Bibliographical Project

X-Rays and Radiography
(based on the work of Wilhem Röntgen)

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Abstract

In this abstract, we wil at the end of the redaction summarize goals and challenges of our report. This section is made as sum-up of our work.

Contents

Introduction

Before starting explanation of Wilhelm Röntgen's work and discovery we have made the choice to introduce a brief abstract on current theorical aspect of X-rays. There are several elementary points usefull to understand. Please keep in mind during lecture those notions.

Basics of X-rays's physics

X-rays, also recognized as X-radiation, are a form of electromagnetic radiation characterized by high energies. Radiation categorization is based on its wavelength λ, representing the length of one complete wave cycle. This wavelength can alternatively be defined in terms of frequency ν and the propagation speed of the wave, denoted as the speed of light. The relationship between these parameters is fundamental in characterizing different types of radiation, illustrating the interplay between wavelength, frequency, and the speed of light in the electromagnetic spectrum.

$$\lambda = \frac{c}{\nu} \tag{1}$$

The energy of a photon is characterised by the following formula :

$$E = \frac{hc}{\lambda} = h\nu \ = [eV] \tag{2}$$

The energy of photons can be expressed using Planck's constant $h \approx 6.626.10^{-3} J.s$ and the speed of light $c \approx 2.997.10^{8} m.s^{-1}$. This energy is directly connected to the wavelength λ or frequency ν of the photon, measured in electron volts [eV]. The relationship reveals that the photon energy is directly proportional to its frequency and inversely proportional to its wavelength. In simpler terms, an increase in frequency corresponds to higher energy, highlighting the direct relationship between these fundamental properties of photons.

These high-energy photons possess short wavelengths, resulting in exceptionally high frequencies. The pivotal parameter defining all photons is their radiation frequency, which, in turn, determines their energy. Photons are classified based on their energies, spanning from low- energy radio waves and infrared radiation, progressing through visible light, and culminating in high-energy X-rays and gamma rays.

Here is the complete electromagnetic spectrum :

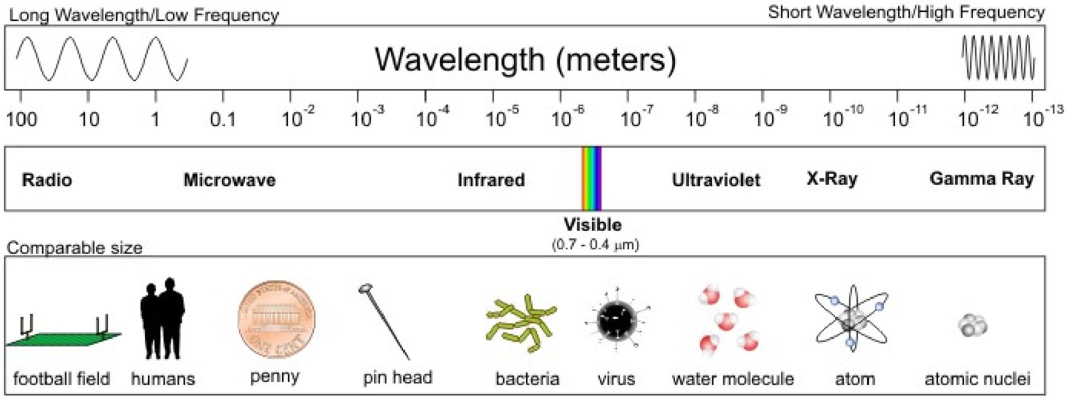


Figure 1: The Electromagnetic Spectrum (Credit : David Babb, PennState)

It is relevant to note that *X-rays and Gamma-rays* are also called *ionizing radiation* meaning they have engough energy to transform atom they go through into ions. Hence, the atom loose or receive an electron. This can make matter unstable.

Bremsstrahlung effect or braking radiation

In today's world, X-rays are generated using specialized X-ray machines. These machines offer the flexibility to adjust both current and voltage settings, enabling the manipulation of the properties of the X-ray beam produced. This capability allows for the application of distinct X- ray beam spectra tailored to specific body parts during medical imaging procedures.

Nowadays, Science explains the generation of X-rays the *Bremsstrahlung* effect from the German, braking radiation. According to the following Maxwell-Lorentz equations, "any electric charge with a variating speed emits an electromagnetic radiation".[1]

Maxwell's equations:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \tag{3}$$

$$\nabla \cdot \vec{B} = 0 \tag{4}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{5}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \tag{6}$$

Lorentz force equation:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{7}$$

[1] D. è. s. p. Jean-Jacques Samueli, "La découverte des rayons x par röntgen," *BibNum*, 2009. DOI: https://doi.org/10.4000/bibnum.714. [Online]. Available: http://www.bibnum.education.fr/sites/default/files/RONTGEN-ANALYSE.pdf.

You can observe on Figure 2 that emitted electrons are deviated by the positive charge of target's atoms.

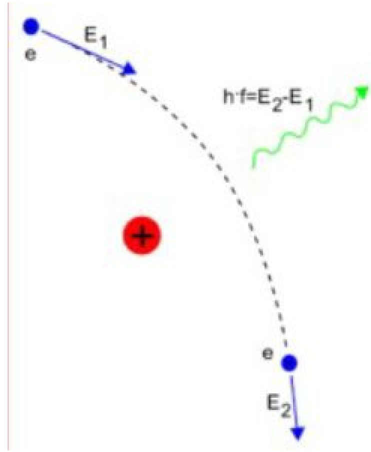


Figure 2: *Bremsstrahlung effect*

During the deviation, a photon is emitted by the atom. This is the radiation. The energy balance of the interaction is given by :

$$E_c' - E_c = h\nu \tag{8}$$

The majority of X-rays exhibit wavelengths that fall within the range of 0.01 to 10 nanometers (corresponding to frequencies of $3.10^{16} Hz$ to $3.10^{19} Hz$), with energies spanning from 100 eV to 100 keV. Notably, X-ray wavelengths are shorter than those of ultraviolet (UV) rays and generally longer than those of gamma rays.

Chapter 1

Historical Background

1.1 Radiation Understanding in the Late 19$^{\text{th}}$ century

The 19th century stood as an era dominated by an abundance of brilliant minds, particularly in the field of physics, showcasing an unprecedented concentration of intellectual prowess in the department of sciences. This period unfolded with a cascade of remarkable discoveries, groundbreaking inventions, precise measurements, and novel theories.

It was characterized by significant advancements in different domains in physics like electricity and thermodynamics, leading to transformative technical and medical applications. These innovations collectively revolutionized our world, shaping the course of history and influencing the present day.

In the late 19th century, significant progress was made in the exploration of atomic structure and radiation. We could for example talk about Dmitri Mendeleev groundbreaking contribution in 1869 with the introduction of the periodic system of elements. Going back in time, William Herschel's 1800 discovery of infrared rays using a prism revealed previously unseen rays beyond the red spectrum, termed "calorific rays.". Johann Wilhelm Ritter, in 1801, explored ultraviolet radiation, noting its darkening effect on silver chloride. James Clerk Maxwell's equations laid theoretical groundwork, proposing that visible light, infrared, and ultraviolet rays are disturbances in the electromagnetic field. Heinrich Hertz's 1887 deliberate creation of radio waves applied Maxwell's equations practically.

W.C. Röntgen was especially interested in the work of Mrs. Hertz and Lenard,two german researchers. Their worked on cathod-rays, and the electricity discharges in low-pressure gazes. Röntgen studies on this subject is fundamental for his future discovery.

Chapter 2

Life and Career of Wilhelm Conrad Röntgen

2.1 Early Life of an enthusiastic genius

Figure 2.1: WIlhelm Conrad Röntgen

Sometimes history is made of incredible destiny. Wilhelm Conrad Röntgen, born on March 27th, 1845 near Dusseldorf, Germany was not incline to brillant physics studies. His father a sheet merchant did not push him throughout this way. Röntgen's early life was marked by a move to Netherlands for his father's business. Röentgen's journey into science began at the Utrecht Technical School at the age of 16, leading to a diploma in engineering three years later. His academic pursuits continued, culminating in a Ph.D. under the guidance of A.E.E. Kundt, focusing on gas properties.

Röentgen was described as a tall, dark, and slender man, maintained a modest and meticulous approach to his scientific endeavors. Röentgen's career progressed with his mentor, Kundt, to the University of Würzburg and later to Strasbourg, where he became an associate professor in theoretical physics. In 1879, he assumed the position of professor of physics at Giessen, eventually returning to Würzburg in 1888. It was here, on November 8, 1895, that Röentgen accidentally observed what he later named X-rays. Promptly sharing his findings with the Physics-Medical Society of Würzburg in December, his discovery quickly captivated the global scientific community.

The Vienna Presse reported the phenomenon in January 1896, highlighting the potential applications of X-rays in medicine. The discovery opened doors to radiology, with practical uses imaging, such as locating bullets in the human body and visualizing fractures before surgery. Despite initial challenges in applying X-rays to obstetric[1] and prenatal diagnosis due to limited penetration through tissues, subsequent decades saw significant progress, particularly in the 1930s with the development of more powerful X-ray beams.

2.2 Röntgen's groundbreaking experiment

On November 8, 1895, Röntgen covered a Crookes tube with black cardboard. The Crookes tube was powered by a Ruhmkorff coil, functioning as a step-up transformer that received recurrent electrical pulses. Each pulse resulted in an electrical discharge within the low-pressure gas filling the tube. In a dark environment, Röntgen noticed fluorescence on a paper screen coated with platinum-barium platinocyanide. This substance exhibited the property of fluorescing, emitting light when stimulated by photons. The fluorescence manifested when the paper was positioned at a distance of less than two meters from the tube, even when shielded by black cardboard. Röntgen deduced that an imperceptible radiation, of unknown nature, which he termed X- radiation, emanated from the tube and caused the observed fluorescence.

On December 28, 1895, following the six weeks of relentless effort and without confiding in anyone else about the X-rays, Röntgen opted to announce his breakthrough. on the subject titled "Über eine neue Art von Strahlen" (On a new type of rays)[2]. This article provided early insights into the absorption properties of various materials, including paper, wood, and metal. Wood and paper (even *thoousand pages books had no effect*) for blocking rays at the contrary of some metals. He presented a series of "shadow-pictures," a term coined by Röntgen himself, drawing inspiration from the realm of photography. These images served as tangible evidence of his groundbreaking discovery.

[1] P. Dunn, "Wilhelm conrad röentgen (1845-1923), the discovery of x rays and perinatal diagnosis," *Archives of disease in childhood. Fetal and neonatal edition*, vol. 84, F138–9, Apr. 2001. DOI: 10.1136/fn.84.2.F138.

[2] M. Röntgen, "Sur une nouvelle espèce de rayons," *J. Phys. Theor. Appl.*, vol. 5, no. 1, pp. 101–108, 1896. DOI: 10.1051/jphystap:018960050010100. [Online]. Available: https://hal.science/jpa-00239851.

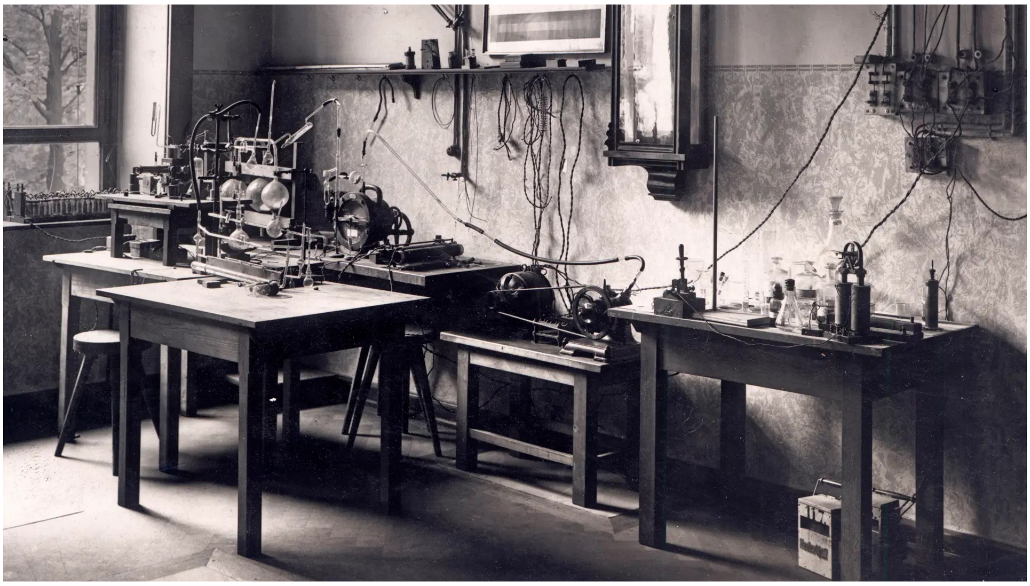


Figure 2.2: Röntgen's lab at the University of Würzburg (Credit : German Röntgen Museum)

His lab in the University of Würzburg was kind of spartiate but he had enough means to conducts every experiments he wanted. This is a particularity of German's research organisation. Even universities of small town receive consequent subventions. This with the aim of promoting initiatives.

Röntgen, obviously because of it technical school background and a intrinsic curiousity, was an extremely fine experimenter. This is characteristic of its knowledge and work. After his discovery, he said *I was not thinking, only searching...* Always, he had deep humility, often this was too much toward his talent.

In January 1896, Röntgen demonstrated his groundbreaking discovery to the German medical- physical society. A compelling moment during this demonstration involved creating an X-ray image of the hand of Albert von Kölliker, a prominent anatomist of that era (refer to Fig. 7.4). This live demonstration immediately convinced Röntgen's colleagues of the practical significance of his invention.

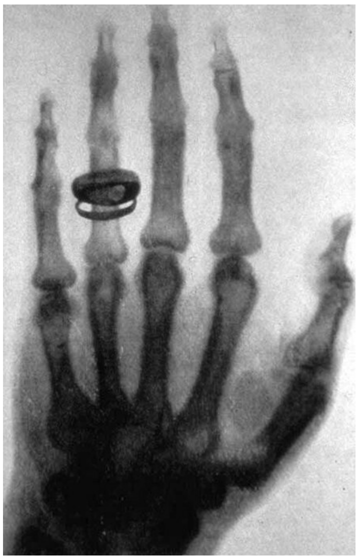


Figure 2.3: X-ray of Kölliker's hand, made by Röntgen on 23 Jan 1896 (Credit : German Röntgen Museum)

While the appearance of these photographs was described as ghastly, the article emphasized their significant scientific implications. The practical applications of this discovery were extensive, including the ability for surgeons to use this new form of photography to precisely locate embedded bullets in the human body or visualize fractures in bones before surgical procedures. The method also held promise for addressing conditions such as caries and other bone diseases. The Vienna Press assured its readers that this was a serious and genuine discovery by Professor Röentgen, marking the birth of radiology. Despite his reputation for being quiet and reserved, it is ironic that Röntgen's discoveries garnered instant global attention. This can be attributed to another aspect of his character. Röntgen's willingness to forgo patenting his findings allowed researchers worldwide to explore and experiment with X-rays. He firmly believed that his "inventions and discoveries belong to the world at large."

Chapter 3

The Discovery of X-Rays

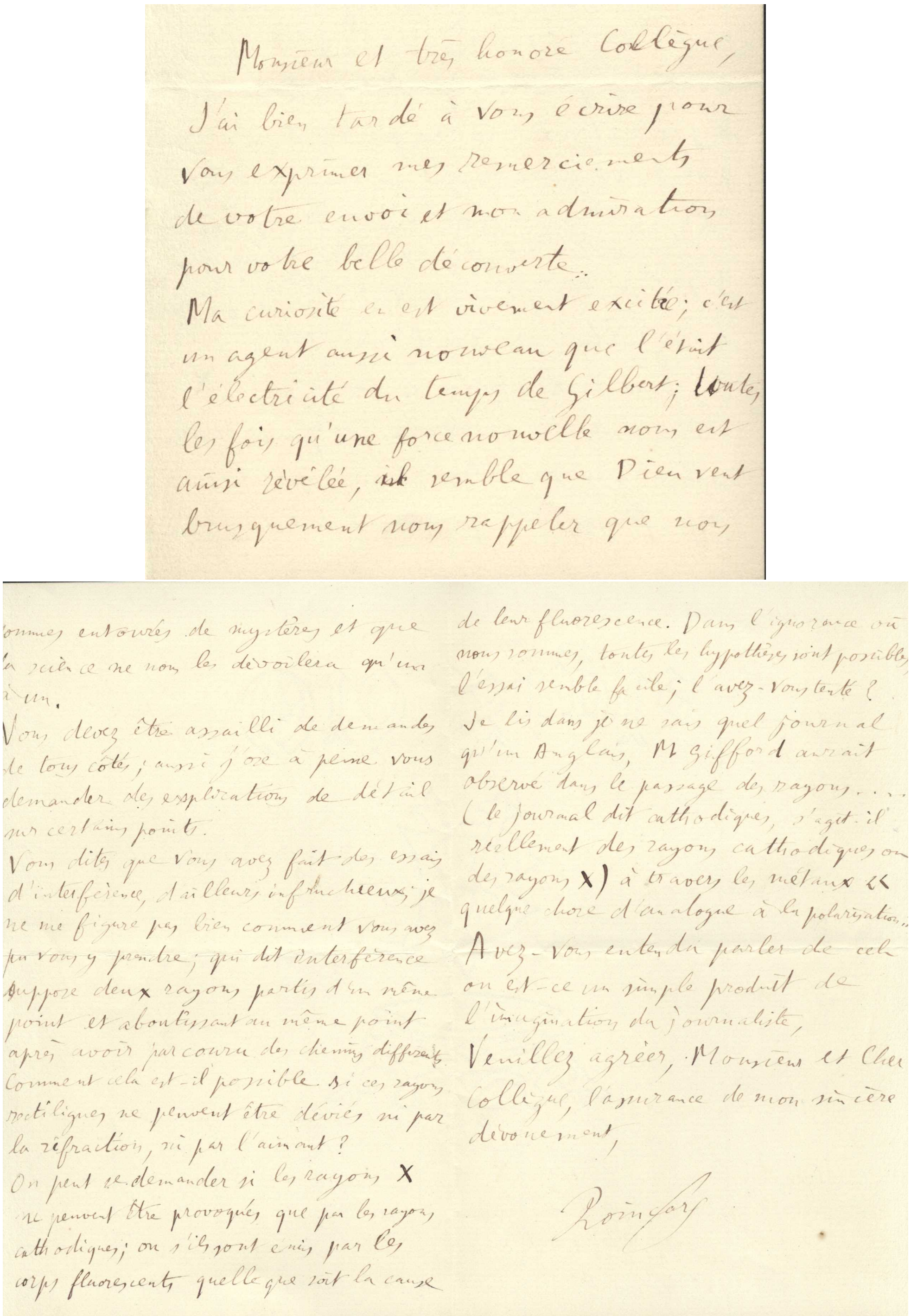
In this chapter we will reveal Röntgen's experimental setup and methodology, the moment of his discovery. Then we will show the first X-ray images, and the reaction of the public and scientific world after the discovery.

3.1 Impact of Röntgen's X-Rays discovery

In this section, we will reveal Röntgen's experimental setup and methodology, the moment of his discovery. Then we will show the first X-ray images, and the reaction of the public and scientific world after the discovery.

Wilhelm Röntgen's accidental discovery of X-rays in 1895 marked a seismic shift in the realms of medicine and physics. The serendipitous moment, capturing the image of his fingers on a cardboard screen, set the stage for an unprecedented revolution. Within months, X-rays found applications in medicine, with studies initiated to explore vascular anatomy and the gastrointestinal tract. The rapid dissemination of Röntgen's findings worldwide showcased the extraordinary impact of this breakthrough. By 1896, over a thousand scientific papers on X- rays had been published, with widespread implications for both medical and physical sciences. Industrial advancements, such as Thomas Alva Edison's contributions, further propelled the transformative wave. This discovery pushed other physicist to explore the X-ray spectrum, with the discovery by Compton/Rayleigh of high/low energy waves. Röntgen's recognition culminated in numerous honors, including the inaugural Nobel Prize for Physics in 1901, underscoring the enduring influence of his revolutionary discovery.

For example, Henri Poincaré, a French great physician, congratulated Röntgen in a letter[1] for his experience and discovery. It reveals a real enthusiasm. Please have a look.



Monsieur et très honoré Collègue,

J'ai bien tardé à vous écrire pour vous exprimer mes remerciements de votre envoi et mon admiration pour votre belle découverte.

Ma curiosité en est vivement excitée; c'est un agent aussi nouveau que l'était l'électricité du temps de Gilbert; toutes les fois qu'une force nouvelle nous est aussi révélée, il semble que Dieu veut brusquement nous rappeler que nous sommes entourés de mystères et que la science ne nous les dévoilera qu'un à un.

Vous devez être assailli de demandes de tous côtés; aussi j'ose à peine vous demander des explications de détail sur certains points.

Vous dites que vous avez fait des essais d'interférence, d'ailleurs infructueux; je ne me figure pas bien comment vous avez pu vous y prendre; qui dit interférence suppose deux rayons partis d'un même point et aboutissant au même point après avoir parcouru des chemins différents. Comment cela est-il possible si ces rayons rectilignes ne peuvent être déviés ni par la réfraction, ni par l'aimant?

On peut se demander si les rayons X ne peuvent être provoqués que par les rayons cathodiques; ou s'ils sont émis par les corps fluorescents quelle que soit la cause de leur fluorescence. Dans l'ignorance où nous sommes, toutes les hypothèses sont possibles, l'essai semble facile; l'avez-vous tenté?

Je lis dans je ne sais quel journal qu'un Anglais, M. Gifford aurait observé dans le passage des rayons.... (le journal dit cathodiques, s'agit-il réellement des rayons cathodiques ou des rayons X) à travers les métaux «quelque chose d'analogue à la polarisation».

Avez-vous entendu parler de cela ou est-ce un simple produit de l'imagination du journaliste,

Veuillez agréer, Monsieur et Cher Collègue, l'assurance de mon sincère dévouement,

Poincaré

Figure 3.1: Letter from H. Poincaré to W. C. Röntgen

[1] H. Poincaré, *Letter from h. poincaré to w. c. röntgen*, Congratulation for his discovery and questions on his work, Archives Henri Poincaré, Jul. 1896. [Online]. Available: https://henripoincare.fr/s/correspondance/item/8007 (visited on 11/24/2023).

Here is a transcript and translation of some sentences.

J'ai bien tardé à vous écrire pour vous exprimer mes remerciements de votre envoi et mon admiration pour votre belle découverte.(...)

Ma curiosité en est vivement excitée; c'est un agent aussi nouveau que l'était l'électricité du temps de Gilbert.(...)

Vous devez être assailli de demandes de tous côtés; aussi j'ose à peine vous demander des explications de détail sur certains points.(...) On peut se demander si les rayons X ne peuvent être provoqués que par les rayons cathodiques; ou s'ils sont émis par les corps fluorescents quelle que soit la cause de leur fluorescence.

I have been quite delayed in writing to you to express my gratitude for your shipment and my admiration for your wonderful discovery. (...)

My curiosity is greatly aroused by it; it is an agent as novel as electricity was in Gilbert's time. (...)

You must be inundated with requests from all sides; therefore, I hardly dare to ask you for detailed explanations on certain points. (...) One may wonder whether X-rays can only be provoked by cathode rays, or if they are emitted by fluorescent bodies regardless of the cause of their fluorescence. (...)

This piece of history from 1896, announces well how revolutionary this discovery is. Poincaré makes a comparison with discovery of electricity.

3.2 Explanation and phenomenons behind Rongtens discovery

3.2.1 Crookes's Tube

The main tool at the disosal of Röntgen was a cathode-rays tube. Known today as *Crooke's Tube* from the name of the invento r a british physician.

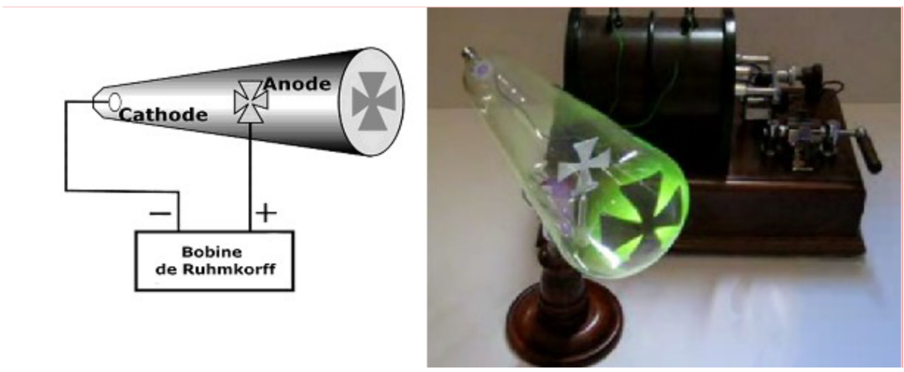


Figure 3.2: A Crooke's Tube and its schematic

This tube is the firt means of observation for X-rays. It is a vacuum-sealed glass tube housing a cathode and a solid metal anode. In a classical X-ray tube, there's a part called the cathode with a heated filament. When this filament gets really hot, it releases electrons. These electrons are then pushed or accelerated by the tube's electric power (voltage) from the cathode (negative side) to the anode (positive side). When these speedy electrons hit the anode, they slow down and change direction because of the anode's electric field. This slowing down process creates electromagnetic waves, and specifically, it produces X-rays. So, in simpler terms, the X- ray tube works by heating up a filament to release electrons, accelerating these electrons with electric power, and then letting them hit a metal target, which produces X-rays in the process.

The anode is angled at a specific degree to guide the X-rays in the intended direction. Normally, each electron undergoes multiple slowing down or deflection actions, leading to the production of several photons. Nevertheless, there's a possibility that an electron loses all its speed and energy in a single step. In such instances, only one photon is generated, encompassing the entire energy of the electron.

It is important to note that cathode-rays observed originally in Crookes tube are rays of electrons and therefore may be deviated by an electric or magnetic field. According to Röntgen experiments this is not the case, X-rays are longitudinal and can not be deviated by electric or magnetic field. We demonstrate later that is because X-rays has no charge.

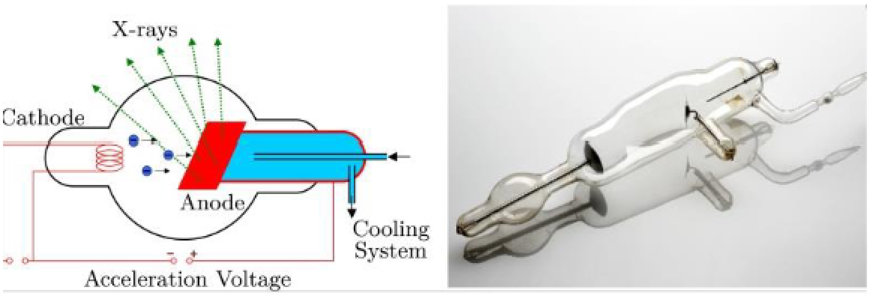


Figure 3.3: A more modern Crooke's Tube with its schematic (Credit : Science Museum, London)

The modern vacuum X-ray tube, depicted in the images, operates through the acceleration of electrons from the cathode to the anode, ultimately leading to the generation of X-ray photons. In the schematic on the left, the acceleration of electrons is illustrated as they travel from the cathode to the anode within the vacuum tube. This process results in the production of X-ray photons. The image on the right displays a historical vacuum X-ray tube, providing a tangible representation of the technology. This visual insight into the apparatus underscores the significance of these tubes in the historical development of X-ray imaging.

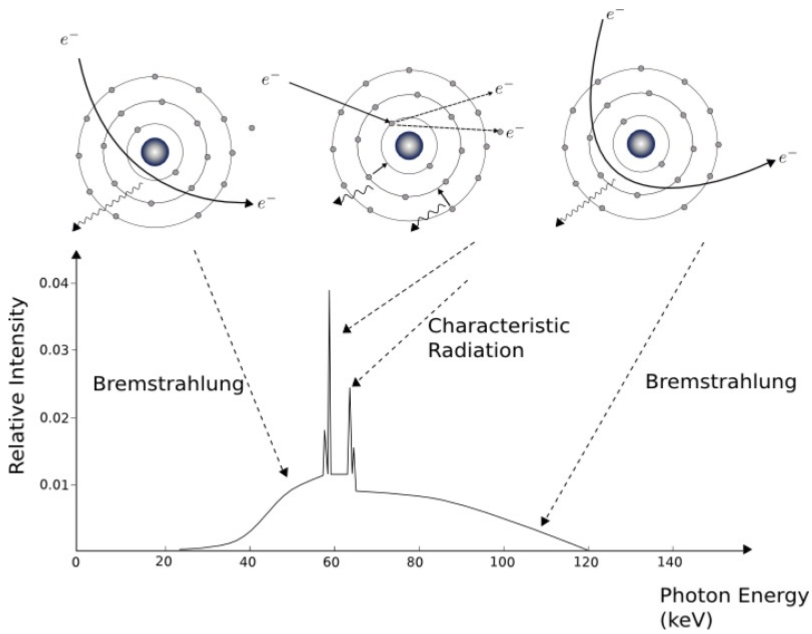


Figure 3.4: X-ray spectrum of a tungsten tube. (Credit : NCBI Bookshelf)

The X-ray spectrum produced by a tungsten tube exhibits characteristic radiation peaks, with the continuous portion of the spectrum representing Bremsstrahlung.

This report[2] explained the peculiar nature of invisible light rays, revealing that wood and other organic materials were transparent to these rays, while metals and bones, whether human or animal, were opaque. This meant that these rays could be absorbed by bones or metals enclosed in a wooden or woolen covering, enabling the photographing of bones or metals within such materials. The article noted that human flesh, being organic, behaved similarly, allowing the photography of bones without the accompanying flesh appearing on the plate. Vienna already had photographs demonstrating this, showcasing human hand bones along with rings worn on the fingers.

[2]M. A. Berger M Yang Q, *Chapter 7, X-ray Imaging*, Springer, Ed. 2018. DOI: 10.1007/978-3-319-96520-8_7.

3.2.2 Ruhmkorff Coil

Crookes tube is nothing without a high voltage pulse generator called *Ruhmkorff's Coil*. It is necessary to provide high electric discharge for the radiation.The following figure explains the operation.

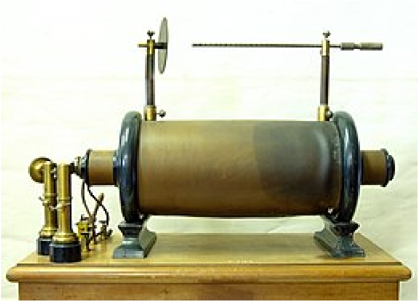


Figure 3.5: Original Ruhmkorff Coil

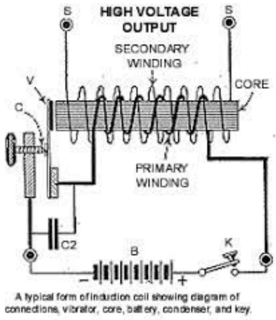


Figure 3.6: Diagram of a Ruhmkorff Coil

Röntgen used generally a current of 20 A to generate adequated sparks.

3.2.3 The Lambert-Beer's Law

To understand the apparition of more or less dark spot. The *Lambert-Beer 's Law* is necessary.

The Beer-Lambert law asserts that the absorbance of a solution is directly proportional to its concentration. Here is the relation.

$$I = I_0 \cdot e^{-\mu x} \tag{3.1}$$

Here I is the intensity output, I_0 is the intensity input, μ is the linear attenuation coefficient. It is important to note that this formulation works inside liquid solution. This formula is derived from a first order homogenous differential equation of the radiation intensity.

$$\frac{dI}{dx} = -\mu I \tag{3.2}$$

Therefore, we may show that biological matter such as bone or soft tissue have different absorption properties. It follows X-Rays densities for human body.

3.2.4 The 5 X-ray densities

The contrast observed in an overall medical image is contingent on variations in both the density and thickness of anatomical structures within the body. The extent of contrast between two adjacent structures within the image is directly proportional to the disparities in either the density or thickness of those structures. Descriptively, five distinct densities can aid in discerning the characteristics of abnormalities. Notably, unexpected changes in the density of a recognized anatomical structure, whether an increase or decrease, can provide valuable insights into the tissue composition of the abnormality, aiding in its identification and characterization.

Figure 3.7: 5 different colours according to type of matter[3]

The classification of X-ray densities encompasses five distinct categories. Low-density substances, like air, are visualized as black on the final radiograph, while highly dense materials such as metal or contrast agents appear as white. Bodily tissues exhibit a range of grey tones, dictated by both their density and thickness. This grayscale spectrum allows for nuanced differentiation among various anatomical structures, facilitating a comprehensive and detailed interpretation of X-ray images in medical diagnostics

3.3 Radiography's Early Applications and Pioners

Here, we will dive thought on how Röntgen's discovery led to the development of radiography. We will also discuss about the pioneers in radiography who followed Röntgen We will finalize by talking about the early applications of radiography in medicine and industry.

3.3.1 Wilhelm Conrad Röntgen: Pioneer of Radiology

Wilhelm Conrad Röntgen, the founder of radiology, made a transformative discovery in 1895 by accident. While experimenting with cathode-ray tubes and glass, he uncovered invisible rays capable of passing through most substances, naming them "X-rays." Röntgen's groundbreaking work led to the publication of "On a New Kind of Rays" on December 28, 1895. His findings spread rapidly, and by February 1896, clinical applications of X-rays had begun. Röntgen's remarkable contributions earned him the first Nobel Prize in physics in 1901, establishing the foundation for modern radiology.

3.3.2 Study of Crystal atomic structures

Röntgen at his time thought that diffraction was not possbible with X-rays. This was a big question weeks after his discovery, but he did not continue researches on the subject.

However during his life other scientists found a way to differentiate authentic diamonds with fakes one using radiology. Fake diamonds, made at the time with very dense type of glass, observed a lot more absorption than real ones that were almost transparent. The reason why is true diamonds are crystal with well organised atomic structure letting radiations go through. Whereas fakes one had disorganised structure more opaque.

This observation was the premisces of using X-rays diffraction to precisely determined the atomic structure of crystal. Nowadays[4], the technique is very powerful and used in chemistry. Calculations based on diffraction spot resolve the atomic structure or monocrystal.

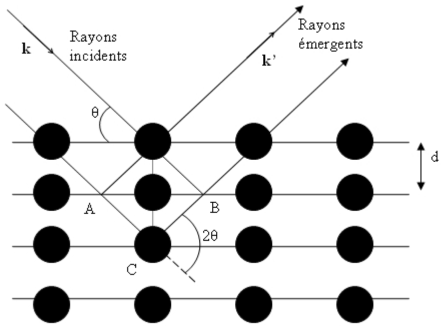


Figure 3.8: Reflection of X-rays by a family of lattice planes spaced at a distance d

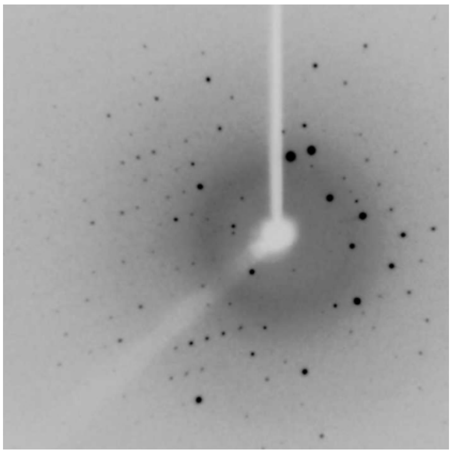


Figure 3.9: Image obtained during the exposure of a single crystal to an X-ray beam.

3.3.3 Evolution of Radiology Technology

The history of radiology technology evolved from early glass photographic plates to contemporary digital imaging and archiving technologies like PACS/MIMPS. In contrast to traditional X-ray films, which directly utilize X-rays to alter the chemical properties of the film material, modern detection systems follow a different approach. They initially convert X-rays into light and subsequently transform this light into electrons for the imaging process. The progression continued with significant leaps, including George Eastman's introduction of film in 1918. Advances persisted with the advent of ultrasound technology post-World War II, followed by the introduction of computed axial tomography (CAT scan) and magnetic resonance imaging (MRI) in the 1970s.

[4] E. J. Christophe Aronica, "Diffraction des rayons x - techniques et études des structures cristallines," *CultureSciences Physique*, 2009, ISSN: ISSN 2554-876X. [Online]. Available: https://culturesciencesphysique.ens-lyon.fr/ressource/Diffraction-rayons-X-techniques-determination-structure.xml.

Figure 3.10: R. Damadian, L. Minkoff, M. Goldsmith and the "Indomitable," the world's first MRI scanner which they developed (Credit : BBC)

3.3.4 Timeline of Advances in Radiology

The timeline of advances in radiology marks significant milestones in medical imaging technology. In 1895, Wilhelm Röntgen's discovery of X-rays revolutionized the field, laying the foundation for future developments. Fast forward to 1972, when Godfrey Hounsfield introduced the first CT scanner, a groundbreaking innovation that provided detailed cross-sectional images of the body. In 1977, Raymond Damadian achieved another milestone with the completion of the first MRI, offering a non-invasive method for imaging soft tissues. The turn of the millennium brought recognition to the PET-CT scanner, named the medical invention of the year in 2000, highlighting the ongoing strides in enhancing diagnostic capabilities and patient care through radiological advancements

3.3.5 Transformative Journey

From glass plates to cutting-edge digital modalities, radiology has revolutionized patient care. Technological advances have given rise to tailored software solutions like PACS, RIS/PACS integrations, teleradiology, and Imaging EMRs, setting the gold standard for 21st-century medicine and healthcare administration. The journey, highlighted by groundbreaking discoveries and innovations, continues to shape the future of radiology and healthcare delivery.

Chapter 4

Advances in Radiographic Technology

4.1 Evolution of Radiography Equipment and Techniques

Here, we will talk about the evolution of radiographic equipment and techniques.

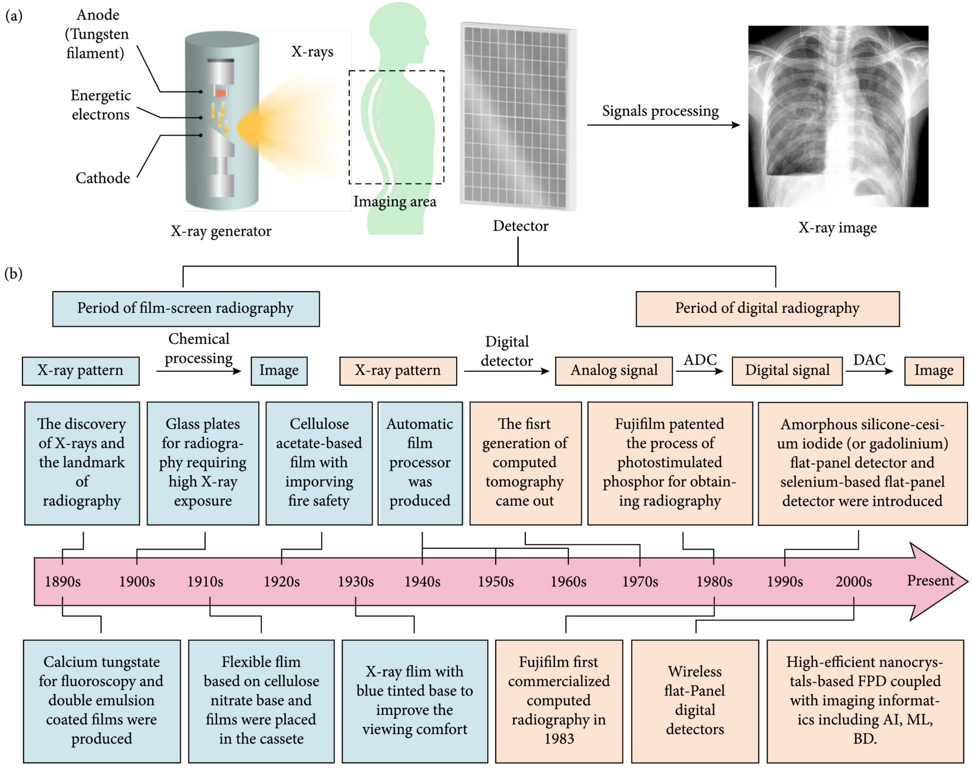


Figure 4.1: (a) Schematic illustration of an X-ray imaging system. (b) The development of X-ray radiography with the evolution of X-ray detectors

4.2 Technological Breakthroughs in Radiography

We will follow up by discussing technological breakthroughs in radiography.

In this era, patients underwent notably invasive tests, and awareness of the hazards associated with radiation exposure was on the rise. The 1970s marked a transformative period in radiology, often referred to as the "golden decade," as the introduction of the CT scanner ushered in a new era of possibilities and groundbreaking discoveries. The advancements made during this time laid the foundation for further innovations in the subsequent decades, particularly in the 1980s and 1990s.

To better understand the progress in the field, it is helpful to categorize each decade into distinct areas of focus. These subdivisions encompass radiology, radiography, radiotherapy, radiobiology, medical physics, and diagnostic imaging. By examining developments within these specialized domains, one can gain a comprehensive overview of the dynamic evolution of medical imaging and radiation-related disciplines over the years.

4.3 Radiography During World War I and II

We will extend this chapter by talking about the impact of World War I and World War II on radiography.

Soon after Wilhelm Roentgen's discovery of X-rays in late 1895, their application in medical operations swiftly emerged. Recognizing their utility, military surgeons embraced X-rays for identifying broken bones, bullets, and shrapnel in wounded soldiers. This newfound technology played a crucial role in diagnosing injuries during various conflicts, including the Greco-Turkish War, the Russo-Japanese War, and the Balkan Wars over the next few years. To support field hospitals, mobile units were developed, ensuring that X-rays could be readily available wherever surgery was performed, underscoring their vital role in advancing medical practices on the battlefield.

In 1914, Marie Skłodowska Curie, already renowned for her groundbreaking work in radioactivity, including the discovery of radium and polonium, found a practical application for 20 her expertise when World War I erupted in Europe. Recognizing the potential of X-rays in aiding the treatment of wounded soldiers, Curie saw an opportunity to make a significant impact on battlefield medicine.

Figure 4.2: Portrait of Marie Curie. First female to win the Nobel prize (Credit : Flickr/Okänd)

Understanding that X-rays could assist in locating and extracting bullets, shrapnel, and identifying broken bones within the bodies of injured soldiers, Curie took action to bring this technology closer to the front lines. Despite many hospitals in France having X-ray equipment, the machines were often situated far from the immediate battlefield.

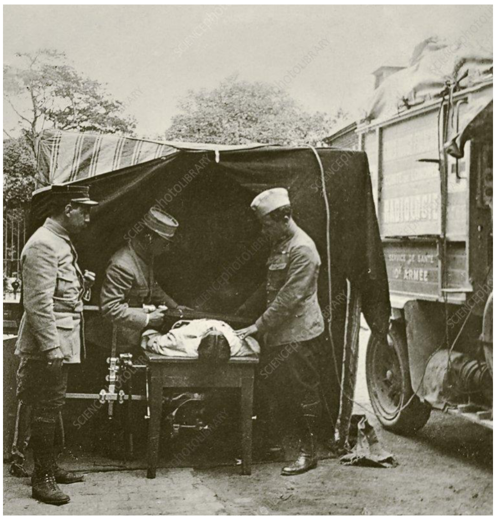


Figure 4.3: A mobile X-Ray Unit during WW1

To bridge this gap, Curie and her daughter organized a fleet of vehicles equipped with X-ray machines. Over the first two years of the war, they established 200 radiological units in more permanent posts, strategically placing them closer to the areas where medical attention was urgently needed. This initiative, spearheaded by Curie, played a vital role in improving the efficiency of medical care on the battlefield, showcasing the innovative application of scientific knowledge to address urgent wartime challenges.

The advances in technology, particularly the widespread use of X-rays during the First World War, held profound significance on two fronts. Firstly, they directly contributed to saving lives by enhancing the medical response to injuries, especially those caused by gunshot wounds and shrapnel. The ability to swiftly and accurately identify foreign objects within the body facilitated more effective surgical interventions, thereby increasing the chances of survival for wounded soldiers.

Secondly, these technological advancements played a crucial role in preventing illness by addressing the persistent threat of infection. Infection, a major cause of fatalities throughout the war, posed a significant challenge to medical care. By aiding in the precise detection and removal of foreign objects, X-rays contributed to minimizing the risk of infection and its subsequent spread. Consequently, the integration of cutting-edge technology not only improved immediate patient outcomes but also played a pivotal role in mitigating the secondary health risks associated with wartime injuries.

To ensure timely medical intervention on the front lines during wartime, the development of portable X-ray equipment became crucial. Recognizing the significance of proximity in enhancing the chances of saving lives, military x-ray units were established to deploy this technology efficiently. Casualties typically undergo multiple stages of care, emphasizing the importance of having X-ray capabilities as close to the front line as possible. The responsive solution was the creation of mobile X-ray units, equipped with portable machines that could swiftly and effectively be set up in field hospitals and forward medical stations. This strategic deployment aimed to minimize the time between injury and diagnosis, facilitating prompt and targeted medical responses in critical situations.

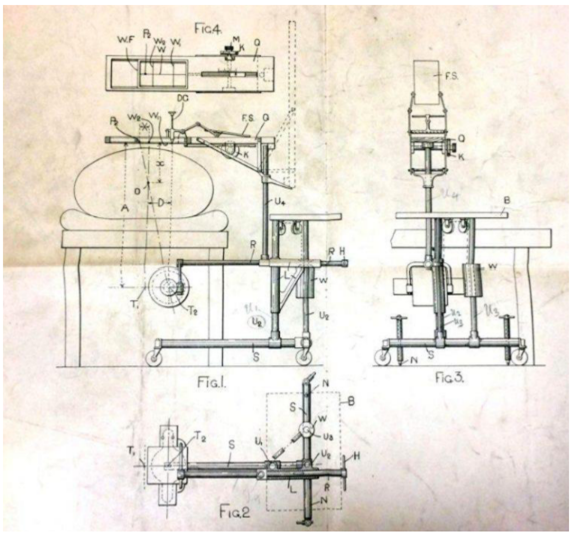


Figure 4.4: Assembling schematic of a mobile Unit for X-Rays

Chapter 5

Modern Applications of Radiography

5.1 Contemporary Uses and Challenges in Radiography

We will emphasize here the contemporary uses of radiography in medicine, industry, and other fields, along with the benefits and challenges of modern radiographic technology.

Radiological technology, once in a disruptive phase, is now transitioning into a sustaining phase, presenting a spectrum of challenges and opportunities that shape the future of medical imaging. Two critical challenges in medical imaging are the pursuit of precise, noninvasive tissue characterization and the enhancement of micro resolution for early lesion detection. Despite its current share of only 5 % of total healthcare expenditure, concerns about the affordability of imaging technology arise due to its increasing costs amid rapid utilization. The perception of radiologists as 'invisible' figures, secluded in dark cubicles, poses a challenge in the era of digitalized medicine and virtual visits. The evolution towards in vitro diagnostics (genomics, proteomics) is a challenge but offers potential solutions for earlier disease diagnosis, revolutionizing radiological screening policies

On the flip side, numerous opportunities await the field. Quantitative imaging, with its emphasis on precision and evidence-based medicine, holds the potential for growth. Improved networking and communication facilitated by Picture Archiving and Communication Systems (PACS) and Radiological Information Systems (RIS) offer active sharing of databases, contributing to 'value- based radiology.' Interventional radiology stands out as a significant opportunity, minimizing invasiveness and lowering costs through advanced techniques and semi-automated guidance software. The integration of over 50 billion connected devices, including medical devices, in the coming years presents opportunities for telemonitoring, emergency notification systems, and portable laboratory testing, revolutionizing the diagnostic approach.

Examining technological advancements in X-ray imaging since 1895 reveals ongoing efforts to address challenges. The search for advanced X-ray energy converting materials continues to achieve low-dose, high-resolution, large-area, and flexible X-ray detectors. Technical hurdles, such as scintillation decay, synthesis processes, and optical crosstalk, persist but must be overcome for practical radiography. Metasurface technology, combining high-efficiency X-ray converting layers, emerges as a promising strategy to enhance X-ray sensitivity. On going developments aim to create large-area and flexible X-ray imaging detectors, opening possibilities for applications in dental X-ray inspections, imaging irregular objects, and portable X-ray testing.

In conclusion, while radiological technology faces challenges in evolution, the fusion of innovation, adaptability, and advancements offers a promising future for medical imaging, where precision, accessibility, and patient-centric approaches take center stage

Chapter 6

Ethical and Safety Considerations in Radiography

6.1 Ethical and Safety issues in Radiography

We will talk about ethical and safety issues related to radiographic procedures

The historical development of regulations for radiation protection. Initially, individuals sought protection through professional guidelines, with the German Roentgen Society providing guidelines in 1913. George Pfahler in the U.S. urged the creation of guidelines, emphasizing the mastery of radiology principles and legal protection for radiologists. In 1927, the National Bureau of Standards initiated a voluntary inspection program for radiation equipment. The International Commission on Radiological Protection (ICRP) and the U.S. Advisory Committee on X-Ray and Radium Protection played pivotal roles in formulating guidelines. Concepts like "tolerance dose" and "maximum permissible dose" were established, with ongoing revisions based on health risks rather than arbitrary limits. The Nuclear Regulatory Commission (NRC) emerged in 1974 to separate conflicting objectives and continue regulatory functions, ensuring a balance between fostering nuclear technologies and protecting public health.

6.2 Development of Safety Protocols and Regulations

Medical imaging's centrality to patient care, akin to labs or pathology, has spurred concerns about radiation safety dating back to the field's inception. Over the last decade, several states, following California's lead, have mandated enhanced radiation dose management, presenting a considerable operational challenge for healthcare providers. Dose Management Systems (DMS) have emerged as vital support in navigating these regulations. The imperatives for dose management excellence encompass data aggregation and processing, ensuring compliance with regulations and best practices, leveraging visualizations for insights, interoperability with existing IT infrastructure, and scalability. Modern DMS, exemplified by Siemens Healthineers' Teamplay Dose, address these imperatives, providing easy access to dose data, supporting quality assurance, and offering advantages such as reduced infrastructure costs and continuous feature releases, thus contributing to the systematic monitoring of patient radiation dose with enhanced efficiency and efficacy

The development of safety protocols and regulations in the context of radiation exposure is crucial, considering the intricate nature of its effects on living organisms and the environment. Nuclear power reactors, while containing the majority of radioactivity, still emit a small percentage as gas or liquid effluent, contributing to global background radiation. Despite efforts to minimize exposure, cancer treatments involve doses significantly larger than environmental radiation, underscoring the need for stringent safety measures. Radioactive releases from nuclear bomb explosions or accidents can contaminate the atmosphere and water over long distances, emphasizing the importance of regulatory frameworks to mitigate such risks. The impact of radiation on cells, including interference with division and damage to chromosomes and genes, necessitates careful consideration in safety protocols. Gene mutations escalate with radiation dose, emphasizing the significance of dose accumulation rate. Furthermore, early-life radiation exposure has been linked to reduced longevity in laboratory animals due to the induction of benign and malignant growths. While some substances offer protection against radiation, their toxicity limits practical application in humans. Activities involving radiation exposure are rigorously assessed for risks in medicine, science, and industry, with a concerted effort to avoid unnecessary exposure. The benefits of radiation in medical procedures are weighed against risks, particularly in population-wide screenings. Additionally, non-ionizing radiation, such as Hertzian waves and infrared rays, poses heating effects, necessitating safety considerations in various applications, including diathermy, microwave ovens, and occupational exposure limits. The ongoing development of safety protocols and regulations remains essential to navigate the complex landscape of radiation and ensure the well-being of both humans and the environment.

6.2.1 The invere square law

The inverse square law states that for a point source of waves that is capable of radiating omnidirectionally and with no obstructions in the vicinity, the intensity I decreases with the square of the distance, d, from the source.[1]

Understanding the 'inverse square law' is instrumental in minimizing radiation exposure. Essentially, this principle asserts that by reducing the distance from the radiation source by half, the dose to a specific area becomes quadrupled. In simpler terms, maintaining a distance from a radiation source is an effective means of decreasing the radiation dose to personnel. This becomes especially crucial in interventional radiology scenarios where radiologists or radiographers often operate in close proximity to the X-ray beam.

The intensity of the X-ray beam exhibits an inverse square relationship with the distance from the source (X). Specifically, doubling the distance from the radiation source, from 'd' to '2d,' results in a reduction of the dose to the radiologist or radiographer to one-fourth of the original amount. This underscores the importance of maintaining a safe

[1]M. Talbot-Smith, *8 - Sound, speech and hearing*, F. Mazda, Ed. Butterworth-Heinemann, 1993, pp. 8-1-8–16, ISBN: 978-0-7506-1162-6. DOI: https://doi.org/10.1016/B978-0-7506-1162-6.50014-9. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780750611626500149.

distance from the radiation source to mitigate exposure risks effectively.

Chapter 7

Wilhem Conrad Röntgen's Legacy

7.1 Importance of Radiation Dose Management

he evolution of X-ray-based radiology examinations since their discovery in 1895 and the subsequent increase in patient radiation dose exposure, particularly with the adoption of multidetector computed tomography (MDCT). The public's heightened interest in radiation exposure, fueled in part by events like the Fukushima nuclear disaster, has led to concerns about medical radiation exposure.

The Korean National Evidence-Based Healthcare Collaborating Agent (NECA) published a report[1] in 2011, emphasizing that radiation exposure from the Fukushima disaster in Korea was minimal and below harmful levels. It highlights the need for public education to dispel vague fears of medical radiation exposure, emphasizing the benefits outweighing the disadvantages.

The International Commission on Radiological Protection (ICRP) emphasizes the importance of using radiation exposure to benefit patients while optimizing protection. The principle of "As Low As Reasonably Achievable" (ALARA) guides radiology studies to minimize radiation dose without compromising patient care.

The text underscores the increasing importance of monitoring, optimizing, and decreasing patient medical radiation exposure globally. Efforts to educate the public and healthcare professionals on proper radiation knowledge are deemed insufficient, and the focus is shifting toward systemic and organized approaches for managing radiation dose.

The subsequent section delves into radiation dose units, explaining concepts such as exposure, absorbed dose, equivalent dose, and effective dose. The importance of understanding these units in the context of medical radiation management is highlighted. The text concludes with a table summarizing the relationships between different radiation dose units.

[1] E.-Y. Bae, "Role of health technology assessment in drug policies: Korea," *Value in Health Regional Issues*, vol. 18, pp. 24–29, 2019.

7.2 Lasting Impac and Legacy Röntgen

Wilhelm Conrad Röntgen's discovery of X-rays in the late 19th century had a profound and lasting impact on science, medicine, and technology. This breakthrough earned him the first Nobel Prize in Physics in 1901 and inspired generations of scientists. Röntgen's legacy is commemorated through the "Röntgen," a unit of measurement for X-ray and gamma-ray intensity, as well as various medical institutions and awards bearing his name.

Figure 7.1: Artistic view of X-ray discovery, W.C. Röntgen and his wife Anna Bertha Ludwig. (Credit : picture-alliance/primaarchivo)

His meticulous approach to experimentation and emphasis on documentation set a standard for scientific research. Beyond his immediate discoveries, Röntgen's work ignited scientific curiosity globally, leading to the development of other imaging techniques like MRI and ultrasound. Despite his groundbreaking achievements, Röntgen remained humble and selflessly refused to patent his discovery, advocating for free accessibility for the benefit of humanity.

While Röntgen's X-ray discovery revolutionized medical imaging, it also prompted concerns about potential risks. Over time, stringent safety measures and guidelines were established to ensure responsible use, minimizing harm to both patients and healthcare professionals. Röntgen's contributions continue to shape the field of medicine and exemplify the spirit of inquiry that propels scientific advancements

7.3 Recognition and Honors for Röntgen

In this chapter we will talk about the lasting impact of Röntgen's work on X-rays and radiography. Then we will see the recognition and honours he received, and how his legacy continues to influence the field.

Wilhelm Conrad Röntgen, the pioneering physicist, received widespread recognition and honors for his revolutionary discovery of X-rays. In 1901, he was awarded the first inaugural Nobel Prize in Physics, an esteemed acknowledgment that solidified his position as a trailblazer in the scientific community. The establishment of the Nobel Prizes was not a direct response to Röntgen's discovery but rather a broader initiative by Alfred Nobel to recognize and reward outstanding achievements across various fields that contribute to the betterment of humanity. Röntgen's legacy is further immortalized through the naming of the unit of measurement for X- ray and gamma-ray intensity, known as the "Röntgen" or "Roentgen." Numerous medical institutions, research centers, and awards globally bear his name, underscoring the profound impact of his contributions. The German Physical Society established the Röntgen Memorial Lecture, providing a platform for distinguished scientists to honor his legacy and present their research.

Beyond accolades, Röntgen's meticulous approach to experimentation and his humanitarian gesture of refusing to patent his discovery have set enduring standards in scientific research. His influence extends globally, inspiring generations of scientists and shaping the field of medical imaging. Röntgen's recognition encompasses not only his scientific achievements but also his lasting impact on the spirit of inquiry and the ethical principles that guide scientific advancements

Figure 7.2: Röntgen's Physics Nobel Prize, the first in History. (Credit : Röntgen Memorial)

Chapter 8

Future Trends in Radiography

8.1 Emerging Technologies and AI in Radiography

Here we will discuss and argue about the potential advancements and innovations in radiography. The emerging technologies and applications in the field, and the role and influence that of artificial intelligence could have inradiography.

The integration of artificial intelligence (AI) into radiography is a growing trend, and the future role of radiographers is expected to involve working with AI-based tools. The provided text emphasizes the importance of robust validation for new AI tools using unseen data, advocating for more prospective interdisciplinary research and comprehensive approvals. The involvement of service users, including practitioners, patients, and their caregivers, is deemed essential in the design and implementation of AI tools. Additionally, the text stresses the need for clearer accountability and medicolegal frameworks in cases of erroneous results from AI- powered software and hardware. It calls for clearer career pathways, role extension provisions, and education in the field, recognizing the central role AI will play in healthcare. The paragraph highlights the expectation that AI applications in medical imaging will evolve to be more accurate, cost-effective, and widely accessible, potentially improving patient-centered care and precision medicine. The convergence of efficiency, increased patient throughput, and a focus on patient well-being is seen as a goal for the future of radiographic practice with AI

Chapter 9

Conclusion

In summary, Wilhelm Röntgen's breakthrough in discovering X-rays has left an enduring and transformative mark on the realms of radiography and medical imaging. His innovative contributions provided the groundwork for the evolution of sophisticated imaging methodologies, fundamentally altering the landscape of medical practice. The continuous progress in radiography technology further refines X-ray imaging, enabling more precise diagnoses and elevating standards in patient care. Despite these advancements, a crucial emphasis is placed on maintaining awareness of radiation safety and optimizing dosage to address potential risks linked to ionizing radiation.

In 1894, Röentgen had stated: "The scientist must considerthe possibility, which usually amounts to a certainty, that his work will be superseded by oth-ers within a relatively short time, that his methods will be improved upon and that the newresults will be more accurate and the memoryof his life and work will gradually disappear." Considerable advancements have occurred since Röentgen's groundbreaking discovery in 1896. Nevertheless, the memory and reputation of this selfless and gifted scientist are bound to endure and be esteemed.

Bibliography

Books

[1] R. W. Conrad, N. Jacques, W. C. Röntgen, and N. Jacques, *Röntgen : choix de textes, bibliographie, portraits, fac-similés / présentation par Jacques Nicolle* (Savants du monde entier), fre. Paris: Seghers.

[3] N. Jacques and J. Nicolle, *W. C. Röntgen (1845-1923) et l'ère des rayons X : conférence donnée au Palais de la Découverte... le 21 janvier 1967 / Jacques Nicolle,...* («[Les »Conférences du Palais de la Découverte] Histoire des sciences), fre. Paris: Palais de la Découverte, cop. 1967.

[14] D. G. Kate-Louise and G. Penn, *Radiation in Medicine: A Need for Regulatory Reform*, C. for Review and I. o. M. Evaluation of the Medical Use Program of the Nuclear Regulatory Commission, Eds. Washington, D.C.: National Academies Press, 1996, ch. G - History of Radiation Regulation in Medicine, pp. 249–257, ISBN: 0-309-58875-8. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK232703/.

[17] M. A. Berger M Yang Q, *Chapter 7, X-ray Imaging*, Springer, Ed. 2018. DOI: 10.1007/978-3-319-96520-8_7.

[20] M. Talbot-Smith, *8 - Sound, speech and hearing*, F. Mazda, Ed. Butterworth-Heinemann, 1993, pp. 8-1-8–16, ISBN: 978-0-7506-1162-6. DOI: https://doi.org/10.1016/B978-0-7506-1162-6.50014-9. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780750611626500149.

Articles

[2] F. Nüsslin, "Wilhelm conrad röntgen: The scientist and his discovery," *Physica Medica*, vol. 79, pp. 65–68, 2020, 125 Years of X-Rays, ISSN: 1120-1797. DOI: https://doi.org/10.1016/j.ejmp.2020.10.010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1120179720302532.

[5] "Wilhelm röntgen," *Encyclopædia Britannica*, [Online]. Available: https://www.britannica.com/biography/Wilhelm-Rontgen.

[9] P. M. Graif, "Radiology in 2020: Opportunities and challenges," *Journal Of Health Management*, vol. 14, 2014, *3, Management Matrix*. [Online]. Available: https://healthmanagement.org/c/healthmanagement/issuearticle/radiology-in-2020-opportunities-and-challenges#:~:text=%E2%80%A2%20Radiological%20technology%20is%20shifting%20from%20a%20%E2%80%9Cdisruptive%

E2%80%9D,In%20vitro%20diagnostics%20will%20change%20radiological%20screening%20policy.

[11] C. Malamateniou, K. Knapp, M. Pergola, N. Woznitza, and M. Hardy, "Artificial intelligence in radiography: Where are we now and what does the future hold?" *Radiography*, vol. 27, S58–S62, 2021, The Future Role of the Radiographer, ISSN: 1078-8174. DOI: https://doi.org/10.1016/j.radi.2021.07.015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S107881742100095X.

[12] "Ethical issues in diagnostic radiology," *American Medical Association Journal of Ethics*, vol. 9, no. 11, pp. 735–783, Nov. 2007.

[15] D. è. s. p. Jean-Jacques Samueli, "La découverte des rayons x par röntgen," *BibNum*, 2009. DOI: https://doi.org/10.4000/bibnum.714. [Online]. Available: http://www.bibnum.education.fr/sites/default/files/RONTGEN-ANALYSE.pdf.

[16] M. Goldman, "La découverte des électrons," *Académie des Sciences*, vol. Histoire des sciences / Évolution des disciplines et histoire des découvertes, May 2013. [Online]. Available: https://www.academie-sciences.fr/archivage_site/activite/hds/textes/evol_Goldman1.pdf.

[18] P. Dunn, "Wilhelm conrad röentgen (1845-1923), the discovery of x rays and perinatal diagnosis," *Archives of disease in childhood. Fetal and neonatal edition*, vol. 84, F138–9, Apr. 2001. DOI: 10.1136/fn.84.2.F138.

[19] X. Ou, X. Chen, X. Xu, *et al.*, "Recent development in x-ray imaging technology: Future and challenges," *Research*, vol. 2021, 2021. DOI: 10.34133/2021/9892152. eprint: https://spj.science.org/doi/pdf/10.34133/2021/9892152. [Online]. Available: https://spj.science.org/doi/abs/10.34133/2021/9892152.

[21] E.-Y. Bae, "Role of health technology assessment in drug policies: Korea," *Value in Health Regional Issues*, vol. 18, pp. 24–29, 2019.

[22] H. D. atherine Simand, "Qu'est-ce qu'un rayon x ? comment en produire ? quel mécanisme permet d'obtenir une radiographie ?" *CultureSciences Physique*, no. La radiographie II, 2009, ISSN: 2554-876X. [Online]. Available: https://culturesciencesphysique.ens-lyon.fr/ressource/imagerie-medicale-radiographie-principe.xml.

[23] E. J. Christophe Aronica, "Diffraction des rayons x - techniques et études des structures cristallines," *CultureSciences Physique*, 2009, ISSN: ISSN 2554-876X. [Online]. Available: https://culturesciencesphysique.ens-lyon.fr/ressource/Diffraction-rayons-X-techniques-determination-structure.xml.

[24] M. Röntgen, "Sur une nouvelle espèce de rayons," *J. Phys. Theor. Appl.*, vol. 5, no. 1, pp. 101–108, 1896. DOI: 10.1051/jphystap:018960050010100. [Online]. Available: https://hal.science/jpa-00239851.

Online Resources

[6] "Principles of radiography." (), [Online]. Available: https://www.radiologymasterclass.co.uk/tutorials/physics/x-ray_physics_densities.

[7] "Radiology masterclass uk." (), [Online]. Available: https://radiologykey.com/principles-of-radiography/.

[8] "History of radio." (), [Online]. Available: https://www.ramsoft.com/history-of-radiology.

[10] "Artificial source." (), [Online]. Available: https://www.britannica.com/science/radiation/Effects-of-visible-and-ultraviolet-light.

[13] "Physica medica." (), [Online]. Available: https://www.sciencedirect.com/journal/physica-medica/vol/79/suppl/C.

Other Documents

[4] H. Poincaré, *Letter from h. poincaré to w. c. röntgen*, Congratulation for his discovery and questions on his work, Archives Henri Poincaré, Jul. 1896. [Online]. Available: https://henripoincare.fr/s/correspondance/item/8007 (visited on 11/24/2023).