmitted intensity, I_0 is the initial intensity, μ is attenuation coefficient, and x is thickness (Edinburgh Instruments, 2021). In the case of X-rays, this applies to the idea that denser tissues have a higher attenuation, henceforth, a contrast can be created in the final image.

5.X-Ray Detectors and Image Formation

There comes a point after the initial interaction of the X-ray photons with human tissue where they must reach the ray detectors to be converted into digital images. The ray detectors are devices designed to measure the properties of the X-ray radiation and convert their energy into measurable signals that can be used for medical imaging. As digital detectors, they can exists as flat panel detectors (a more common device in modern usage, offering a high level of sensitivity and resolution to the final image) or image plates that use phosphor to store the X-ray

2 Beer-Lambert's law shows the linear relationship where a higher absorbance is directly proportional to the concentration of a material and the amount of light that can pass through it.

energy and release it as light when a laser is shone on it, that a detector can then read (ADM Nuclear Technologies, 2025).

In other modern systems, scintillation detectors are also used. In this case, instead of converting the X-ray radiation into other forms of measurable energy, it is instead converted into visible light, which naturally releases an electric signal that can be measured to form images. Other instances of modern measurements include photodiode arrays detectors, which are more sensors than detectors, made up of numerous individual photodiodes arranged on a single chip, usually in a line or 2D grid. It uses a scintillator to convert the X-ray radiation into visible light and then generates the subsequent electric signal proportional to the intensity of the light at each point in travel.

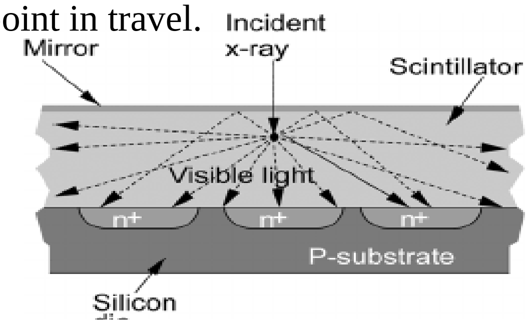


Figure 7. How a photodiode array detector uses a scintillator in X-ray radiation imaging

From this, it can be inferred that digital imaging of X-rays relies heavily depends on converting photon energy into an electronic signal that forms a pixel matrix. A higher rate of X-ray exposure increases the number of detected photons which in turn reduces noise and improves the resolution of the final image (Seibert, 2016). The image-processing software then adjusts contrast, sharpness, and grayscale to create diagnostically useful images.

6.Contrast Agents and Enhanced Imaging

Contrast agents are substances utilised in X-ray imaging to enhance the visibility of tissues and organs, so medical abnormalities are more easily detected. While different to the effects of natural tissue properties, the agents can alter how X-rays or magnetic fields interact with the body. The type of agent that influences the imaging modality, or what area the image may be used to identify and examine.

There are certain agents in X-ray imaging that are used for the enhancement of contrast in images su
ch as iodine and barium which absorbs X-rays strongly due to their high atomic numbers, allowing for soft tissues to be more easily visible on radiographs (Hughes, 2020). Iodine-based agents are mainly used for CT scanning, angiography and arthrography, to attenuate or even block X-rays, which creates clearer visibility. Meanwhile, for barium (more specifically, barium sulphates), they are insoluble compounds that are used for imaging the gastrointestinal tract (either orally or as an enema). Other agents used in enhancing image quality and contrast are gadolinium-based agents, used primarily in the studying of MRI scans. It utilises gadolinium, a metal that decreases the reaction time of nearby protons of water, increasing the signal in tissues where it's concentrated, typically administered intravenously (Inside Radiology, 2016).

7.Safety, Dose and Radiation Protection

Because a significant property of X-rays is that they are a form of ionising radiation, exposure to it can carry extreme risks, both short-term and long-term. Ionisation can damage DNA, leading to deterministic effects like skin burns and radiation sickness from more high doses. This is also referred to as acute radiation syndrome, which mostly occurs after a large exposure in a short amount of time. In fact, extremely high doses can be lethal. It can also stimulate an increase in the risk of cancer and hereditary mutations, even in the incidence of low dosages. The ionising radiation, in this case, has enough energy to break electrons from atoms, changing the structure and makeup of DNA in living tissues (US Environmental Protection Agency, 2014).

3

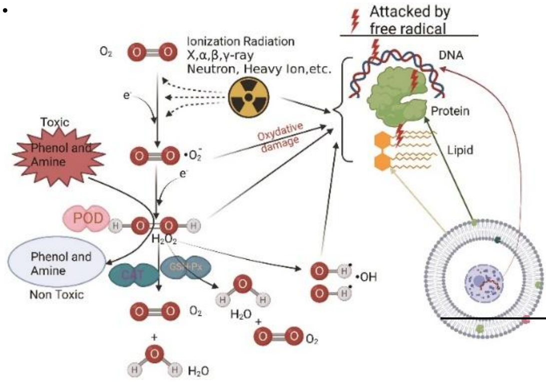
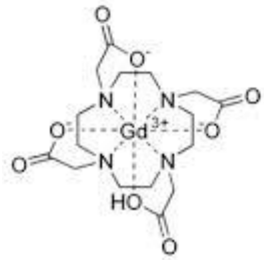
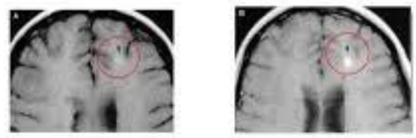


Figure 9.The effects of ionising radiation on cells, it's aftermath and it's contribution to active oxygen metabolism





Visualization of a tumor before (A) and after (B) injection of the contrast agent Gd-DOTA

Medical imaging operates under the ALARA principle which is simply an abbreviation of the phrase “As Low as Reasonably Possible”, using shielding techniques, collimation and optomised exposure settings, while also keeping levels of exposed radiation relatively low and stable enough, so as to not bring about any long-term or short-term consequences (ICRP, 2021). Typical effective doses vary by procedure—for example, a chest X-ray is about 0.1 mSv, while a CT scan can range from 2 to 10 mS

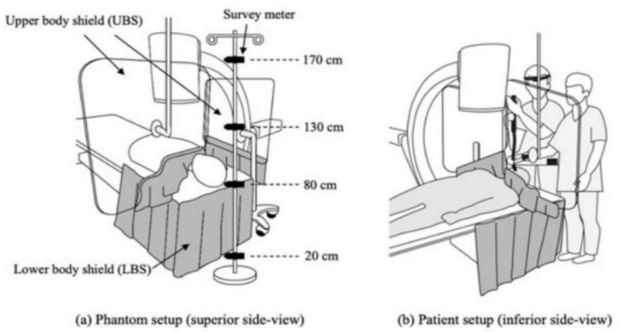


Figure 10. The setup of basic radiological shielding in image formation

8.Conclusion

X-ray imaging has stood as one of the most significant diagnostic tools, widely used across numerous scales in modern medicine. Through high-energy electromagnetic interactions, the penetrating nature of X-ray radiation, structural differences in bodily tissue can be detected and transformed into digital images. This understanding of how such radiation is produced, their individual interactions with matter and how detectors capture and process this information, allows for further inference of the theoretical physics and practical applications of this revolutionary technology, along with the help of contrast agents enhancing images. And yet with that, despite the inherent risks that come with X-ray imaging, the proper safety measures and limitations set in place allow for more effective usage of X-ray radiation as a diagnostic tool, further allowing utilisation of the technology that sets the groundwork for treatment planning and life-saving medical interventions.

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