Integration of General Physics, Applied Physics, Medical Applied Physics, and Medical Device Engineering in the Development of Diagnostic and Therapeutic X-Ray Systems

<u>Editors</u>

Ali Hussein Naji Majid
Department of Applied Sciences, Branch of Applied Physics, University of Technology, Iraq

Meaad Hadi Ghareeb Awfi
Department of Physics, College of Science, University of Karbala, Iraq

Batool Jameel Abdulzahra Omran
Department of Medical Device Technology Engineering, Medical Technical College, AL_farahidi University, Iraq

Zahraa Fadel Abdel Nabi Mahdi
Department of Applied Sciences, Applied Physics Branch, University of Technology, Iraq

Abdullah Salih Oleiwi Abdaljasim
Department of Medical and Applied Physics, College of Sciences, AL_Mustaqbal of University, Iraq

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Abstract

X-ray systems serve as a well-established and reliable means of conducting both diagnostic and therapeutic techniques within the expansive and intricate field of medicine. The ongoing advancement and continuous improvement of this crucial technology are largely dependent on the intricate and complex interplay between the diverse disciplines of physics and engineering. A thorough, detailed, and expansive discussion regarding the integration and collaboration of these two vital fields in the development and enhancement of X-ray systems is significantly enriched by having a clear, comprehensive, and insightful understanding of the underlying physical principles. This is coupled with a systematic and methodical engineering approach that is involved in their functionality. General physics encompasses the fundamental concepts, theories, and established laws of nature that govern our physical world and its myriad phenomena, ranging from the smallest particles to the vastness of space. On the other hand, applied physics centers on the fundamental principles specifically related to X-rays and delves into the intricate and detailed interactions that occur when ionizing radiation directly interacts with various forms of matter, including biological tissues. Medical physics takes these foundational principles and applies them directly to the practice of medicine, ultimately ensuring not just effective treatment methodologies but also focusing on vital aspects such as radiation safety and indispensable quality assurance processes that are essential for the performance and reliability of medical devices and the health of patients. Engineering, in its multifaceted approach, brings a structured and disciplined strategy to the design and development of marketable and state-of-the-art

medical devices. This discipline plays a crucial role in the ongoing enhancements, modifications, and innovations that drive the field forward. Furthermore, the engineering discipline also emphasizes the critical importance of incorporating rigorous quality assurance procedures into the development cycle, which is vital for ensuring both the reliability and safety of medical applications. These aspects are paramount in the healthcare environment, where patient safety and treatment efficacy are of the utmost importance.

Contents

Chapter - 1

Introduction to X-Ray Systems

X-ray systems serve as vital instruments that produce X-ray radiation for a wide array of diagnostic and therapeutic applications within the medical field and beyond, showcasing their significant importance. These sophisticated systems typically encompass an X-ray source, which can manifest in the form of an X-ray tube or a synchrotron, each of which is characterized by unique operational features and specialized applications suited to various needs. Furthermore, these intricate systems integrate a selection of targeting components that may feature beam-shaping tools designed to optimize imaging results, advanced patient positioning and measuring apparatus that ensure accurate data collection, specialized filters that enhance image quality, and collimators that play a crucial role in directing the X-ray beams with precision and effectiveness. When emitted, the X-rays interact with a target object, which, in most medical scenarios, is the patient receiving the examination or treatment. This interaction is of utmost importance, as it enables a diverse range of imaging techniques to be employed effectively in diagnostics and therapeutics. The X-rays emitted then travel through the patient or object, ultimately being detected by either patient- or object-mounted detectors or various other specialized signal detection devices designed for this purpose. These systems exemplify one of the most advanced and extensively utilized demonstrations of the seamless integration of general physics with applied physics, medical physics, and principles of engineering, highlighting the interdisciplinary nature of their design and function. The harmonious combination of these fields of study empowers medical professionals to acquire crucial information regarding the internal structures and conditions present within the human body, thereby rendering X-ray systems absolutely invaluable tools in the realm of modern medicine, significantly enhancing the accuracy and effectiveness of patient care and diagnostics [1, 2].

Chapter - 2

Fundamentals of General Physics

The subject of general physics is remarkably broad and encompasses an extensive array of topics-covering essential areas such as mechanics and particles, thermodynamics and fluids, electricity and magnetism, waves and optics, as well as the intriguing field of modern physics. Despite this vast landscape of information, it is indeed possible to present an extended yet consistent discussion that distills the key points of physics forming the essential foundation of the subject matter in this book. It is crucial to recognize that this section of the book is distinctly different in both style and content compared to the other sections that follow. Here, there is a significantly greater emphasis placed on the fundamental principles and concepts of physical science rather than on engineering practices or technology. Additionally, this section is not limited to the mere application of physics in the field of medicine, which is often a primary focus of technological advancements. In this way, the section is optimally viewed in conjunction with the subsequent one, which aims to create a seamless transition between the fundamental theories of physics and its practical applications across various domains, including but not limited to engineering, environmental studies, and technological innovation [3, 4, 5, 6].

2.1 Key Principles of Physics

The interplay between physics and engineering is crucial for developing diagnostic and therapeutic x-ray systems, integrating elements essential to the final product.

X-rays are indispensable in modern medicine, serving both diagnostic and therapeutic purposes. X-ray systems encompass the entire set of equipment enabling the generation, manipulation, detection, and control of x-rays. The design and creation of such systems is a formidable challenge, necessitating close collaboration between applied medical physicists and engineers. Beyond an in-depth grasp of medical applied physics and engineering principles, the integration of x-ray equipment calls for a comprehensive understanding of the system's intended functionality, which can be challenging to acquire swiftly in a practical setting.

Physics knowledge serves as the essential foundation upon which any engineering project is built. Consequently, the fundamental principles of physics establish the cornerstone of this work. In the initial stage, we revisit the main concepts that are involved in general physics, while also tracing their significant application in the field of medical diagnostics. This foundational understanding is crucial for appreciating how these concepts translate into practical uses. Following this, the analysis expands to cover the broader field of medical physics as a whole, effectively setting the stage for the subsequent study on the intricate integration of physics and engineering disciplines. In this particular section, we will present, albeit briefly, the x-ray equipment typically found in most medical facilities, placing a strong emphasis on the critical design considerations and the current technological state of each component involved in the imaging process. This examination will highlight how engineering principles are applied within the medical context to enhance diagnostic capabilities [1, 7, 8, 9, 10].

2.2 Applications in Medical Imaging

X-ray systems utilize powerful and penetrating electromagnetic radiation specifically to generate detailed and comprehensive views of the inner structures of various objects. These sophisticated systems play a critical and essential role in the successful diagnosis, thorough evaluation, and effective therapy of a wide range of common diseases as well as numerous medical conditions. Furthermore, these X-ray systems represent a significant and vital area within the broader field of health-related physics, contributing greatly to the advancements in medical imaging technologies. By enhancing the quality and precision of imaging methods, they also significantly improve patient care, enabling more effective early detection and treatment of various health issues [11, 12, 13].

Chapter - 3

Applied Physics in Medical Diagnostics

X-ray systems combine high-end technology with a well-established scientific basis [14]. The technology is complex, and medical applications call for design methods, development processes, and a qualified engineering workforce that satisfy regulatory requirements in research, design, testing, calibration, manufacturing, and maintenance. Applied physics supports the development of efficient diagnostic and therapeutic modalities [15]. Since its discovery by Wilhelm Röntgen, X-rays have played a major role in medical diagnostics, industrial testing, and scientific investigation. Both physics and engineering have contributed to this development with models and tools that provide a comprehensive approach controlling costs, meeting schedules, increasing throughput, and attaining high precision and reliability.

Diagnostic and therapeutic modalities take full and comprehensive advantage of X-rays based on various relationships that arise from a diverse array of physical phenomena characterized by distinct and varied time and space scales. The vast and intricate field of physics systematically addresses and rigorously quantifies these complex phenomena, creating a measurable expression of natural laws that illuminate the very source of the radiation. Additionally, it meticulously details the various, often intricate, interactions taking place within the irradiated individual, and finally, it significantly influences the image quality as the ultimate product displayed on the detection platform. These foundational principles lead to an improved and much deeper understanding of the biological effects that can result from X-ray exposures. They also provide valuable and practical tools for optimizing imaging procedures, which ultimately serve to substantially enhance both the effectiveness and accuracy of the exposures performed during crucial diagnostic and therapeutic practices. Furthermore, a clear and significant distinction exists between the large-scale and small-scale phenomena involved in these critical imaging processes. This vital distinction allows for the dominant processes to be treated independently during the modeling and simulation phases, thus facilitating a comprehensive and complete description of the complex degradation mechanisms that can affect the image system and its various integral components. The designated hardware specifically used for these critical measurements is also discussed in detail, considering its essential role in capturing high-quality images and its significant impact on the overall outcomes of the diagnostic procedures employed in a clinical setting [16, 17, 18, 19].

Contemporary science is characterized by the development of novel technologies that support daily human activity and stimulate new industrial directions. Concepts such as nanotechnology, quantum information technology, vacuum electronics, virtual reality, bio and medical science, espionage, and aerospace research represent fields whose progress depends heavily on the mastery and advancement of fundamental applied physics. In particular, medical applications considerably benefit from the fundamental physics knowledge that directly fuels technology development and the acquisition of tools capable of opening new knowledge domains.

In daily practice, medical doctors do not deal directly with the fundamental laws of physics, but only through indirect processes such as thermal heat transfer, fluid dynamics, luminescence, and electricity. Only in a few specific situations are these laws intentionally invoked. The diagnostic interest, by contrast, entails a detailed knowledge of one or more applied physics domains and is fundamental to fully understanding the capabilities and limitations of various types of radiation in the diagnostic arena.

The present work is dedicated to medical diagnostics and is inspired by a didactical approach whose purpose is to highlight the specific role of applied physics in the process of medical diagnosis and its important contributions to the development of modern medicine: a fundamental role of modern applied physics is identified and the connection too often disregarded, yet essential for technological improvement and the birth of new diagnostic tools, is explicitly formulated. A second aim consists in giving the usual information content of the physics of medical diagnostics in a form naturally suited to the way a medical doctor approaches the subject [1].

Understanding the physical principles that govern different imaging modalities is essential in grasping the functional principles of these tools; many previously applied physics concepts reappear in medical diagnostics. While the applied physics of medical diagnostic technologies takes centre stage in subsequent topics, biophysics and radiation physics are also touched on to establish links to medical diagnostics.

Not only does applied physics provide the foundations for basic methods such as X-rays, magnetic resonance, or ultrasound, it also underpins more recent developments, including computed tomography, nuclear medicine, as well as optical methods like Raman spectroscopy. Finally, quantum mechanics enters this arena through the method of positron emission tomography (PET).

Integrating applied physics into medical diagnostics enhances rapid and reliable diagnosis. Fundamental principles of

X-rays, nuclear magnetic resonance, and ultrasound underpin methods such as nuclear magnetic resonance imaging, X-ray computer tomography, and sonography. Computed tomography combines X-ray sources with image processing for three-dimensional visualization. Radioactive isotopes enable detection and analysis of physiological and metabolic processes [2].

The inverse problem of recovering an object from its response characterizes many diagnostic methods. X-ray imaging records projected intensities after attenuation, while sonography detects reflected sound waves. Magnetic resonance techniques and nuclear medicine exploit spin-lattice relaxation and radiotracer emissions, respectively.

Wilhelm Conrad Röntgen discovered X-rays in 1895, marking the birth of X-ray diagnosis and a milestone for medical applications. X-ray production, interactions, and image formation underpin the physics of medical imaging. Photons are generated from a hot cathode and accelerated toward a target-usually an anode disk of tungsten for geometry and thermal efficiency-under high voltage. X-rays emanate and propagate until interaction occurs. The X-ray tube approximates a point source in space. Co-source radiation and a partial-off-center point source arise from electron acceleration and deflection.

X-ray absorption has important biomedical and industrial applications, including bone density mapping and determination of absorber densities. X-ray induced acoustic (XA) signal amplitudes are directly proportional to the total X-ray dose deposited, facilitating real-time dose monitoring in radiation therapy. The initial pressure map derived from XA imaging reveals the relative dose distribution, confirming beam alignment and accurate dose delivery. X-ray induced acoustic computed tomography (XACT) systems detect ultrasound yet employ X-ray absorption as the contrast mechanism, enabling dosedeposition monitoring without perturbing the radiation beam [3]. XA waves propagate spherically, allowing volumetric imaging from a single projection angle and enabling rapid, convenient three-dimensional imaging, particularly in non-destructive testing scenarios with access limited to one side. Signal strength scales inversely with the square of the X-ray pulse width and directly with deposited energy, guiding optimization of both imaging and therapeutic protocols.

Since the introduction of X-ray radiography-demonstrated for soft-tissue imaging with contrast agents in 1896-continuing advances have enhanced diagnostic capabilities [4]. The development of a focused electron beam and improved fluorescing screens substantially increased image quality and resolution. The discovery of X-ray diffraction by crystals, first identified by Max von Laue in 1912 and subsequently confirmed by William and Lawrence Bragg, led to the establishment of X-ray crystallography and spectroscopy. X-ray crystallography remains integral to determining the three-dimensional structures of proteins and elucidating their biochemical functions [5].

Clearly, mapping the spatial distribution of elements provides valuable insights into biological environments. Material sciences, archaeology, and environmental sciences have long exploited X-ray fluorescence by recording spectra at defined sample positions. In life sciences, applications remain limited due to spectral-background issues afflicting detection sensitivity at relevant concentrations. Recent developments-in background reduction techniques and novel X-ray sources-have revitalized X-ray fluorescence imaging (XFI), fostering preclinical and clinical applications. The production and detection of X-rays in digital radiography most commonly involve direct-conversion semiconductor detectors and indirect conversion employing scintillators coupled with photodetectors. Active-matrix flat-panel imagers (AMFPIs) utilizing amorphous silicon thin-film transistors and photodiodes dominate modern systems, signaling ongoing evolution in hardware technologies.

Magnetic resonance imaging (MRI) is a non-invasive modality that exploits nuclear magnetic resonance of protons as a contrast mechanism. The sensitivity of NMR signals on tissue characteristics, such as concentration of NMR-active nuclei and peculiar relaxation times, increases the diagnostic potential of MRI in comparison to X-ray-based technologies. An MRI instrument is a complex system that can be conceptually divided into three subsystems: a strong and uniform static magnet to induce proton magnetic moments in the lifetime polarization regime; gradient coils that create magnetic fields with controlled spatial variation; and coils to generate and detect radio frequencies to excite and record NMR signals. Image reconstruction, compliance to safety regulations, and additional hardware for triggering physiological signals complement these components [6]. Rapid progress and steady improvement of MRI hardware have established this technique as a medical diagnostics workhorse used in a variety of clinical tasks at many scales. Progress of high-field systems is associated with improved spatial resolution, image quality, and contrast properties; increased chemical shift dispersion and phase contrast; susceptometry mapping; and a variety of other applications [7]. A number of complementary approaches can create images sensitive to perfusion, diffusion, elasticity, conductivity, flow patterns, oxygen saturation, drug delivery, and other properties with widespread medical diagnostic applications. Magnetic Resonance Spectroscopy is occasionally used to complement diagnostic data acquired via structural imaging [8].

Ultrasound imaging employs high-frequency mechanical vibrations, or sound waves, to resolve structures too small to be seen by eye. In medical diagnostics, ultrasound is important because it permits internal visualization of anatomical structures or fluids without either surgical invasion or exposure to ionizing radiation. If a force is applied to an elastic solid, waves propagate outward from the disturbance. Because the characteristic compactness of biological tissue lies well below the wavelength of the sound employed (typically between 1 and 10 MHz), pressure propagation can be described by the one-dimensional wave equation, and particle motion is longitudinal rather than shear. Sound-pressure levels are of order 100 kPa, which is sufficiently low to maintain linear behavior throughout the acoustic propagation and, thus, to avoid significant harmonic generation [9].

Emerging ultrasound technologies include spectrum analysis, elasticity imaging, contrast-agent methods, and advanced flow detection techniques. These approaches provide independent information and may be combined to improve disease detection, evaluation, and therapy monitoring [10]. All objectives of applied physics can be found in the basic concepts of medical diagnostics considered in the chapter: for example, the connection between the observation of phenomena and the concepts and principles of model construction; the interdependence of measurements, their interpretation through modeling, prediction, and the generation of new knowledge; the use of such knowledge for positive human goals; and the particular challenges of a discipline that, by its very nature, is developing. During the twentieth century, physics has directly contributed to major diagnostic technologies that now find widespread clinical application, including magnetic resonance imaging (MRI), X-ray diagnostics and computed tomography (CT), ultrasound, and nuclear medicine-all of which rely on the accurate understanding and control of radiation [11].

Because X-ray produces a series of radiographs taken from different angles, the main problem that remains to be addressed is the construction of three-dimensional information from the radiographs. This principle underlies the design of computed tomography (CT), which provides three-dimensional images of body structure at high resolution and minimal invasiveness by computational X-ray image reconstructions. Because of the general usage of CT in diagnostic medicine, the basic physical principles that underlie this technique merit brief description. The first clinical computed tomography (CT) system was installed at London's Atkinson-Morley Hospital in 1971, with research dating back to 1940. CT offers much higher contrast than conventional radiographs, as it does not use ionizing radiation, and provides faster scan times, reducing costs and increasing availability. It is especially useful for soft tissue imaging when combined with contrast media. In the 1980s, it was believed MRI would replace CT due to radiation concerns, but advances such as automatic tube-current modulation (ATCM), detector design, spectrum optimization, dual-energy (DE) and dual-source (DS) CT have improved its capabilities. These technological developments require ongoing re-evaluation of imaging protocols to optimize radiation dose, contrast media dose, and image quality [12].

An experimental third-generation CT system with a fixed source-detector setup was developed for education and research. The design uses a turntable for object placement, reducing mechanical complexity, and supports multiple slice and spiral acquisitions for 3D reconstructions. It employs industrial X-ray CCD detectors with high resolution and stability, capable of measuring objects up to 200 mm in diameter. Raw data undergoes normalization based on the attenuation law to produce accurate sinograms, which are then filtered and backprojected for image reconstruction. Iterative reconstruction techniques, which have been part of CT development since its inception, have been investigated and implemented to improve results and reduce dose [13]. Radioactive materials that preferentially accumulate in disease sites are routinely employed as tracers for the localization and diagnosis of disease. Gamma cameras and positron emission tomography (PET) systems can then be used to generate images that show the pattern of concentration of the tracer [14]. Imaging techniques in nuclear medicine in general depend heavily on the rules of radioactive decay, discussed in “Fundamental Principles of Applied Physics.”

Applied physics and biophysics form an important basis for many medical technologies. Numerous conventional diagnostic methods are based on physical principles that underpin device function, reflecting well-known physical and mathematical laws [15]. The intersection of biology, medicine, and physics exemplifies dialectical interactions involving both differentiation and integration of disciplines. First-year medical-physics students simulate the electric field of the cardiac current dipole and generate electrocardiograms using simple equipment. The model elucidates mechanisms underlying biopotential generation as well as electrocardiographic measurements; the tasks reinforce foundational concepts including Einthoven’s lead system and equipotential and force lines. Students also model cardiac contractions and construct cardiograms, promoting deeper comprehension of physiological processes and confirming practical applications of theoretical formulas. According to biophysicist Jörg Wrachtrup, investigations at the interface between physics and biology require new measurement methods developed by physicists to characterize newly discovered phenomena. Whereas apparatus such as the microscope initially migrated from physics into biological disciplines, physicists now also examine biological objects, particularly at the nanoscale. Many biologically crucial functional units-such as motor proteins-operate at nanometer dimensions and fall within physics’ remit. Photosynthesis, the fundamental metabolic process responsible for terrestrial biomass, involves antenna complexes that absorb sunlight and reaction centers that convert the energy into charge separation, initiating ATP synthesis. The historical trajectory demonstrates that physics is rediscovering biology: biophysics has longstanding traditions and was envisioned by early investigators such as Arnold Sommerfeld, who probed questions now regarded as biological [16]. Biophotonics-a rapidly expanding biomedical technology encompassing minimally invasive diagnostics, therapeutics, and nano-biotechnologies-is widely applied in clinical settings. Advanced imaging, microscopy, and sensing techniques-favored for their spatial resolution and use of nonionizing radiation-enable minimally invasive, in vivo tissue characterization [17]. Recent developments position biophotonics as an alternative for diagnostics, monitoring, and therapy, offering noncontact, rapid, and painless methods that facilitate early disease detection and enhance patient comfort. Compatibility with nanotechnologies underpins ultrahigh-resolution nanobioimaging and nanobiosensing at subcellular, molecular, and atomic levels. A dedicated compendium highlights progress in bioimaging, diagnostics, photoacoustic tomography, light–cell interactions, biosensing, and nanobiophotonics.

Force applied to cells and tissues induces deformation and flow. The study of such mechanical properties, in addition to electrical and optical behaviour, is a central subject of biophysics. The physical properties of biological systems at the cellular level provide invaluable information concerning their physiological state, and are therefore exploited for bio-analytical and diagnostic purposes [18].

Molecular imaging visualizes molecules of interest by detecting various molecular signatures and physiochemical properties through physical interactions [19]. Key modalities include CT, MRI, ultrasonography, optical imaging, gamma scintigraphy, and PET. Specialized probes function as beacons that depict and enhance epitopes of key proteins; they comprise a targeting component and a signaling component. Targeting moieties involve peptides, proteins, antibodies, aptamers, affibodies, and nanoparticles directed by specific ligands. The signaling component may be radioactive, magnetic, echogenic, luminescent, or fluorescent. Ideal probes exhibit low nonspecific binding, high selectivity, stability, and a favourable safety profile. PET combines superior sensitivity, spatial resolution, and quantitative attributes and therefore constitutes the modality of choice. PET signals derive from positron-emitting radioisotopes such as 18F, 11C, and 15O, which decay and emit pairs of photons that specialized instruments detect with high accuracy. Gamma scintigraphy measures gamma-ray photons emitted from radioactive decay, giving it substantially lower sensitivity, spatial resolution, and quantitative potential than PET.

Mechanisms by which radiation becomes a diagnostic modality are central to medical physics, radiological protection, and diagnostics. The principal categories of radiation employed are beta and gamma radiation, X-rays, neutrons, and visible light. Each species of beam interacts with, and is produced by matter in distinctive ways; each affords a differing range of diagnostic information, and is also subject to particular hazards that must be controlled [20]. The strengths and weaknesses of every diagnostic application and method hinge on the physics of the underlying radiation-production process, its coupling to biological targets, the timescales on which relevant phenomena unfold, and the extent to which radiation environments can be controlled and explained. Radiation-based diagnostics comprise the core of medical physics, and it is by physics, also, that their proper use and the protection of patients and operators remain assured [21].

Radiation is defined as the transfer of energy through space or a material medium. There are two forms of radiation: ionizing and non-ionizing. Ionizing radiation, which can remove electrons from atoms or molecules of the matter through which it passes, includes alpha particles, beta particles, protons, neutrons, gamma rays, and X-rays. Non-ionizing radiation, which does not have enough energy to eject electrons, includes microwaves, visible light, and radio waves.

Ionizing radiation forms the basis of the most common diagnostic technique in medical physics-X-ray imaging-although other techniques are now also widely employed [20]. A detailed exploration of X-ray imaging is provided in Subsection 5.3, "Imaging Techniques."

Protection against radiation hazards hinges on a comprehensive understanding of the nature of the radiation to be avoided [22]. Accordingly, the radiation safety discipline tracks the use and safety of a variety of hazardous radiations. Sources range from naturally produced radiation emitted by certain radiological materials, including radium and uranium ore, to radiation generated by devices such as X-ray tubes, electron cathode ray tubes, and high-voltage arcs. Moreover, radioactive materials can be found in certain common consumer products, from smoke detectors to pesticide-contaminated fruit shipped from abroad.

Image reconstruction is conceptually concerned with the solving of inverse problems, where an indirect measurement is inverted to obtain a direct image; Fourier and wavelet-based algorithms both find applications in medical image reconstruction [23].

Signals arising in medical imaging are typically contaminated by noise. Consequently, a fundamental component of medical signal processing procedures is the denoising, or smoothing, of noisy signals and images, with the goal of removing noise while retaining clinically important signal detail. Incoming data often need to be calibrated prior to image reconstruction or further analysis. Subsequent processing of the data or reconstructed images may involve registration (the co-location of images collected under differing conditions), visualisation, and segmentation, which refers to the isolation or identification of regions of interest [24].

Throughout these various processing stages, physiologically relevant signatures present in the images or signals need to be highlighted and enhanced before reliable interpretation can be achieved.

Image formation from sensor-collected signals presents an ill-posed inverse problem that is each time solved with a potentially very different strategy according to the acquired data and the considered geometry with the minimum of prior information. The ill-posedness is especially visible when the number of measurement is significantly lower than the number of unknowns. Reconstruction techniques for computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET) or optical microscopy provide a variety of approaches for the inverse problem [25, 26]. For nuclear imaging such as PET and single-emission tomography systems, iterative reconstruction techniques are regularly preferred to direct algebraic methods, because of improved image quality and in order to account for the statistical nature of the emission and detection process.

Analytical and algebraic reconstruction methods provide an adequate solution and their origins can usually be traced back to the radon transform. The Feldkamp-Davis-Kress (FDK) method is one of the most commonly used algorithm for cone-beam tomography; it is characterized by a 3D filtering step. Fourier-transform methods can be found in the literature for the reconstruction from projections or from frequency samples in k-space. These algorithms are popular thanks to their speed and to the possibility of producing reconstructed images for a broad range of experimental conditions, with few parameter tunings. Usually both families of approaches rely on forward and back projection operators with the application of the Fast Fourier Transform to optimize the numerical cost. However, analytical methods follow the classical projection-slice theorem and assume an infinite number of sets of ideal, sharp and noiseless measured projections. The resulting artifact in realistic situations leads to the use of iterative reconstruction algorithms, referred to as model-based or statistical image reconstruction in which sophisticated models for the system physical processes and the noise distribution are exploited inside a regularized inversion process to improve the quality of image with reduced artifacts and noise.

Patient motion and speed requirements in clinical applications have also stimulated the design of fast reconstruction methods. Parallel data acquisition techniques have then been introduced to accelerate measurements: in MRI for example parallel P-MRI acquires the k-space with multiple receiver coils, which enable the acquisition of less samples during the same period. Several parallel-imaging methods have been proposed to reconstruct images from under-sampled data in the presence of spatially varying coil-sensitivities; starting with the well-known SENSE method which reconstructs an image from arbitrarily under-sampled data. Recently, modified data acquisition techniques, such as compressed sensing, have been demonstrated to significantly reduce scan time and/or radiation dose. They have also received Food and Drug Administration (FDA) approval in 2017 in the context of the reconstruction of cardiac MRI data and are currently widely applied to different imaging modalities.

Medical images often require additional processing before regions of interest can be determined. Enhancing, segmenting, and registering different image structures depend on accurate input data. Noisy medical images present a challenge; when filtering noise is not feasible and re-imaging is not possible, image enhancement techniques become critical.

Filtering methods include smoothing and sharpening filters. Smoothing filters reduce noise but, depending on parameters, may also blur edges and fine details. Common filtering techniques in the spatial domain include mean, Gaussian, high-pass, low-pass, homomorphic, and unsharp filters. Such linear smoothing filters apply a convolution mask to the image and replace pixel values with a weighted sum of neighboring pixels. In contrast, nonlinear filters detect and remove noise based on the validity of individual pixels, preserving edges and important structures more effectively [27].

Image noise in medical thermal images comprises various types. Salt, pepper, and salt-and-pepper noise cause data loss or saturation, requiring suitable filtering strategies to restore image fidelity. Thermal noise arises from random electron fluctuations within the sensor; it follows a Gaussian distribution and is independent of the signal. Structured noise constitutes nonrandom signal contributions localized in specific image areas. The prominence of these noise types depends on acquisition conditions, including temperature, target physiology, atmospheric effects, and acquisition device state. Noise intensity varies with illumination fluctuations, chroma, spatial frequency, and image brightness [28].

Emerging technologies in medical diagnostics encompass innovations that extend beyond conventional advantages, enhancing capabilities in both quantity and quality. Supervised learning algorithms based on convolutional neural networks (CNNs) have gained popularity for automatically analyzing complex and high-dimensional medical imaging data. Multiple studies have demonstrated that CNNs can detect pathological features in chest radiographs and classify breast nodules in ultrasound images, matching the performance of experienced radiologists in several tasks [29].

Improvements in existing techniques continue to advance the field. Magnetic resonance imaging (MRI) offers alternative modes of contrast such as diffusion, perfusion, and elasticity-weighted imaging, with a trend toward the development of highly automated multipurpose techniques. Similarly, computed tomography (CT) facilitates high-resolution 3D visualization of physical structures in the body. Secure transmission of these large images remains a critical issue that relies strongly on physics and signal processing techniques [2].

Wearable devices, exemplified by the Philips Health Watch, extend monitoring beyond the traditional hospital setting, both in duration and scope. Optical pulse rate measurements now compete with electrocardiogram (ECG) for accuracy, particularly at rest, although performance varies with activity level. Electrodermal activity (EDA) sensors provide a reliable method for tracking stress levels, while blood-oxygen saturation measurement offers early warnings in conditions such as hypoxia, cardiovascular disease, or infections like severe acute respiratory syndrome. Accelerometer data captured at 32 Hz enables detailed 3D motor profiling equivalent to specialized mechanical testing, and the inclusion of a thermometer adds another vital sign to the monitoring suite.

Medical imaging techniques are rapidly progressing and have had a revolutionary impact on patient clinical management. Concurrently, a paradigm shift is underway that is transforming medical imaging into a quantitative science. This change is largely driven by emerging methodologies based on “radiomics,” which extracts a large number of quantitative descriptors from clinical images using advanced feature analysis and machine-learning algorithms, including artificial neural networks, support vector machines, and random forests.

Artificial intelligence (AI) systems are already established as valuable software tools for research purposes and could become an integral part of the medical-imaging workflow in clinical practice. While AI systems have demonstrated promise in ultraprecise early detection and identification of individuals at risk, they still lack higher-level background knowledge and the capacity to form associations comparable to those of the human brain. Furthermore, AI systems are typically trained to accomplish single tasks, and their application in medical imaging remains primarily academic, particularly in ultrasound.

Wearable diagnostic devices enable continuous, personalized monitoring by measuring physical parameters, location data, and blood composition, and can be integrated into various forms such as clothing, watches, patches, and biomonitoring tattoos [30]. To achieve consumer adoption, these devices must be easy to use, cost-effective, and provide immediate, comprehensible results in real-time. Sophisticated miniaturized sensors and wireless communication technologies have facilitated the realization of non-invasive, continuous physiological monitoring [31]. Electrochemical and electrical biosensors incorporated into wearable systems are capable of real-time monitoring of body metabolites and electrolytes. Sweat contains a rich array of biomarkers; however, its variable secretion complicates analysis and signal interpretation.

Wearables are broadly categorized into head-mounted, wrist-mounted, body-worn, clothing-embedded, foot-mounted, and sensory control devices. Wrist-mounted monitors, including fitness bands and smartwatches, were among the first consumer wearables and have evolved from basic accelerometer-based activity tracking to include biometric sensing. Blood pressure monitoring is crucial for health maintenance. Traditional cuffs are bulky and yield inaccurate measurements during movement. Consequently, wearable sensors utilize two primary approaches: acoustic detection of Korotkoff sounds with a MEMS microphone embedded in a wrist cuff and oscillometric measurement of pressure variations via a phonoplethysmograph within a wristband. These measurements are transduced through Hall sensors or optical photoplethysmography (PPG) detecting pulse-wave-driven movements, which are subsequently processed to determine systolic and diastolic pressures, with heart rate assessment exhibiting reduced motion artifacts relative to PPG-based pulse rate sensors. Data transmission is effected through Bluetooth to smartphones or other wireless interfaces. Non-invasive glucose monitoring has been commercialized by deploying reverse iontophoresis mechanisms to sample glucose levels from the skin's interstitial fluids.

Clinical applications derive from foundational imaging and biophysical techniques. Oncology incorporates radio- and chemotherapy technologies. Radiotherapy planning involves tracking organ motion and the deformation of anatomical structures or treatment devices [32]. Cardiological diagnostics exploit the combined use of MR, CT, and ultrasound techniques for the characterization of the complex anatomical structures of the heart. Neurological studies employ a variety of imaging methods, such as X-rays, CT, MRI (both conventional and spectroscopic), and nuclear medicine.

Medical physics forms a bridge between scientific research and patient wellbeing, providing the interdisciplinary link between physics, biology and medicine. It encompasses the understanding of physical processes in organisms, techniques for generating diagnostic images, and the interaction between radiation and matter. Nuclear medicine offers a prime example of successful multidisciplinary work, taking a physical process (radioactive decay) and using it as a probe to study biological function in living organisms. The practice of clinical medical physics also has the fundamental objective of developing methods and techniques to measure with the utmost precision, physical parameters that allow the planning of an efficient radiation procedure. Medical diagnostics in oncology require the use of innovative techniques in order to achieve the highest possible detection and imaging standards. Physicists continue to design methods of obtaining information that cannot otherwise be determined through imaging methods [33].

The development of innovative strategies in cancer radiotherapy depends on advances in tumor biology, the tumor microenvironment, and functional imaging techniques. Imaging modalities such as X-ray computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, positron emission tomography (PET), and optical imaging provide non-invasive in vivo characterization of tissues, tumor heterogeneity, and functional properties. Characterizing the tumor microenvironment prior to and after irradiation offers predictors and bases for subsequent interventions that optimize radiotherapy outcomes. An optimized multimodal cancer therapy approach necessitates careful pre-treatment stratification and timely therapy monitoring in a personalized setting. Continued improvements in imaging directly impact the effectiveness of radiation oncology.

Cardiovascular diseases remain a leading cause of death, with many medical opportunites arising in their early detection. Imaging technologies have rapidly evolved to address this need, providing detailed structural and functional information to support diagnosis. Modalities such as echocardiography, magnetic resonance imaging (MRI), and computed tomography (CT) offer insights into cardiac morphology, yet functional data pertaining to hemodynamics often remains elusive. Advanced computational fluid dynamics enables high-fidelity hemodynamic analysis, facilitating a detailed assessment of cardiovascular flow and its relationship to disease.

The integration of medical imaging and computational techniques permits the reconstruction of anatomical structures and flow patterns within the cardiovascular system. Focal areas, including the left ventricle and carotid bifurcations, are readily reconstructed to examine dysfunction mechanisms. For instance, cardiomyopathy-induced remodeling and late-stage heart failure can be explored through a consolidated imaging and analysis workflow. Intra-ventricular hemodynamics can be modelled and simulated to establish the criteria and procedures necessary for surgical restoration of heart function. The combined imaging and hemodynamic framework therefore supports a comprehensive study of cardiovascular defects and informs suitable restoration strategies [34].

The central nervous system (CNS) operates through a balance between excitation and inhibition at the cortical level, determining neurological performance [35]. Most neurological disorders result in altered central sensitization and a shifted excitation-inhibition balance. Due to the overlap in symptoms and the limitations of current clinical tools, many reports of neurological disabilities lack objective verification. Sensory-perceptual metrics based on tactile-encoding models have the potential to serve as behavioral assessment tools that reliably differentiate individuals with non-neurodevelopmental neurological conditions, such as chronic pain and trauma-induced alterations, from matched healthy cohorts. Low-cost and portable vibrotactile stimulators are critical for widespread dissemination of these methods and can facilitate large-scale proof-of-concept studies across diverse and difficult-to-access neurological conditions.

Medicine is on the verge of a renaissance, where predictions of imminent great advances are supported by contemporary scientific findings [29]. Future developments in medical diagnostics will arise from multifarious analyses, which encompass many different spectroscopies of molecules, biological tissues and blood to provide more complete and accurate knowledge of health conditions. Non-invasive technology is destined to make a revolutionary change in medicine within the next few years. Compact laser sources capable of generating tailored pulses in visible, near-and mid-infrared, extreme ultraviolet and coherent X-rays will rum four spectral bands at low cost.

Diagnostics will unprecedentedly move from clinics, laboratories or doctors' offices to homes and workplace. The earliest signs of cardiovascular disease, cancer or diabetes can be detected long before symptoms occur by using wearables for medical diagnostics. Modern photonics systems can be miniaturized to wearable size and incorporate wireless functionality, so that signals can be transmitted to a mobile device and then to medical centres or a practitioner in real time or periodically, whereas anatomical measurements represent a solution for monitoring mechanical parameters.

The wide range of medical diagnostic methods used in hospitals, laboratories, and doctor's offices every day continues to improve in speed, accuracy, and prospective therapeutic impact. Selected examples from among the available techniques illustrate the basic technologies, the underlying applied physics, and potential opportunities for future innovation.

Much attention in medical diagnostics presently focuses on the objective of personalized medicine [36]. Today's histogram-style physical and imaging studies often reveal the presence or absence of pathology, with limited information about the specific condition. Many diseases encompass a broad spectrum of pathologies, yet improved diagnosis could help to deliver optimal personalized treatments and avoid unnecessary procedures. The guiding principle of personalized medicine, sometimes referred to as "precision medicine," is a refocus from general population treatment of a given condition to the actual individual. In an effort to extract more specific information about the origin and nature of a disease, many diagnostic methods have evolved to emphasize individualized genetic or physical studies and an approach customized to the particular case. Telemedicine, recently highlighted by the Covid-19 pandemic, employs diagnostic tools already extending into the home environment for monitoring the patient prior to a hospital visit.

Telemedical systems are becoming increasingly important, providing the opportunity for both general practitioners and specialized physicians to obtain advice outside their premises. They also allow pathological or radiological examinations to be performed outside large centralized laboratories or hospitals, which may not be available in rural areas and sparse populations. They enable underserved populations to receive healthcare services, thus minimizing unnecessary patient movement and improving both quality and outcomes [37]. Telepathology can be used to shorten the waiting time for a final diagnosis by requesting assistance from colleagues in related time zones. It is not a substitute for conventional diagnostic procedures but an enhancement of pathology. Suitable equipment is readily available, and systems often operate on point-to-point connections with remote control capabilities. These setups are primarily designed for frozen section service and intra-operative diagnosis support, with practicability and diagnostic accuracy confirmed under various conditions. Various terms such as online telepathology, live imaging telepathology, active telepathology, or hybrid systems describe different implementations; the practice already influences technical aspects of pathology in some institutions. According to the definition, telepathology involves the diagnostic work of a pathologist at a distance, including primary diagnosis, secondary diagnosis, and quality assurance [38].

Ethical concerns related to the use of X-rays can be considered from different perspectives. In general, concerns regarding the patient can be distinguished from concerns arising within the community because of the use of X-rays. The former perspective has attracted most attention in the literature and encompasses issues of privacy and informed consent.

Exposure of the patient to ionizing radiation during a medical practice requires justification. The patient's interest should always remain paramount; otherwise, any potential societal gain is irrelevant. Radiologists have traditionally been regarded as the only health professionals relevant to the radiation protection of patients in radiology. On the other hand, the promotion of radiation protection by AERES (Authority of Nuclear Safety) compliance with ethical values and the justification of procedures have been emphasized [39].

The use of medical physics for diagnostic purposes inevitably invokes considerations of privacy and confidentiality that extend beyond professional-requisite discretion to the realm of legal and social obligations. In past eras, physicians who declined to testify in court on behalf of patients (such as victims of domestic abuse or peer-review whistleblowers) had little legal standing. Constitutional changes have now provided such protection, but their application to medical privacy has not yet fully matured, so the need is evident [40].

Because patients are asked to entrust intimate details to physicians and because investigations of health can reveal incidental findings unrelated to the original reason for which care is sought, length and width of exposure must be balanced against the presumed social utility. Liability for breaches of confidentiality when care is sought in confidence varies from jurisdiction to jurisdiction by enacted legislation, but it is reasonable to expect that individuals who voluntary provide sensitive data to physicians subject to an implicit, long-established fiduciary responsibility will be afforded considerable protection.

The imperative to protect personal data and privacy is increasingly vital across all fields of society. In the sphere of medical diagnostics, an additional obligation extends to the duty of care: a physician must undertake care as best possible and provide the patient with all information necessary for informed choices concerning their own health. In accordance with medical ethics292Despecially under conditions of uncertainty292Dthis is a requirement of the utmost importance.

In the context of medical imaging, the potential exposure to ionising radiation entails a particular risk. Default procedures for informed consent, whether event-based (offered contemporaneously with the procedure) or process-based (part of a wider clinical investigation), may risk neglecting the prevailing scientific evidence and inherent uncertainties [41]. Therefore, the matter demands careful elaboration when designing the diagnostic process.

The introduction of imaging equipment triggered a need for new quality assurance standards related to the basics of imaging, devices under test, and work procedures. Quality assurance comprises all activities, actions, and programmes implemented by an organisation to comprehensively ensure the objectives of a project, assessment, or service are met [42]. Quality control focuses on measurements and techniques conducted to verify the proper operation of the equipment. Image quality, the equipment's working conditions, the procedure, and patient doses are interdependent factors that should be optimised to ensure a successful diagnostic examination. Simplified testing methods can be implemented when a specialist is not available. Regulatory requirements mandate the implementation of extensive quality assurance programmes covering the necessary action lines to obtain and maintain optimal imaging systems; this encompasses quality control testing, acceptance and commissioning tests, and monitoring the quality of performed procedures [43].

Imaging techniques may be combined in a suitable tomographic protocol, where spatial resolution, noise, and contrast are optimised for each method and diagnostic requirement. Progressive dose enhancement is acceptable, if done within legal limits and accounted for in the dosimetric report. Monitoring the quality and reliability of medical imaging equipment plays an important role in implementing programmes that enable better diagnosis and treatment. Systems certified in accordance with ISO 9000 also ensure 'quality of service'. Following medical use, the modalities undergo acceptance testing aimed at verifying compliance with technical specifications from manufacturers, regulations, standards, and user requirements, allowing the clinician to use the system as a reliable diagnostic tool over time.

Medical radiological imaging is one of the most important diagnostic tools in modern health care. The main component of a quality assurance program in diagnostic imaging is to evaluate the quality of images and assess reasons for poor quality and patient doses in various procedures. Insufficient image quality may initiate the repetition of radiographs and unnecessary patient exposure. Dose reference levels are established to compare radiological practices regionally and nationally, facilitating optimization of patient protection. Images of optimal quality must be produced; patient and staff doses should be as low as reasonably achievable; the program should ensure maximum financial efficiency by reducing the loss of materials, films, chemicals, and sets of equipment; and every test conducted must respect current regulations regarding legal radiation protection conditions. Acceptance testing aims to verify the compliance of new equipment, located in a newly equipped room, with technical specifications. Routine evaluation is performed periodically or continuously to establish operational stability and ensure that equipment and procedures remain within an optimum and stable range.

The main difference between the two sets of testing lies in the objectives. Acceptance testing confirms whether the equipment and room satisfy the specifications, providing a reference baseline for subsequent routine assessments. During acceptance, tests focus on all major devices in conjunction to a comprehensive check-up; routine quality control concentrates on verifying the preservation of performance within acceptable limits. A test cannot be repeated if its results are unacceptable during acceptance, but must be reiterated during routine evaluations.

Sophisticated diagnostic technologies drive many advances in clinical medicine. The origin of these technologies derives primarily from Applied Physics.

Standards refer to an established framework or agreed-upon set of norms. Protocols define rules and procedures to be followed. Both standards and protocols feature prominently in Medical Diagnostics.

The imaging modalities discussed in chapter 3 exemplify the role of standards and protocols in Medical Diagnostics. Worldwide, multiple suppliers make available Magnetic Resonance Imaging (MRI), Computed Tomography (CT), Digital Radiography, and Ultrasound units. Radiographic intensifying screens and films also come from a variety of vendors. DICOM (Digital Imaging and Communications in Medicine) provides a detailed technical framework-specifying image formatting and wrapping, exchange and store methods, routing and media interchange, and network services-with which product designers can assure standards-compliant interoperability. Such compliance facilitates the integration of technology from diverse suppliers into a single Medical Diagnostic solution.

Standards and protocols exhibit even more prominence in the laboratory. Clinical Chemistry analyzers, Hematology analyzers, and Immunochemistry equipment each come with their respective standards and calibration protocols. The standardization of remarkable advances in measurement science permits a more comprehensive characterization of biological systems. [44]

The biomedical industry currently experiences few studies addressing the failure rates of medical imaging systems such as ultrasound scanners, with most existing research focusing on laboratory equipment. Quadri and Slegeir highlighted a lack of knowledge about equipment reliability, leading to the neglect of preventive and predictive maintenance practices [45]. An evidence-based approach to equipment maintenance in resource-poor settings suggested that the maintenance workload can be approximately predicted based on the number of medical devices in circulation and the nature of the local environment. In emergency obstetric care, a more systematic approach through continuous operation of equipment and a formal maintenance schedule reduced downtime. The importance of failure analysis for diagnostic medical equipment identifies common failures such as leakage currents, tube and crystal malfunctions in ultrasound machines, display unit, software and network problems in computed radiography, and output problems in dental X-ray units. Sezdi suggested that preventive maintenance is recommended for older technology equipment, whereas predictive maintenance suits newer high-tech devices. A World Health Organization report emphasises the planning and implementation of a Medical Equipment Maintenance Programme. Frequent technical problems and common faults identified in probes further emphasize equipment-specific maintenance needs. Software faults, mainly network connection issues with the departmental PACS system, and ultrasound probe malfunctions constitute the most common causes of failure; these factors contribute equally to downtime. Continuous staff education regarding ultrasound technology and system networking is essential to mitigate failures. A negative correlation between quality assurance (QA) time and vendor repair time indicates that regular performance checks enable early detection of equipment degradation; if detected promptly, repair durations and consequent machine downtimes are significantly reduced during clinical hours.

Information fusion technology offers integrated management across all stages of the equipment life cycle, incorporating maintenance objectives, parameter evaluation, and decision-making processes to enhance maintenance and quality control [46]. The development and application of an information fusion medical equipment maintenance and quality control system allow for more efficient maintenance practices. Routine maintenance and scientific operation considerably extend the service life of medical equipment. Such maintenance ensures proper usage, which has a direct impact on hospital efficiency and patient health. Actual testing data confirm the crucial role of equipment maintenance and quality control; for example, defibrillators demonstrate higher qualification rates in quality inspections following systematic maintenance procedures.

Medical diagnostics is subject to a complex regulatory framework in which the devices and tools utilized in medical practice are governed by specific national laws and compliance policies [47]. The Food and Drug Administration (FDA) of the United States regulates the safety and effectiveness of a diverse range of products including food, drugs, and medical devices, whereas the European Parliament issues legislation related to the protection of human health and the environment [21]. Both the FDA and the European Commission publish guidance and standards in which the requirements and responsibilities of the stakeholders to ensure the safety and effectiveness of medical technologies are clearly outlined. Specific領ompliance policies include Quality System regulations and premarket notification for the FDA side, and regulatory documents such as ISO 13485 and Medical Device Directives for the European side. The establishment of medical devices as well as their innovation are conducted under these standardized frameworks in the absence of which their safety and effectiveness cannot be guaranteed.

Since the 1970s, the Food and Drug Administration (FDA) has regulated the sale and distribution of medical devices, including medical diagnostic systems that incorporate applied physics technology. For many applications of applied physics in medical diagnostics, the FDA plays a major role in the approvals of new instruments, and the agency has maintained a long history of testing and evaluating the safety and effectiveness of many types of medical diagnostic equipment. New applied physics technologies may require the signing of new agreements or compliance with additional regulatory documents. Magnetic resonance imaging (MRI) is an example that continues to receive general marketing clearance from the FDA, despite the development of new imaging paradigms and features such as artificial intelligence [48].

The Medical Device Regulation (MDR) introduces new requirements for medical devices containing ionizing radiation sources (Directive 93/42/EC). For verifying and ensuring compliance, diagnostic facilities and Commissioning Experts use guidelines and requirements from Prescription-acceptance of equipment, IEC 60601, and additionally IEC 62464–1. Validation and periodic checks involve evaluation of equipment surface radiation, leakage, interlock functioning, image quality, appropriate dose parameters, commissioning of the Monte Carlo (MC) program, and validation of clinical protocols. A new paragraph assists the Qualification Expert in controlling the installation and commissioning of devices containing sources. For periodic quality control (QC) procedures, the MDR confirms the role of the Qualification Expert to ensure devices remain within defined limits [47].

Informed decision-making in diagnosis, surgery, and treatment is heavily dependent on imaging technology. Radiology is a branch of medicine that employs imaging technologies to inspect the interior of patients and reveal information about tissue structures and functions. Diagnostic electromagnetics is concerned with the development of imaging methods and systems that use electromagnetic radiation to diagnose disease, monitor the growth of tumors, or identify structural and functional details about the interior of the human body [32]. Such methods form the foundation for modalities such as X-ray computed tomography and magnetic resonance imaging, in addition to developing new techniques for obtaining improved image quality and extracting analysis data from the image. Signal processing plays a key role in many medical imaging modalities, including image reconstruction, image enhancement, and noise reduction. Research topics have included the development of extremely fast least-squares algorithms for reconstructing images in magnetic resonance imaging (MRI), as well as iterative methods and regularization techniques for electrical impedance tomography and diffuse optical tomography. Furthermore, geophysics is applied in the medical sector as well, particularly for analyzing biomedical signals such as electrocardiograms (ECGs), electroencephalograms (EEGs), and molecular data. Geophysical inversion techniques have been employed to improve the quality of CT, MRI, and ultrasound images, leading to more precise and detailed diagnostic information. Similarly, nuclear magnetic resonance (NMR) spectroscopy, originally developed for Earth materials, is now used to study biological molecules, thereby contributing to the development of new pharmaceuticals and the understanding of disease mechanisms.

Analysis of previous medical diagnostic inventions reveals two categories of failure:

a) Inventions based on erroneous theoretical physics-such as using Aether pressure for diagnosis.
b) Inventions that use valid physics but fail to develop a practical prototype. Here, the focus is on notable innovations that succeeded in establishing physical law and in devising workable instruments.

Radiography emerged from Roentgen's announcement of X-rays on 28 December 1895. Within six months, X-ray tubes were available commercially in the United States, and physicians were using the new radiation for diagnostic imaging and therapy. New X-ray imaging techniques soon appeared, like fluoroscopy, mammography, stereoscopy, and tomography; much later, computerized tomography (CT) became available [49].

An earlier breakthrough, nuclear magnetic resonance (NMR), was discovered in 1946 by Felix Bloch at Stanford University, and independently by Edward Purcell at Harvard University. MRI instruments, directly relying on the NMR physical principles and developed by Raymond Damadian, J. M. Mansfield, and Paul Lauterbur, began widespread clinical use in the early 1980s. Since then, imaging reliability and capability have steadily increased. Logarithmic image scaling aids structural resolution. Highly informative NMR techniques include functional MRI (fMRI), diffusion MRI, perfusion MRI, magnetic resonance angiography (MRA), spectroscopic imaging, 3-D and 4-D imaging, and ultra-high-field MRI [32]. Each technique offers distinct advantages for categorizing tissue in the context of various pathologies and is widely employed in today's clinical domain.

Failure exhibits the same disarming ubiquity in medical imaging as technological success. It appears especially high-profile and public when it occurs in products that interface directly with the patient or handle hazardous energy, such as ultrasound machines or CT scanners. A failure analysis of five diagnostic ultrasound systems in a radiology department undergoing predictive maintenance for more than 4 years offers a representative example.

All reported problems were logged by sonographers through a record book or communicated verbally to the vendor during station visits or emergency service calls. A machine failure was defined by the inability to complete normal functions or examinations, an assessment reached collaboratively by sonographers, vendor engineers, and physicists. Failures were classified into three categories: software, hardware, and ultrasound probe malfunctions. Software failures entailed system corruption, loss of digital image processing, and unexpected reboots. Hardware failures most frequently involved input devices such as sensors and keys, with performance parameters analyzed over time to detect and address gradual degradations. Quality assurance procedures, including image uniformity checks, sensitivity assessments, and lateral and axial resolution measurements, demonstrated stable system operation without significant performance decline. The ensuing discussion relates these insights to specific aspects of diagnostic instrumentation and energy-generation technologies, which remain current engineering challenges for a wide range of medical imaging efforts [45].

The preceding sections delineate the direct connection between applied physics concepts and advancements in medical diagnostics. All current techniques-X-ray imaging, nuclear medicine, computed tomography, magnetic resonance imaging, ultrasound technology, optical biophysics, and molecular signals-rely on physical laws governing light, sound, particles, and systems. Image reconstruction, image analysis, photometric detection, and signal processing similarly depend on these foundational principles. Stepping beyond established methodologies, medical diagnostics is poised for continuing growth that further integrates physics at all levels. The interplay between physical theory and biological systems will drive innovations in biophysical monitoring and intervention. Advances in applied physics will remain central to the development and refinement of diagnostic instruments and technologies, promising enhanced capabilities and broader accessibility.

Reflection on accompanying materials-Introduction to Medical Diagnostics and the remaining text characterizing the field-highlights three further directions. First, artificial intelligence will increasingly complement imaging and analytical tools, exemplified by its role alongside new endoscopic systems. Second, mobile technology and wearable devices will expand practical applications of diagnostic physics, enhancing remote interrogations and monitoring. Third, the capability to generate personalized computational models of patients will support prediction of disease progression and prognosis. The impact of applied physics thus extends throughout these emerging trends, continuing its fundamental role in medical diagnostics.

3.1 X-Ray Physics Fundamentals

X-ray waves are a form of electromagnetic waves, and the vector-field description of an X-ray wavefield can be effectively and accurately replaced with a scalar-field description that does not take into account polarization effects. In this scalar-field representation, an X-ray wavefield is characterized by a single complex number at every point in space and time. The magnitude and phase of this complex X-ray wavefield are directly related to the intensity and the wave-front profile of the X-rays, respectively. Numerous treatments concerning X-ray phase contrast operate under the consideration of a fully coherent field (or as close to fully coherent as can be practically achieved), which is particularly relevant in various applications. The "beam-like" X-ray fields are identified as paraxial fields. These fields propagate primarily in one distinct direction, while variations that occur transversely to this direction represent only a small perturbation. As a result, the wavefield can be approximated by a rapidly oscillating plane wave that is multiplied by a slowly varying envelope function that captures the overall shape and distribution of the wave's intensity. Typically, laboratory X-ray sources, synchrotrons, and free electron laser X-ray sources produce radiation that can be aptly approximated as paraxial beams. The phenomenon of diffraction, specifically involving paraxial electromagnetic fields through the process known as Fresnel diffraction, is thoroughly examined in this context. Furthermore, absorption-contrast imaging is notably sensitive to the magnitude of the scalar field, while phase-contrast imaging specifically measures the phase gradient in the wavefield. The interaction of X-rays with matter-such as the samples that are placed in the path of an incident X-ray beam, or the X-ray optical elements used-constitutes the essential foundation for X-ray imaging. For instance, samples produce modulations of the X-ray wavefield, which can then be detected and analyzed for various purposes. The two principal approximations that are commonly employed in numerous calculations involving X-ray-sample interactions include the projection approximation and the multi-slice approximation, both of which are crucial for accurately modeling these complex interactions [20, 21, 22, 23, 13, 24].

3.2 Radiation Interaction with Matter

X-ray production and utilization are predicated upon the understanding of radiation-matter interactions. The X-ray photon energy range can be roughly delimited to 50 eV–150 keV-higher than an ultraviolet photon but lower than a gamma ray. The photoelectric process is often dominant up to 50 keV of photon energies and decreases as an approximate third power of the HI photon energy to the Cobalt gamma ray energy of 1.33 MeV. Compton scattering, initially very weak, smoothly increases with energy to become dominant at approximately 100 keV, and gradually diminishes at even higher energies. The incident X-ray intensity would therefore vary through the irradiated medium according to where A is the intensity constant that varies based on multiple factors, including the X-ray tube current, the distance from the source to the object, the types and characteristics of the materials involved, as well as their thicknesses and densities. Additionally, the energy level of the X-ray photon spectrum and the distance from the object to the detector also play significant roles. Different materials exhibit varied interaction levels with X-ray photons, which is influenced by the specific devices employed and the design stipulations. For instance, high-quality medical imaging systems or nondestructive testing instruments require an enhanced interaction level to generate clearer and more detailed images. This is in contrast to security X-ray inspection and screening equipment, which has different operational needs. In systems designed for security inspections, an X-ray energy level typically exceeding 160 kV is employed to effectively screen thick mass containers. The X-rays must penetrate through various materials to identify hazardous substances; therefore, it becomes essential to minimize the interaction between the X-ray beam and the objects that are being examined. It is crucial to understand that the operation of an X-ray system generally follows a repetitive procedure, indicating that the radiation exposure levels encountered at each trial can be nondeterministic. This is characterized by inherent statistical uncertainties, denoted as σ, which are typically assumed to follow a Poisson distribution model. Each phase of control activities initiates at the X-ray machine, and every operational cycle establishes the need for specific predetermined intensity levels; consequently, these required source intensities heavily influence the design and configuration of the system. Noise generated due to Poisson variance emerges at the output level of the detector. After determining the parameters of the detector and the media involved, it is the combination of the system's X-ray intensity and additional settings of the detector that governs the quality of the noise present in the outputs received. [22, 16, 25, 13]

Chapter - 4

Medical Applied Physics: An Overview

Medical physics represents a vital and scientific branch within the larger field of healthcare, which is dedicated to the numerous applications of concepts, principles, and methods that are derived from physics as they are utilized in various medical contexts. This important and specialized discipline underpins and addresses the stringent requirements that are imposed by the healthcare industry, thereby ensuring the safety and efficacy of medical equipment. Moreover, it establishes suitable acceptance tests, in addition to recommended guidelines for quality assurance, which are fundamental to maintaining high standards in medical practice. Furthermore, medical physics actively contributes to the ongoing development and refinement of diagnosing and therapeutic techniques, along with the essential devices that are used in hospitals and clinical settings. Noteworthy examples of such advanced technologies and techniques include magnetic resonance imaging (MRI), which provides detailed images of internal structures, radioisotopes that are utilized in the diverse field of nuclear medicine for both diagnostic and therapeutic purposes, and the sophisticated radiotherapy techniques that heavily rely on specialized linear accelerators. Additionally, medical physics is instrumental in defining precise measurement protocols and standardized treatment procedures that adhere to various codes of practice. This encompasses critical activities such as the careful determination of air-kerma within a mammography beam, as well as the detailed dosimetry of radiotherapy megavoltage beams, ensuring not only accuracy but also efficacy in patient care and treatment outcomes which are paramount in any clinical environment. This field continues to evolve, thereby playing an increasingly crucial role in advancing healthcare delivery through the integration of physics principles. [14, 26, 27, 28, 29]

4.1 Role of Medical Physics in Healthcare

Medical physics plays an absolutely vital role in the modern landscape of medical care; medical physicists serve within hospitals, collaborate with industry, and engage with regulatory bodies across the globe. Today's complex healthcare systems are profoundly dependent on a diverse array of advanced technology, which includes magnetic resonance imagers, X-ray imaging equipment, linear accelerators, and various sophisticated radiosurgery systems. It is the responsibility of medical physicists to ensure that this cutting-edge medical technology is utilized not only optimally but also safely and effectively. Comprehensive quality assurance programmes, in addition to regular audits and performance reviews, confirm and maintain the necessary confidence that patients and healthcare providers expect in today's modern healthcare systems. Over the past twenty years, regulatory standards governing medical practices have changed significantly in many countries, reflecting ongoing advancements in technology and patient safety. For instance, within their respective departments, medical physicists may be appointed in crucial roles as radiation protection officers and radiation safety advisers, where they are trusted to write, implement, and regularly update procedures and protocols that govern the handling of radioactive materials and the safe operation of radiation-emitting devices. They are also tasked with the implementation of suitable safety programmes that comply with regulatory requirements. Furthermore, biomedical scientists and postgraduate students specializing in medical physics often actively engage in collaborative projects that focus on enhancing the performance and accuracy of medical apparatus and equipment. Many forensic experts possess some level of medical physics experience; indeed, numerous experts remain actively involved as consultants, providing valuable insights in the field. Additionally, industrial physicists and planners draw upon their extensive knowledge when it comes to the development of innovative medical instrumentation. Within the industry, medical device engineers and developers frequently rely on the expertise of a medical physicist as a consultant throughout the design process, ensuring safety and efficacy in the emerging technologies [30].

Medical physics is an applied branch of physics that plays an essential role in healthcare, combining principles of physics, mathematics, biology, anatomy and physiology in relation to radiation [1]. The field encompasses the development and application of advanced medical technologies, such as medical imaging, image-guided therapy systems and radiation treatment techniques, and the conduct of scientific research contributing to improved diagnosis and treatment through quantitative information. Its continuous growth worldwide is driven by recent advancements in imaging, treatment capabilities and imaging-radiation treatment options that involve large volumes of individual patient datasets, challenging medical physicists to devise novel strategies for statistical analysis and clinical translation.

The origins of medical physics can be traced back to 1895, when Wilhelm Röntgen discovered X-rays and identified the potential dangers of X-ray exposure to the human body. Medical physics has since evolved into a multidisciplinary field, alongside medicine, biology and medical technology, and remains a cornerstone in radiation-related healthcare applications.

Sub-disciplines of medical physics cover topics such as radiation therapy, medical imaging, nuclear medicine, health physics, and physiological measurement. Although medical physics encompasses both optical technologies and non-ionising radiation, it has predominantly originated from the radiological sciences, focusing on ionising radiation and radiation protection aspects. Applications as diverse as ultrasonics, optical interferometry and physiological measurement have subsequently fallen within its extended scope.

The origin of medical physics can be traced to Wilhelm Röntgen's discovery of X-ray in 1895. The science of medical physics evolved following the detailed understanding of X-ray and radioactivity. A medical physicist applies physics to the study of medicine, particularly in healthcare involving radiation. One branch of medical physics is to utilize radiation for diagnostic imaging and radiation therapy. It is an applied branch of physics which makes use of concepts in anatomy, physiology, biology, and mathematics.

Medical physics is concerned with the application of the concepts and methods of physics to the diagnosis and treatment of human disease. Radiation physics describes the physical characteristics of ionizing electromagnetic (x-rays and gamma rays) and particulate (electrons, protons, gamma photons) radiation, and neutron radiation produced in nuclear interactions. Other types of non-ionizing radiation commonly used in medicine include laser light, microwaves, radio and audio frequency waves. The term "radiation" is often used to indicate ionizing radiation in the field of medical physics. The interaction of ionizing radiation with living tissue is governed ultimately by principles of quantum mechanics, the study of the interaction of radiation with matter. This body of knowledge, the biological effects of radiation, is fundamental to radiation oncology and diagnostic radiology. It is used to calculate dose distributions required to kill a tumour in the former and to minimize doses to the patient and staff in the latter [1].

Medical imaging and radiation therapy have led to many important advances in medical physics and radiation safety. It is undeniable that physics and radiation protection also play an important role in medical diagnosis, treatment, and research.

Radiation physics provides the physical basis for all medical imaging and radiation therapy technologies used in hospitals and clinics [2]. Ionizing radiation has been used in medical diagnosis ever since Wilhelm Röntgen first demonstrated the existence of x-rays; modern computation and electronics have vastly improved both the quality and quantity of medical images, and have brought many new imaging modalities into widespread use. On the therapeutic side, modern linear particle accelerators and isotope production and separation techniques have led to both the renewed use of brachytherapy and the availability of high-energy, intensively collimated beams for the radiation treatment of tumors and other medical conditions. Radiation physics also provides the foundation for estimating, generating, and measuring radiation dose in standard clinical procedures, and is thus essential in determining the carcinogenic potential of radiation exposures and in assessing and evaluating radiation doses to patients, medical personnel and the general public.

The biological effects of radiation form the foundation for radiation therapy, dosimetry, and radiation protection in medical physics. Knowledge about different types of radiation, their interactions with tissue, and the accompanying biological effects provides valuable criteria for optimizing medical uses of radiation. The cumulative experience gained from the wide-ranging applications of ionizing radiation throughout the twenty-first century is also a key factor in the continual improvement of radiological protection standards.

The biological effects of radiation are complex, varying with radiation type, dose, dose rate, the affected tissue, and the biological endpoint considered. The interaction of energetic photons or charged particles with human tissue can cause excitation or ionization of the atoms and molecules; charged particles can also transfer energy through Coulomb interactions with nuclei or nucleons. In diagnostic imaging, the dose levels are very low and, consequently, biological damage is also of a low level. Conversely, in radiation therapy, much higher doses are administered with the aim of destroying as many tumor cells as possible.

A wide range of medical imaging modalities are used in today's healthcare worldwide for expedited diagnosis and treatment of various diseases, including X-Ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Nuclear Imaging, and Ultrasound. These techniques rely on fundamental principles of medical physics-especially radiation physics-and the capabilities of modern information technologies.

X-rays have been employed since the late 19th century as an effective non-invasive industrial and medical inspection tool. The general principles of X-ray machines and techniques, including tomography, Computed Tomography, and Digital Subtracted Angiography, remain central to contemporary medical imaging. However, X-ray imaging exposes tissue to mildly ionizing radiation and therefore is limited in certain clinical circumstances. In contrast, MRI uses non-ionizing electromagnetic fields, is non-invasive, and delivers high resolution and contrast between soft tissues.

In the practice of radiation oncology, information technology is critical to the clinical decision-making process. Treatment planning, image-guidance, dose delivery, and verification rely on high-quality information communicated within and across clinic networks. The planning and provision of the requisite data may be more challenging in smaller clinics; as smaller clinics are unlikely to have dedicated, trained IT portals it is common for the medical physicist to undertake all or part of this responsibility [2].

X-rays are produced by passing charged electrons through a potential difference of many tens of kV and directing the electrons upon either a heavy metal target or through an X-ray transparent medium. The X-ray emission spectrum and the yield depend on the atomic number of the medium and the potential difference [3]. By understanding the production of X-rays, the nature of the interactions with matter and the physical mechanisms of X-ray image formation, one can gain an insight into the principles of X-ray imaging.

The discovery of X-rays by Röntgen in 1895 stimulated much interest in possible new scientific and commercial applications in medical diagnosis and therapy. Since then X-ray imaging technology has been proven to be an indispensable diagnostic tool and a significant part of health care worldwide. Computed tomography, angiography, fluoroscopy, and digital radiography are the most common medical X-ray imaging techniques utilized today. From the 1970s, efforts to develop X-ray imaging sensors with integrated electronics have motivated research on direct conversion X-ray detectors, which convert the incident ionizing radiation directly into electrical signals. The Laboratory of Radiation Dosimetry and Medical Radiological Physics supports a wide range of measurement standards for ionizing-radiation quantities in health care applications. The accurate measurement of broad-spectrum X-ray beam exposures used in general radiography and in mammography is an important element of this activity [4]. Recognizing the need for a radiation-exposure standard for mammography led to the development of the US national standard for radiation exposure from X-ray beams used in standard mammography. This standard is widely used in the US for voluntary and regulatory compliance of over 13,000 mammography facilities.

Computed tomography (CT) is an X-ray technique that produces high-quality, cross-sectional images of human anatomy. CT scans can be acquired in seconds and virtually any anatomical area can be examined. This rapid scanning capability and wide range of clinical applications have made CT the most frequently used imaging modality after radiography [5]. The rapid decline in cost and widespread availability of CT systems also contribute to its large institutional usage worldwide [6]. During image acquisition, the patient will receive a significant radiation dose. Particular attention must be paid to optimize CT scanning conditions to deliver the lowest possible dose to ensure patient safety and reduce the risk for late somatic effects, such cancer [7].

MRI uses the phenomenon of nuclear magnetic resonance, primarily exploiting hydrogen atoms, to generate images [8]. First demonstrated on humans in 1977, ongoing developments have yielded faster scan speeds, increased magnetic field strengths, and advanced image processing, enhancing soft-tissue contrast and enabling functional imaging sequences that characterize tissue physiology [9]. MRI facilitates noninvasive evaluation of internal anatomy and function, supporting applications such as diagnosis, disease staging, treatment planning, response monitoring, and surveillance.

Modern oncology practice increasingly integrates MRI into radiotherapy strategies for brain, gastrointestinal, and prostatic tumors. Tailored protocols specify standardized imaging sequences and slice thicknesses to delineate target volumes and organs at risk with precision. The introduction of MRI-linear accelerator (MR-Linac) technology combines high-quality MR imaging with delivery of conformal, high-precision radiotherapy, enabling real-time treatment adaptation and potential improvements in therapeutic outcome and toxicity profiles. Clinical trials currently investigate the efficacy of MR-Linac, particularly in prostate stereotactic body radiotherapy (SBRT).

Driven by the demands of conformal, high-precision techniques such as intensity-modulated radiotherapy, volumetric-modulated arc radiotherapy and stereotaxis, advanced imaging modalities have become indispensable for accurate delineation of anatomy, thereby improving the therapeutic ratio. Functional MRI and molecular imaging approaches, such as positron emission tomography, have motivated dose-painting and adaptive radiotherapy concepts, supporting ongoing reductions in treatment margins and dose escalation. Image-guided radiotherapy with integrated MRI scanners (MR-Linac) constitutes a further step forward, enhancing the precision and accuracy of the dose delivered.

Ultrasound uses high-frequency sound waves to generate images of internal organs, blood flow, and fetal development [10]. Transducers-the probes of ultrasound machines-convert electrical energy into acoustic energy for transmission into the body and receive echoes converted back into electrical signals to produce real-time images [11]. Two main probe types are curved and linear. Curved probes operate typically at 2–5 MHz, providing lower-frequency sound suitable for deep abdominal imaging with wide fields of view. Linear probes operate at higher frequencies of approximately 5–13 MHz, delivering excellent near-field resolution for superficial structures like soft tissue and blood vessels but with limited penetration depth [12]. Ultrasound has widespread clinical use where real-time visualization of tissue structure and blood flow is needed. It is a key diagnostic and therapeutic tool in gynecology, obstetrics, soft tissue examination, and vascular assessment, producing highly descriptive images of anatomy and motion.

Nuclear medicine exploits nuclear physics techniques for diagnostic imaging and therapeutic treatment of disease. It originated as an effort to employ radiation produced artificially by cyclotrons, reactors, and other devices to investigate biological processes. Today, it uses internally administered radioactive materials (radiopharmaceuticals) to monitor physiological functions of specific organs [13]. Radioisotopes prepared outside the body possess all the characteristics of substances normally used by particular organs in their daily functioning. Their concentrations in diseased organs differ from those of healthy organs, frequently permitting early disease detection. Early examples include iodine concentrates in the thyroid and phosphorus and calcium in the bone. Nuclear medicine modality requires the development and daily practical application of specific models of human morphology and function. The radiopharmaceuticals prepared and used in nuclear medicine investigators contain radioactive elements that emit photons of various energies in the gamma or X-ray zone, and these photons are detectable external to the body by scintillation or semiconductor detection devices. The distribution of the radionuclide intraorganically and interorganically can be measured and recorded with a technique called scintigraphy. Recording data is performed by multichannel analyzers linked to a computer, permitting a reconstruction that results in cross-sectional or vertical slices or longitudinal, horizontal, or tangential slices of the whole organ. Large camera assemblies capable of making these sections within a very short time interval are used to acquire the data. The information thus obtained can detect functional activity variation within an object such as a tumor. In addition to the diagnostic aspects of nuclear medicine, many of the radiopharmaceuticals can deliver a concentrated high dose of radiation to a specific target area in the body. This approach may arrest, retard, or even reverse the condition present in that region. The major indication for this type of treatment is malignant neoplasia, where the targeted dose kills tumor cells and controls local conditions [14]. Practitioners who supervise these treatments must fully understand large radiation-dose behavior in tissue, pharmacokinetic behavior, and related effect prediction mechanisms. Specific education and training in quality control have become essential in modern nuclear medicine. The nuclear medicine physicist understands the clinical use of the technology and can assist clinical colleagues in assessing trade-offs to achieve desired outcomes. The physicist is also an expert in dosimetric and radiation safety aspects of therapeutic radiopharmaceuticals.

Radiation therapy employs ionizing radiation, typically high-energy photon and electron beams, to treat malignant tumours. It involves extensive collaboration among medical physicists, oncologists, dosimetrists, and radiation therapists to develop diagnosis-specific protocols. Treatments may be external (teletherapy), where radiation is delivered from outside the patient, or internal (brachytherapy), where radioactive sources are placed within the body near the treatment site. Medical physicists are deeply involved in quality assurance, calibration, and design of radiotherapy equipment [15].

Radiation therapy involves the administration of high energy particles to treat human cancer using an external machine or from radioactive sources inserted inside the body; this is the oldest direct therapeutic application of radiation [15]. Since radiation targets both healthy and diseased tissue, the goal of therapy calls for the delivery of a therapeutic dose to the tumor while minimizing the exposure to normal structures.

Historically, the successful delivery of radiation therapy demands an accurate knowledge of the absorbed dose contributed by each individual beam, the ability to calculate the dose at any point in the patient's body and to access technologies to verify that the treatment machine is able to accurately deliver the desired dose distribution [2]. Radiation therapy is carried out in two forms:

- **External beam radiotherapy (Teletherapy):** Treatment time required by teletherapy range from a few days to a several months depending on the type of the tumor and this treatment is mostly using ionizing radiation.
- **Internal Radiotherapy (Brachytherapy):** This method is used when patient is accompanied by an internal or external radioactive source for destruction of cancerous tissue in the target area as fast as possible.

Radiation therapy employs ionizing radiation to eradicate tumors, predominantly through irradiation of x-ray photons in the 1-25 MeV range, with doses spanning several grays. Precision in dose delivery is paramount to safeguard normal tissue, necessitating strategies such as maximizing tumor dose, fractionating therapy to permit normal tissue recovery, and conforming dose to the tumor's exact shape. When detected promptly, early-stage tumors may be treated with curative doses; otherwise, radiation serves a palliative purpose, aiming to alleviate symptoms associated with tumor growth or metastasis [16].

Modern radiation therapy encompasses conventional and three-dimensional conformal radiotherapy (3D-CRT), as well as intensity-modulated radiation therapy (IMRT). Each methodology operates on the foundational principle of administering ionizing radiation to suppress or eradicate cancer cells, with variations in beam number, intensity, and delivery geometry. External beam radiation therapy (teletherapy) utilizes high-energy X-rays from linear accelerators, sometimes enhanced through artificial beam modifiers such as wedges and compensators to achieve optimum dose distribution. Alternative external sources include cobalt-60 teletherapy machines and Varian Clinac 2500 accelerators. Other treatment modalities involve the application of particles, such as electrons or carbon ions, under the auspices of proton therapy.

Innovations in cancer treatment frequently necessitate revisions in quality assurance (QA) directives. Medical physicists assume a critical role in implementing these QA systems and devising approaches to examine emerging techniques in clinical settings. Cancer therapy with photon beams encompasses a complex, multidisciplinary process extending beyond the simple application of radiation. The treatment team includes oncologists (radiation oncologists, medical oncologists, and surgical oncologists), oncology nurses, medical physicists, dosimetrists, and radiation therapists, all playing crucial roles at various stages of the process. Given the complexity involved at every step, the implementation of a robust QA program is essential [17].

Radiation-therapy equipment is before, during, and after treatment, necessitating a periodic QA program for individual unit components and the entire equipment system. Mechanical, dosimetric, and geometrical parameters of the equipment are checked at predetermined intervals or after major repairs or interventions. New technological developments in modern radiation-therapy equipment, such as the integration of in-line and/or off-line imaging systems, electron arc therapy, compensators for high-energy electron beams using advanced scanning systems, and real-time imaging verification and gating systems, have potential implications for QA practices [18].

Modern radiotherapy units incorporate various in-built dosimetry tools, facilitating the establishment of electronic data records and continuous time-stamped information on equipment, thereby enhancing verification of equipment functionality, features, calibrations, and services. As the number of safety experiments required for clinical validation continues to rise, the role of the medical physicist remains central in overseeing and coordinating QA tasks.

Medical physics specialists advises physicians and other healthcare workers adopting radiation sources for both diagnostic and therapeutic purposes. The functions of measuring and monitoring radiation doses are to be performed under their supervision, and so are the characterization and calibration of sources. In addition, medical physicists assume an important role in the investigation of accidental or unintended exposures, in registry analyses of such incidents and, if necessary, in the development of corresponding prevention strategies [19]. As regards dosimetry, the main objective pursued is the measurement of the amount of ionizing radiation absorbed by a medium. Adopting an operational approach, the dosimetric method to be used must be both appropriate to the type of exposure in which it is applied and sensitive enough to register the range of doses expected. Several methods and instruments are commonly used to perform such measurements.

When dealing with patients, a different approach has to be taken depending on whether the main purpose is merely assessing radiation dose or if, on the contrary, the goal is to gain information about the concentration of any of the different components under exposure. In the former case, for example, the amount of radiation absorbed by living tissues of animals in external irradiations involving electrons, neutrons, x-rays, protons and gamma-rays at different energies can be accurately measured by pairing thermoluminescent dosimeters with a PWDT-03 reader, provided dose values do not exceed approx. 30 cGy. In the latter, such potentialities are fulfilled by the combined model Ts/B Gamma, which is able to detect micrograms of phosphorus in a P-labeled biological medium. Once enlarged to account for residual levels, the upper limit of lineality extends up to approximately 6 [units]. The field of ionizing radiation protection is frequently grounded on personnel classification in two different categories depending on the estimated annual dose. Category A corresponds to a group of selected professionals whose effective dose is expected to exceed 6 mSv per year, when the annual equivalent dose to the eye lens is larger than 45 mSv, or when, except for the eye lens, the annual equivalent dose received by the skin and extremities is likely to be above 150 mSv [20]. Such exposure estimates imply the compulsory implementation of individual dosimetry techniques, preferably using passive dosimeters. Workers belonging to this category are usually those who handle radiation sources on a regular basis or who carry out their professional activities close to beams of ionizing radiation, for instance in Nuclear Medicine, Interventional Radiology or Radioactive Therapy and Brachytherapy. All the remaining personnel have to be ascribed to Category B, which covers those individuals whose effective dose, the equivalent dose to the eye lens and the equivalent dose to the skin and extremities remain below 6 mSv, 45 mSv and 150 mSv per annum respectively, i.e. they are exposed to relatively low levels of ionizing radiation. Finally, a third group refers to non-exposed workers who only receive doses far inferior to the dose limits established by the prevailing legislation, the maximum effective dose generally being lower than 1 mSv per year.

Dosimetry is the measurement, calculation, and assessment of the ionizing radiation dose absorbed by a human body. One of the challenges faced by clinical medical physicists is the estimation of the absorbed dose in patients undergoing external beam radiation therapy or brachytherapy. Careful dosimetry in these procedures is necessary because the tissues being treated must receive sufficient radiation to achieve good control of the tumour burden, yet should not be damaged more than the disease requires.

With external beam radiation therapy, direct measurements of the absorbed dose are impossible, as no probes may be placed within the body during treatment. Therefore, pre-treatment calculations must be made using phantoms, dosimeters, and treatment planning software. In-vivo dosimetry can also be used, in which doses are measured inside the patient using instruments such as thermoluminescent dosimeters (TLDs) and semiconductor probes. Several different types of external beam radiation therapy are available, classified by particle type, and dosimetry methods are available for all of these. There are also a variety of different forms of brachytherapy sources and clinical situations, so a large number of dosimetry methods are used in this sub-field of radiotherapy.

Once the radiotherapy treatment plan is determined, the medical physicist may use a dosimeter to verify the dose predictions of the treatment planning system. Some of the most common dosimeters used for in-house quality assurance and calibration are ionisation chambers, film, and TLDs [21].

Accurate measurement of ionising radiation doses plays a critical role in medical imaging procedures such as X-ray, computed tomography, and radiation therapy. Radiation protection and nuclear medicine procedures represent an important component of medical physics services. Staff working in medical physics have established their role in radiological techniques with guidelines published by the International Atomic Energy Agency [22].

Ensuring radiation safety is paramount in modern medical facilities that utilize ionizing radiation [23]. Implementing a comprehensive nationwide radiation safety program, collaboratively maintained by various healthcare disciplines, constitutes a critical step towards protecting both patients and personnel. Such a program typically monitors radiation dose through parameters including fluoroscopy time, air kerma measurements, and peak skin dose calculations, enabling the establishment of dose limits and the application of adequate protective measures. Safeguarding occupational health hinges on an acute awareness of radiation hazards coupled with adherence to rigorous safety protocols. Core elements of the program encompass systematic personnel training, continuous radiation monitoring, strategic shielding design, optimization of imaging equipment use, and ongoing staff educational initiatives. The development and enforcement of radiation safety management protocols-targeting dose reduction in high-exposure settings such as catheterization laboratories and facilitating individual dose minimization-constitute indispensable components of these efforts.

The medical physicist applies scientific principles for the prevention, diagnosis, and treatment of human diseases. The clinical role of the medical physicist includes the operation and quality assurance of medical imaging systems used for routine medical examinations, the calibration and treatment planning of radiation treatment equipment used for cancer treatment, execution of radiation safety programs in order to protect patients, staff, and the public, inspection and testing of implanted medical devices prior to magnetic resonance imaging, development of radio- and opto-physics techniques for cutting-edge clinical research, and participation in classroom and clinical teaching of medical, physics, and other health science students [2].

Medical physics assists in the diagnosis of patients by helping radiologists and other medical specialists during the diagnostic process. Medical physics forms the foundation for many modern medicine and healthcare aspects, the role increasing alongside medical technology development. Modern medical technology supports medical physics by enabling the field to supply information that aids healthcare professionals in patient diagnosis.

X-rays have been used since the 1890s for diagnostic purposes. Since then, x-ray imaging and other new imaging techniques have been applied in most clinical fields.

Medical physics is involved in clinical diagnostic activities. It compares medical physics technologies with other medical technologies to suit clinical applications and effects. Medical physics contributes during clinical trials at preclinical stages [2]. For example, understanding the effective energy of the x-ray spectrum helps medical physicists select materials with appropriate sensitivity and image quality that meet clinical requirements. The use of the gravitational effect on water-fluid systems for developing new dosimetry techniques illustrates these trials. New imaging and dosimetric techniques based on these devices have been investigated and applied in some clinics.

In clinical diagnostic imaging, medical physicists assess whether imaging technologies are meeting clinical needs [2]. The primary objective is to select the imaging system that affords the highest diagnostic quality at the lowest acceptable cost or radiation dose to patients. A key consideration is the interplay between image quality and dose in diagnostic radiology, as dose directly corresponds to the inherent risk associated with radiologic examinations. A second role involves indications for each type of specialized imaging procedure to determine the most appropriate technology for clinical diagnosis in given situations. Thirdly, medical physicists determine the appropriate dose to administer in procedures that entail dose delivery, such as nuclear medicine, interventional radiology, and computed tomography.

In therapy, imaging techniques contribute to confirming the optimal treatment strategy for patients [21]. Another clinical task involves treatment planning; here, medical physics support generates intake images through three-dimensional imaging (e.g., MRI and CT scans). Through computer advancement, treatment plans leverage these images to accurately determine the exact volume of the tumor to be treated. Corresponding images illustrating the tumor location facilitate the generation of a comprehensive treatment plan. Once finalized, the treatment procedures derived from these plans guide the clinician's approach.

Medical physics is the branch of physics applied for the diagnosis and treatment of human diseases. A medical physicist is a professional with expert knowledge for the safe and effective application of physics to healthcare. The range of services offered by Medical Physics includes scientific and technical advice on radiation for diagnosis and therapy, quality assurance (QA), radiation safety (subject to regulatory authority), and the general application of physics to medicine. Medical Physics serves as a link between physics and medicine, assisting the healthcare community in the development and implementation of physical methods of diagnosis and treatment.

Application of physics in medicine is extremely broad. Therefore, Medical Physics comprises several subfields, histologically reflected in the various workplaces associated with the profession. Medical physics expertise is relevant to the operation of a diagnostic imaging facility, the division of radiation oncology, a biomedical research group, a hospital laboratory, the development of medical devices, academic or research laboratories, and the specific subfields of Medical Physics include radiology and diagnostic imagery, radiation oncology, nuclear medicine, radiation protection, and general medical physics. The role of Medical Physics in research and development is nowadays increasing, and the success of innovative medical physics applications during the COVID-19 pandemic confirmed the possibility to be well-prepared to face new challenges. [2]

Artificial intelligence is poised to revolutionize medical imaging, offering the potential to lower radiation doses, reduce biopsy rates, and assist radiologists with lesion detection and classification. Beyond diagnosis, AI-driven image reconstruction and analysis methods enable the extraction of latent patterns from medical images to detect cancer and predict patient outcomes [2]. Two major technological developments in radiation therapy are the continued development of FLASH and ultra-high dose rate radiation therapy and the advent of multi-ion irradiation. The former presents the prospect of ultra-rapid treatments that also normal tissues resist far better than tumors. Interactions of high-energy proton beams with beam-line components, including the energy degrader, lead to the production of neutrons with energies up to the incident proton energy.

Artificial intelligence (AI) is increasingly important in healthcare and the fields of medical physics and medical imaging. It has long been a central theme in medical image analysis, manifesting in tools such as computer-aided diagnosis. Medical image acquisition devices typically generate vast quantities of high-quality data that machine-learning algorithms can exploit, and imaging is intertwined with modern healthcare. AI software can extract informative features from images, integrate patient data (age, medical history, diagnostic test outcomes), and generate quantitative predictions (probabilities of disease, expected survival, likely therapy responses), aiding both researchers and clinicians [24]. Numerous applications of AI to medical image analysis exist, and the volume of published work grows exponentially.

Radiologists and nuclear medicine physicians are expected to incorporate AI tools into practice and should contribute substantially to their development and training. AI already performs many steps in radiomics-style image-analysis pipelines. For instance, AI-based segmentation and feature-extraction algorithms have addressed bottlenecks, often enhancing prediction-model performance. Multiple techniques are combined to reduce individual-method variability, thereby improving reliability [25]. Radiomics traditionally depends on segmented volumes or lesion annotations; however, deep-learning methods can construct predictive models directly from segmented tissues or even entire images, circumventing tedious manual annotation. A principal challenge remains accounting for variability in multi-center and multi-scanner data, with strategies focused on leveraging learning-capable algorithms to exploit diverse datasets or normalizing images to minimize inter-scanner differences. AI also holds promise for radionuclide dosimetry, in particular realizing dose-reduction strategies for patients undergoing multiple scans; down-sampled acquisitions become interpretable via AI techniques (e.g., deep networks and generative adversarial networks), facilitating precise dosimetry. Similarly, elite planning may be informed by AI-predicted post-therapy dose distributions derived from pre-therapy clinical, imaging, and dosimetric information. Advanced AI algorithms, including deep-learning frameworks and GANs, contribute to voxel-level dose estimation and support the development of new radiotracers. As nuclear medicine techniques become more complex, AI will play a pivotal role in facilitating personalized diagnosis and response-assessment protocols.

Medical physics plays a pivotal role in healthcare by applying physics principles and methods to medicine, particularly in the development and utilization of medical physics technologies. Advances in radiation therapy exemplify the significant contributions of medical physics, which draws upon principles of radiation physics and biological effects to control the application of various radiation types [2].

Radiation therapy aims to deliver radiation doses selectively to tumors, sparing surrounding healthy tissues. Historically, tumors were irradiated with low-energy photons for a total dose of 30 Gy, insufficient for complete sterilization of many malignant tumors. The introduction of high-energy linear accelerators revolutionized the field by enabling treatments with megavoltage photons and electrons for higher-dose therapies. Currently, a variety of procedures are routinely performed, including external X-ray therapy, Brachytherapy, Total-Body Irradiation, Intra-Operative (IORT) and Intra-Cavity Radiation Therapy [15].

External radiotherapy differentiates between orthovoltage machines, which generate X-ray beams up to a few hundred kilo-electron-volts (keV), and megavoltage machines operating in the mega-electron-volt (MeV) range. More specialized external radiation treatments involve stereotactic, conformal, intensity-modulated, image-guided, and proton therapy. Dose monitoring in radiation therapy utilizes an array of detectors, including ionization chambers, thermoluminescent dosimeters (TLD), semiconductor diodes, diamond detectors, metal foils, and gels. Additionally, medical physicists develop various non-ionizing methods for tumor treatment and medical imaging, further illustrating their integral role in healthcare.

Informed consent, respect for autonomy, protection of personal information, social equity, and appropriateness of use are central concerns in the deployment of medical-physics-related technologies in healthcare. Ensuring competent execution of specialist activities with a minimum risk of poor performance and identifying appropriate codes of conduct are considered specific ethical responsibilities for medical-physics specialists [26]. Appropriate traceability of data, documentation of decisions, and delegation of work to assistants are also topics of concern.

In medical practice, respect for a person's autonomy is paramount. Patients who have decision-making capacity have the right to make their own decisions about their care and treatment. One pivotal element of this right is the ability to provide or withhold informed consent for a particular procedure or intervention. The prevalent definition of an informative consent has evolved from one in which patients are merely given information to one in which patients must be given sufficient information and are able actively to participate in the decision-making process. Because of their involvement in many patient procedures, medical physicists are encouraged to take an active role when consent is needed [27].

Balancing risks and benefits lies at the heart of medical practice. Overtreatment, excessive radiation doses, wasteful spending, and wasted time pose significant risks to patients and society. Failing to provide optimal treatment or delaying diagnosis and therapy can bring about even graver dangers. The challenge is to use every technology to its fullest potential for the patient's benefit, while limiting needless risk. Medical physics contributes to achieving this balance by ensuring the rational and optimal clinical use of technology, and by developing methods that limit risk. Medical physics thus helps patients, medical personnel, and society to benefit fully from medical technologies [28, 29].

Developments in medical imaging and radiation therapy are outstanding examples of physics applied to medicine. Research and development are continually enhancing available technologies, which increasingly support minimally-invasive procedures. For all new technologies, appropriate clinical and

Medical imaging began with the discovery of X-rays by Wilhelm Röntgen in 1895, which was swiftly adopted for clinical use. The subsequent invention of computed tomography (CT) by Sir Godfrey Hounsfield and Allan Cormack in 1972 marked a pivotal advancement, earning them the Nobel Prize in 1979. Additional modalities such as ultrasound and magnetic resonance imaging (MRI) emerged in the decades that followed, benefiting from parallel developments in digital technology, including Picture Archiving and Communication Systems (PACS), three-dimensional visualization, and automated decision-support tools [31]. Today, widely used techniques-X-ray, CT, MRI, nuclear imaging, and ultrasound-continue to evolve, supporting a spectrum of applications from contrast-enhanced imaging to specialized assessments like those for osteoarthritis and cardiovascular pathologies. Emerging approaches such as Electrical Impedance Tomography further expand the diagnostic repertoire [32].

Revolutionary advances extend into functional and quantitative domains, with molecular imaging playing an increasingly central role in oncologic evaluation. The ability to acquire detailed measurements of tumor volume, uptake, and heterogeneity enhances the accuracy of treatment response assessments. The burgeoning field of radiogenomics couples imaging data with genetic profiling to enable personalized diagnostics and therapy selection. Minimally invasive image-guided interventions have become widespread, benefiting from innovations in robotics, micro-imaging devices, and material science to elevate procedural safety and precision [33]. Emerging trends like cinematic rendering offer photorealistic visualization, while artificial intelligence agents contribute to sophisticated image interpretation. Support for percutaneous interventions and the development of patient-specific computational models with improved predictive capabilities illustrate the expanding clinical and research applications of medical imaging. The trajectory of innovation promises continued progress, facilitating enhanced patient care and cost containment.

Radiation therapy benefits from many different innovations. The use of charged-particle beams in cancer therapy has entered the mainstream. These beams destroy a tumor's cells but spare surrounding healthy tissue. The essence of these radiation treatments has not changed, despite the variety of accelerators and beam conditions employed. The most relevant development in these procedures is the availability of equipment that renders these treatments broadly feasible. This equipment typically supports the long tradition of standard radiation approaches, frequently adding options such as intensity modulation, image guidance, and/or proton or heavy-ion therapy [2]. High energy electrons are used for irradiation when tumors are located on or near the patient's surface. Gamma rays are employed extensively in brachytherapy.

Clinical Medical Physicists collaborate closely with other health professionals [30]. Medical physics is an applied science, and it is necessary for Medical Physicists to understand the clinical context and challenges in order to support the clinical services. Medical Physicists may work individually or as part of a service team. Medical Physicists contribute to interdisciplinary teams with expertise in imaging, physiology, modelling and data analysis. They must remain abreast of developments in physics and associated technologies to ensure ongoing provision of benefit to patients and clinical users. Medical Physicists may be involved in educating and training health professionals, students and the community [1].

Medical physics contributes significantly to healthcare, participating in diagnosis, treatment, and research [34]. Medical physicists join physicians, nurses, and other health professionals as members of an interdisciplinary healthcare team [35]. They interact primarily with the medical and radiation oncology services. This raises the need for appropriate education of other health professionals, including physicians and residents who will work closely with the medical physicist in the clinical program.

Medical physicists play a crucial role in healthcare, especially in the application of ionizing radiation for diagnosis and treatment [1]. Becoming a medical physicist requires academic studies in physics, specialized training in medical physics, and practical clinical experience. Several countries have developed graduate and postgraduate programs in medical physics and offer distance learning options to expand accessibility. Harmonization of professional training and education is achieved through international accreditation guidelines, enabling resource-limited nations to establish effective educational programs. Certification programs assess the knowledge and clinical competencies of medical physicists at entry and advanced levels, with some countries mandating ongoing demonstration of expertise to ensure patient safety.

With the increasing involvement of medical physicists in direct patient care, enhanced physics training and education have been introduced to prepare them for clinical consultations and effective communication. A dedicated training program combines foundational clinical education with a communication skills curriculum, facilitating the development of skills necessary for patient interactions [34]. This program supports a randomized phase II clinical trial in which board-certified medical physicists engage in physicist–patient consults with cancer patients. Additional trainees are currently completing the curriculum in anticipation of a forthcoming phase III study, and a formal evaluation is underway to assess the training methods before broader dissemination.

Throughout this work, it has been evident that medical physics plays a pivotal role in healthcare. By applying physics concepts, theories, and methods, medical physics supports the diagnosis, treatment, and prevention of human diseases. Medical physics is a core activity within healthcare and bridges the physical sciences and medicine. The discipline requires a high level of education and training, from undergraduate degrees to internships, residencies, professional certification, and continuing education [1].

Medical physicists play a critical role in clinical settings, including radiation therapy treatment planning, diagnostic imaging analysis, and research. They ensure the safety, quality, and effectiveness of medical procedures and often collaborate closely with physicians, radiologists, oncologists, and other healthcare professionals [2]. Furthermore, medical physicists contribute to the development of new technologies and methods to advance healthcare by providing patient-friendly, cost-effective, and efficient technologies [30].

In summary, medical physics serves as a bridge between the physical sciences and medicine. The discipline provides essential theoretical and practical knowledge that enhances the delivery of healthcare and improves patient outcomes. A continued and growing recognition of the importance of medical physics will contribute to the advancement of healthcare and the well-being of patients globally. In the Asia Pacific region alone, substantial growth in the medical physics workforce and radiation therapy infrastructure underscores the ongoing need for well-trained medical physicists to meet increasing demand. Globally, training programs, accreditation, and resource management remain priorities to sustain and expand this vital profession.

4.2 Regulatory Standards and Safety

Regulatory standards are indispensable for maintaining the highest levels of safety and quality in X-ray systems. They impose essential requirements that pertain to various stages of a product's lifecycle, including design, manufacture, installation, commissioning, and ongoing maintenance. Such comprehensive standards help to ensure the optimal and safe functioning of critical components such as X-ray tubes, detectors, and collators, particularly in demanding environments such as diagnostic and therapeutic medical settings. These vital regulations assist healthcare providers, device developers, and researchers alike in consistently adhering to safe, effective, and reliable medical practices that are crucial for patient care and treatment outcomes. By maintaining compliance with these regulations, stakeholders in the healthcare field can enhance trust and assurance in the efficacy and safety of their X-ray systems [31, 32, 33, 34, 35].

Chapter - 5

Medical Device Engineering Principles

The successful design and development of a medical device fundamentally depend on a clearly articulated description of the rationale driving the project, paired with a meticulously crafted Specification of Requirements document. This document serves to define, in detail, the essential performance criteria, quality benchmarks, safety standards, and regulatory specifications that are pertinent to the entire scope of the work being conducted. The engineering development process unfolds through a well-defined sequence of stages: starting from concept modeling, which is followed by design optimization, prototyping, engaging in pre-clinical trials, and proceeding through rigorous testing and validation phases. This process culminates in thorough design verification, followed by the actual manufacture of the device, and ultimately leading to deployment in a real-world setting. Each of these stages necessitates a comprehensive multidisciplinary approach, wherein the diverse tools and principles of engineering and physics continue to play a vital and instrumental role in ensuring success throughout the development lifecycle [36, 37, 38].

Medical Device Engineering Principles therefore investigates the engineering processes that underpin the production of medical devices. A large number of topics are addressed including engineering materials; design and prototyping; control strategies; deployment and management; regulatory and safety requirements; mod-elling emerging devices; non-destructive evaluation; and the diagnostic and therapeutic safety of X-ray machines [15].

5.1 Design and Development Processes

The development of advanced diagnostic and therapeutic systems that effectively combine the principles of X-ray physics with the intricate field of medical device engineering is heavily reliant on essential, well-established methodologies. These methodologies are consistently supported by various examples that showcase the collaboration and interaction between these two critical disciplines. It is imperative for medical device products to not only comply with stringent requirements for safety and reliability but also to be manufacturable within practical constraints. Medical device engineering, as a discipline, provides both a guiding principle and a structured process aimed at achieving a high-quality product that meets these important criteria.

There exists a vital need for ongoing communication and collaboration between the scientific realms of general physics, applied physics, and medical physics alongside the engineering discipline of medical device development. This ongoing dialogue is necessary in order to create a common ground that facilitates the effective design and development of sophisticated X-ray systems. To illustrate the intricate relationship between the fields of physics and engineering, as well as to highlight the fundamental connections that bind them, a detailed design of an open platform specifically intended for digital X-ray devices has been meticulously developed. This design framework is thoughtfully divided into two main components: a conceptual model and an architecture that is dedicated to promoting system-level integration, alongside extensibility for future enhancements.

Furthermore, since the evolution of diagnostic and therapeutic systems that utilize the principles of X-ray physics is deeply anchored in the methodologies of medical device engineering, a direct connection is inherently established. This connection allows for the seamless integration of knowledge derived from various realms of physics into the design and development processes of medical devices. Such an integrative approach aligns harmoniously with the conceptual framework that has been articulated for general, applied, and medical physics. It ensures that the specific equipment needed for medical applications can indeed be constructed by adhering to formalism that remains consistent with general principles and a broad conceptual model, thereby enhancing the efficacy and reliability of medical diagnostics and treatments [15, 39, 40, 41, 42].

5.2 Quality Assurance in Medical Devices

Quality assurance (QA) for X-ray systems is fundamental for ensuring the reliable performance of various therapeutic and diagnostic methods, which encompass interventional radiology, fluoroscopy, and the advanced technique of computed tomography. QA assessments serve the critical purpose of monitoring a range of parameters that are directly related to image quality, radiation dose accuracy, geometric stability, and the mechanical components that are integral to the system, including features like dynamic jaws and motorized lasers. These assessments ultimately characterize both the overall integrity of the system and its long-term stability, which is crucial for maintaining the safety and effectiveness of X-ray procedures. The accepted norms and indices that govern X-ray machine quality control are developed based on specific operating conditions that are designed to promote accurate image formation and precise diagnostics. Additionally, they are aimed at preventing the occurrence of excessive radiation doses to both patients and healthcare personnel, ensuring that safety is always a top priority while delivering high-quality imaging services [43, 31, 44, 45, 46, 47].

The design and engineering of such quality assurance processes as well as the development of the X-ray systems themselves requires a comprehensive understanding of the management of mechanical devices and electrical circuitry, components of electromagnetic radiation, and interactions of X-rays with matter. Medical-device engineering, therefore, integrates physics principles with leadership and project-management skills to bring benchtop concepts into practical systems [48]. The deployment of these human and technological resources continues to extend both the generation and utility of medical X-ray systems.

Chapter - 6

Integration of Physics and Engineering

The engineering of X-ray diagnostic and therapy systems relies on a tight collaboration between applied medical physics and contemporary technology. This collaboration delivers state-of-the-art devices for radiation imaging, radiotherapy, and important secondary applications such as medical fluorescence measurements, electron-beam tomography, or microbeam surgery. X-ray systems generally comprise an X-ray source and related collimators, an interface to the subject under examination (patient or material), and various arrangements of photon-sensitive detectors and further components. They may be employed for either diagnostic procedures or therapeutic applications, or a combination of both.

Applied medical physics is fundamentally anchored in the principles of general and applied physics as well as various engineering disciplines. This field systematically addresses the intricate characteristics and comprehensive supply of the primary photon radiation and delves into the complex interaction processes that occur within the exposed object. It also focuses on the containment and meticulous monitoring of the secondary radiation that is produced as a result of these interactions. The field further encompasses the generation of the recorded signal, alongside an assessment of the reliability and suitability of the information conveyed by the final diagnostic image.

Additionally, medical physics incorporates advanced simulations of the parallel physical processes that come into play, alongside physics-based modeling and sophisticated image reconstruction techniques. It emphasizes a structured numerical analysis of a prespecified clinical problem, ensuring accuracy and relevance to real-world applications. On the engineering side, it is responsible for the meticulous design, production, and installation of fully operational systems tailored for medical use. This includes the seamless integration of various devices into extensive medical imaging networks, rigorous quality assurance processes, and thorough verification of compliance with all relevant safety and legal requirements.

Through these efforts, engineering provides crucial means for optimization, intricate analysis, and detailed procedure planning, all with the overarching goal of further enhancing the properties and functionalities of the complete installation used in medical settings. This collaboration between physics and engineering is vital for ensuring that medical imaging systems operate at the highest standards of accuracy and efficiency, ultimately benefiting patient care and clinical outcomes. [15, 26, 49, 50, 51]

6.1 Collaborative Approaches

Development of diagnostic and therapeutic X-ray systems requires substantial knowledge of general physics, applied physics and medical physics along with engineering principles and design methodologies.

Diagnostic X-ray systems rely on principles of general physics, applied physics and medical physics combined with engineering and design methodologies for their development. X-ray systems encompass diagnostic imaging devices such as radiography, fluoroscopy, mammography and computed tomography as well as therapeutic systems like intensity modulated radiation therapy and image-guided radiation therapy.

The successful development of highly efficient X-ray systems necessitates a broad and deep theoretical knowledge of physics that encompasses general physics, applied physics, and medical physics, coupled with extensive practical engineering expertise. Although the field of medical physics can develop comprehensive and sophisticated theories intended for both diagnostic and therapeutic technologies, the realization and practical implementation of these advanced concepts demand a synergistic collaboration between medical physics and various engineering disciplines. This collaboration is crucial for ensuring that innovative ideas can be effectively translated into functional technologies that improve patient care and diagnostic accuracy in the medical field [15].

6.2 Case Studies in X-Ray Technology

Effects of an Electric Field on Carbon Nanotube (CNT) Fibers and X-Ray Generation Mechanisms

A CNT fiber exposed to an electric field experiences a reduction in the electron tunneling barrier [52]. Field-emitted electrons are accelerated to the anode, producing X-rays upon impact. An assembled triode-type CNT X-ray tube, comprising a cathode, gate, focusing electrodes, and anode, was constructed for applications such as stationary chest tomography.

Small-Angle X-Ray Scattering (SAXS) Techniques and Accessible Systems. In the fabrication and analysis of materials such as porous membranes, SAXS is valuable for characterizing nano-sized structures and pores. Systems facilitating SAXS measurements typically necessitate integration of X-ray sources, detectors, positioning, and control units, often complicated by vendor-imposed restrictions [15]. Vendor limitations can impede hardware modification and advanced research. A conceptual model for digital X-ray scanners and an open-source hardware platform named ‘SyncBox’ addresses these limitations, adopting a Plug-Integrate-Play paradigm to enhance integrability and extensibility.

Stationary Chest Tomosynthesis Systems Employing CNT X-Ray Source Arrays

The majority of X-ray photons pass through an object without any form of interaction. However, photoelectric absorption effectively removes specific photons, leading to the generation of photoelectrons and corresponding characteristic X-rays. Elastic Rayleigh scattering causes minor deviations in the photon trajectory, which is relatively insignificant. On the other hand, Compton scattering involves more energetic photons interacting with outer-shell electrons, resulting in the production of lower-energy photons along with recoiled electrons that have gained energy. Furthermore, Bremsstrahlung radiation emerges as passing electrons decelerate when they are in proximity to atomic nuclei, leading to the emission of X-ray photons. Characteristic emissions produced in this process include the specific Kα1, Kα2, and Kβ1 lines. In the context of synchrotron radiation, this phenomena generates sharply collimated beams that are directed forward when charged particles move through magnetic fields. A typical Coolidge tube consists of several key components, namely the cathode, which emits electrons, the anode, which attracts these electrons, and the tube housing that contains them. Filtration is a crucial step that alters the emitted spectrum by attenuating low-energy photons, therefore resulting in a filtered X-ray spectrum characterized by a reduced presence of low-energy content. When we examine the architecture of the system, it is evident that there is a computer-controlled gantry that integrates both an X-ray source and a detector for optimized imaging results. The shift-and-add tomosynthesis technique is particularly innovative; it combines multiple projections that are shifted in accordance with the specific imaging geometry, allowing it to generate sectional images that are focused at different planes for improved diagnostic clarity. Commercial systems such as the GE VolumeRAD DCT and the Shimadzu

SONIALVISION DCT serve as notable examples of implementations utilizing these principles effectively. Moreover, an array of carbon nanotube (CNT) emitters functions as the cathode; field emission is enabled through the application of the electric field, which reduces the electron tunneling barriers encountered in CNT fibers significantly. Within this setup, a triode CNT X-ray tube is designed, featuring a CNT cathode, a gate electrode, a focusing arrangement, and an anode, all working together seamlessly for efficient X-ray generation. [22, 13, 24, 16]

Chapter - 7

X-Ray System Components

An X-ray system facilitates the emission and direction of X-ray onto a target from which the radiation scattered or transmitted is detected and used for diagnostics or radiation-treatment purposes. For example, the progression of a tumor can be assessed during chemotherapy, a fractured bone can be clearly visualized, the right dosage for external-beam radiation therapy can be calculated, and X-ray diffraction can be performed on a tiny portion of an archaeological bead.

To realize these highly effective and specialized applications, the X-ray system is composed of two major pieces of hardware (the X-ray tube and the X-ray detector) and a machine-automating device (the motion controller and the central processor). Data acquisition is controlled by the central processor and the X-ray tube's mechanical and electrical operation is regulated by the motion controller. Subsequently, the collected images are processed and analyzed by the central processor [1].

Regarding the tube, electrical power is transmitted from the central processor to the filament, which allows for the evaporation of electrons onto the cathode. This process is crucial as it sets the stage for the subsequent acceleration of the electrons. The electrons are accelerated by a sufficiently high and adjustable electrical potential before they strike the anode. The anode, which is covered, plays a fundamentally important role; it is not only involved in conducting the electrons but also in the emission of characteristic X-rays as well as bremsstrahlung radiation. To optimize efficiency, the tube incorporates several distinct designs in the filament. These variations are intended to provide adequate and optimized heating of the cathode, ensuring a steady generation of electrons. The X-ray detector itself consists of a matrix of semiconductors. The Z number of these semiconductors is specifically selected to ensure that there is a definite counting of photons. This selection is critically correlated with the intensity of the radiation present in the emitted beam, ensuring accurate measurements and effective functioning of the whole system [53, 54, 55, 56, 57].

7.1 X-Ray Tubes

The growing interest in various kinds of sophisticated investigations involving X-rays has significantly motivated the development of highly advanced X-ray sources with a wide array of specifications and capabilities. The main technical characteristics of these X-ray sources depend heavily on factors such as the specific type of X-ray tube being utilized, the range of tension applied, the current flow, the maximum power output, the focal spot size, as well as the angle of radiation emitted. Within an X-ray tube, the focusing elements work to concentrate the accelerated electrons into a remarkably small point known as the focal spot. For instance, highly specialized microfocus tubes have the capability to achieve an impressively small focal spot size of approximately 3μm, allowing for detailed imaging. Additionally, the choice of target type and material-commonly tungsten, due to its favorable properties-has a significant influence on both the size of the shadow image produced and the minimum distance required between the focal spot and the material being studied. The target's material composition and thickness not only affect the quality of the produced X-rays but also play a crucial role in determining the service life and overall efficiency of X-ray production. It is noteworthy that higher power outputs (measured in kW) drive the generation of radiation with shorter wavelengths, which can penetrate materials more effectively than longer wavelengths. However, it is essential to understand that, despite the advancements in technology, only about 1% of the input energy is actually transformed into usable X-ray radiation during this process. This inefficiency highlights the ongoing need for innovation in the field of X-ray technology [1, 13, 58, 59, 45, 60].

7.2 Detectors and Imaging Systems

Detectors play a critical role in modern medical diagnostic X-ray systems, converting incident radiation into visible signals used to form projection images. Digital radiography, computed tomography (CT), fluoroscopy, and mammography all depend on detecting ionizing X-rays that pass through patient anatomy, thereby enabling visualization of internal structures for diagnosis and treatment. Contemporary detectors are designed to create images at significantly lower radiation doses compared to conventional film-screen systems, which requires enhanced sensitivity and stringent system integration with X-ray tubes and image-processing technologies [61].

Several technologies have been developed to meet these requirements, including scintillating phosphor-based flat-panel detectors, phosphor-coupled charge-coupled devices, and multiwire gaseous chambers. Flat-panel X-ray image detectors are extensively employed in clinical digital radiography systems and remain an active area of research. Unlike traditional X-ray movies that combine a phosphor screen with a photographic film, a digital X-ray system utilizes a photodiode array coupled with an array of thin-film transistor (TFT) elements to convert the transmitted X-ray energy into a digital image [62].

Large-area, high-resolution, flat-panel X-ray detectors are consistently in high demand across the entire medical imaging landscape, reflecting their vital role in diverse diagnostic applications. However, it is noteworthy that a significant majority of the commercially available digital radiography platforms currently utilize photodiode-scintillator-photodiode sandwich arrays for their imaging processes. Meanwhile, magnetic resonance imaging (MRI) has progressed significantly over the years, establishing itself as a widely accepted and cost-effective method for evaluating internal body anatomy and physiology with remarkable precision. A long-standing and ambitious research goal within the medical imaging community has been to blend the superior imaging performance of MRI with external position emitters, such as those employed in positron emission tomography (PET), into a genuinely integrated imaging system. This innovative system aims to exploit the strengths of both modalities, creating a more comprehensive approach to patient diagnostics. X-rays, known for providing excellent spatial resolution, offer detailed insights into structural and morphological changes that can occur within the body. Conversely, radioactive tracers, when combined with emitter detectors, are instrumental in unveiling functional status and biochemical changes that can occur in various tissues and organs. The ongoing development and deployment of combined imaging devices hold tremendous promise; they have the potential to intricately relate physiological function to clinical anatomy. This relationship will ultimately lead to enhanced disease quantification and facilitate better treatment assessment for a wide range of medical conditions. Such innovative approaches are crucial for significantly advancing diagnostic accuracy, optimizing patient management strategies, and improving overall healthcare outcomes in modern medicine. The integration of imaging technologies not only benefits clinical diagnosis but also enriches the understanding of complex health conditions, paving the way for future advancements in the realm of medical imaging [63, 13, 64, 65, 66].

7.3 Control Systems and Software

The hardware components of x-ray systems include x-ray tubes, x-ray detectors, and the control system. The control systems that provide connection between all equipment of x-ray systems and user interface consist of electronic and software solutions. Supervisory Control and Data Acquisition (SCADA) systems are widely used for controlling hardware components of accelerators and beamlines. Some of the existing SCADA solutions are DOOCS, TINE, TANGO, KARABO, and EPICS. Additional communication protocols are used by some of these systems to synchronize and interact with the equipment.

For every new equipment, the corresponding control software needs to be implemented and integrated into the existing system. The amount of used equipment increases considerably in this case as well as the volume of the control software and the required database. This increases the complexity of the overall system. More efficient and flexible hardware control solutions can achieve a similar result in a more compact and manageable form.

In general, research techniques need different equipment and detectors at unrelated institutions. This increases a demand for equipment sharing among facilities and, therefore, the need for corresponding hardware control solutions. It is important for these solutions to be compact, easy to integrate into an existing experiment, and flexible enough to combine devices from various manufacturers.

The XES spectrometer has been developed to operate at the experimental stations of the SASE 3 SXR beamline at the European XFEL facility based on a coherent photon source with a pulse duration of a few tens of femtoseconds. Eventually, it was intended to be installed at the optics branch of the SXR beamline and in the 1400m-long High Energy Density (HED) beamline providing a possibility of an extended energy range, beam focusing, and longer working distance. Both stations use independent control systems. To meet these requirements, a new hardware control solution has been developed. It is optimized for the use with laboratory equipment to provide full control and precise monitoring in real time. The designed software incorporates the abilities to control equipment regardless of the manufacturer or the complexity of the case, and does not impose strict limitations on the hardware specifications or software architecture. A combination of an asynchronous communication protocol and reactive design is exploited in the solution to ensure efficiency, high performance, extendability, and availability for multiple platforms and programming languages [67].

The Synchrotron Radiation Source is a 20GeV synchrotron light source with 18 beamlines serving approximately 38 experimental stations. Control of the major elements of the photon beamlines is the responsibility of the main SRS Control System. The upgrade consists of the development of Linux-based PC front end computers, wherfaces that allow for a more intuitive interaction with the system. By utilizing a Windows NT platform, users are able to experience enhanced graphical applications that vividly portray the physical layout and current operational status of the entire beamline in real-time. This modernization moves away from a purely character-based interface, which was previously in use, and leverages the capabilities of distributed Front End Computers. Each of these computers is tasked with controlling a CAMAC crate via the advanced Hytec 1330 PC/CAMAC interface, effectively replacing the older, single minicomputer setups that were less efficient. The redesigned system not only streamlines operations but also significantly enhances user-friendliness, making it easier for researchers and technicians to manage experimental setups and monitor beamline activities more effectively. This transition to a modernized interface marks a pivotal improvement in functionality and efficiency for experimental stations operating in complex environments [68, 69, 70, 71]. Erfaces and real-time feedback of experimental parameters. It also addresses issues such as security and management to ensure a robust system capable of supporting the anticipated increase in beamlines at the SRS [72].

Chapter - 8

Diagnostic Applications of X-Ray Systems

The main components of a modern X-ray system are quite comprehensive and encompass a range of crucial parts, extending from the X-ray tubes themselves to the essential detectors and the intricate control electronics that govern their operation. The X-ray tube, which is typically housed within an oil-immersed protective casing, is maintained at an elevated negative potential to ensure optimal performance. A high-voltage generator plays a critical role in this system, supplying automatic alternating current (a-c) or direct current (d-c) potential within a wide operating range that spans from 10 to a maximum of 150kV. This high-voltage generator is responsible for feeding the filament circuit with low voltage and providing a heated current, which is vital for producing a well-focused electron beam and a precisely defined focal spot essential for generating X-rays. Furthermore, the primary controls in this system, which include mechanisms to adjust focus size and a dedicated current control, closely monitor the X-ray tube's load and play an important role in ensuring protection against potential overloads. Additionally, secondary controls are operated from within the X-ray room itself, allowing operators to effectively manage vital parameters such as exposure time and the setting of the required dose, which are critical for both precision and patient safety during imaging procedures. [73, 74, 75, 11]

8.1 Radiography Techniques

An X-ray system is an interconnected set of components designed for radiography, tomography, and radiotherapy.

Medical physicists frequently refer to such configurations as X-ray equipment or installations. Typical radiography systems comprise an X-ray generator, a patient-holding framework, a detector system, and an integrated control platform. Common components of the hardware architecture include the X-ray tubes, detectors, and control electronics. Numerous auxiliary elements are also routinely incorporated to form complete systems, notably collimators (which may be motorized, fixed, or mechanical) for beam narrowing, automatic exposure control (AEC) units to preserve image quality, and Dose Area Product (DAP) devices to quantify radiation exposure. A comprehensive radiography scanner necessitates the integration of these components. [76]

Because the available off-the-shelf items that make up these essential functional blocks come from a wide variety of sources and unfortunately lack standardization, device manufacturers face a multitude of significant challenges when it comes to the amalgamation of all these various parts. This situation of fragmentation notably increases the complexity of the necessary cables and interconnections, while also introducing potential incompatibilities that can lead to serious mechanical, electrical, and functional problems. Such issues can ultimately jeopardize both safety and operational efficiency during clinical practice, which is of utmost importance. The replacement of any single component within these systems can reduce overall system reliability significantly, while the integration of complete subsystems permits not only more stable but also more effective operation. This integration is essential for ensuring a seamless workflow. Furthermore, extensive testing and calibration become an absolute necessity whenever a single component is substituted, which dramatically inflates costs and prolongs commissioning times considerably. Additionally, the data that researchers extract from these lengthy acquisition sessions may also become obsolete due to ongoing temporal drifts in system performance, creating further hurdles for users. Researchers who are aiming to transcend contemporary limits in the field and develop entirely novel devices or functionalities often find themselves encountering restricted access to existing installations and proprietary equipment. This situation poses a significant challenge, as the release of such vital information and tools is frequently precluded by vendors due to hard-to-justify strategic considerations, leaving innovators at a standstill. [15, 77, 78, 79, 80]

8.2. Computed Tomography (CT)

Computed Tomography (CT) is a sophisticated imaging technique that utilizes X-rays to generate detailed cross-sectional images of solid objects, which can be invaluable in a range of medical and industrial applications. At the base of an X-ray tube, there are ring-shaped receivers that effectively capture the beams of radiation that have been transmitted through the object being examined. To create comprehensive images, advanced reconstruction techniques are applied, which allow for the transformation of multiple flat projections into a cohesive and comprehensive 3D model, providing an intricate view of the internal structures. Moreover, backscattered imaging is an innovative approach that relies on radiation that is scattered rather than solely transmitted through the object, presenting alternative perspectives that can enhance the overall image analysis. There are various systems developed for these processes, such as Circular Compton Scattering Tomography (CCST), which utilizes fixed radiation sources along with a detector ring that moves through the scanning area. This design serves to minimize mechanical complexity and significantly reduces the overall acquisition time, making it adaptable for accommodating objects of different sizes and shapes. When engaging in CT modeling, it is imperative to consider crucial factors such as detector resolution, the finite size of the detectors themselves, and the phenomenon of attenuation. These characteristics play a pivotal role in influencing the quality of the reconstruction of images and underscore the necessity for employing qualified data correction methods. By addressing these elements, practitioners can ensure that the resulting images maintain their integrity and usefulness in diagnostic processes and beyond. [81, 82, 59, 45, 83, 84]

8.3 Fluoroscopy Methods

Fluoroscopy continues to be a significant and essential technique, especially when it comes to guiding various endovascular procedures. In recent years, advanced technologies, including state-of-the-art three-dimensional (3-D) Pelvis Navigation systems and innovative robotic systems, have been developed to enhance overall precision and safety during these complex medical interventions. However, due to a variety of factors such as system setup, intricate image geometry, mechanical design elements, and the inherent physical characteristics of image intensifiers along with flat-panel detectors, fluoroscopic images inevitably suffer from specific distortions. To achieve accurate two-dimensional (2-D) and three-dimensional (3-D) measurements, the implementation of effective distortion-correction techniques becomes indispensable. This includes methods such as bundle adjustment, self-calibration, forward- and inverse-distortion polynomials, as well as modern convolutional neural networks. These techniques are considered a vital component of the conventional workflow necessary for ensuring high-quality diagnostic imaging and successful procedure outcomes [85, 86, 87, 88, 89, 90].

Chapter - 9

Therapeutic Applications of X-Ray Systems

X-ray systems serve not only crucial diagnostic purposes but also play a significant role in various therapeutic applications, particularly within the specialized field of radiation therapy. These therapeutic applications commonly rely on the utilization of higher-energy X-rays, and they frequently incorporate the use of particle beams to maximize the effectiveness of treatment interventions. Recent advancements and engineering innovations in this field have paved the way for the introduction of cutting-edge technologies such as RapidArc, which facilitates more precise and targeted radiation delivery to patients, enhancing the overall treatment experience. In addition, new imaging techniques like terapixel imaging have emerged, significantly improving image quality and aiding in more accurate diagnoses. Furthermore, the implementation of innovative particle therapies is being explored to precisely target tumors with greater accuracy, minimizing damage to surrounding healthy tissue. Collectively, these continuous advancements not only enhance diagnostic capabilities but also expand therapeutic options for healthcare professionals. Consequently, the ongoing development in these areas presents numerous opportunities for further engineering contributions that can lead to improved patient outcomes while simultaneously advancing the field of medical technology on multiple fronts. [14, 52, 91, 92, 13, 93]

9.1 Radiation Therapy Techniques

Radiation therapy is a complex and meticulous process in which targeted tissue is irradiated with the intent to inactivate or kill specific cells that may be cancerous or otherwise problematic. Most of the radiation therapy treatments utilized in contemporary clinical settings today make use of megavoltage X-rays that are generated from advanced linear accelerators or cobalt-60 units. The primary objective when it comes to both diagnosis and therapeutic application of radiation therapy remains consistently focused on the effective delivery of radiation to a precisely defined volume in a highly controlled manner. Significant advances in X-ray systems have played a crucial role in contributing to more precise, effective, and tailored treatments, particularly through the modification of the shape of the radiation field as it is perceived from the source. Different methodologies for controlling the size and shape of the radiation beam include employing various target materials, utilizing collimators, and implementing devices that can conform the shape of the radiation field to match the specific outline of the tumor. Additionally, compensators-which can include wedge filters, shields, and blocks-serve to further refine this control. More sophisticated techniques for achieving control over the field size and shape in radiation therapy are available with the use of multileaf collimators; however, while they are undoubtedly useful and effective, these systems are often quite expensive and necessitate high levels of mechanical precision for optimal performance. Moreover, the use of intensity modulation can significantly enhance these advanced systems by dividing the therapeutic beam into numerous smaller beamlets, each with the capability of varying independently in terms of intensity. This adds an additional layer of customization that can be crucial for patient-specific treatment plans. Treatment planning becomes an especially critical factor when it comes to determining the necessary intensities for each individual beamlet based on the tumor characteristics and surrounding healthy tissues. In order to provide a comprehensive background that supports the continual optimization of radiation therapy delivery techniques, it is essential to thoroughly discuss the fundamental principles of radiation oncology, alongside the strategies for optimization. [94, 95, 96, 91, 92, 13]

9.2 Brachytherapy Applications

Brachytherapy enables the delivery of a high therapeutic dose of ionizing radiation in close proximity to, or inside, cancerous tissues. The technique was initially employed during the early 1910s for epilepsy lupus, and subsequently extended to brain tumours, eye, head and neck, breast, cervix, prostate, and skin cancers. It is often applied in combination with external beam radiotherapy. The method uses sealed radioactive sources and can be categorised as radionuclide or electronic brachytherapy. Electronic brachytherapy sources feature a miniaturised X-ray tube or source capable of generating X-rays with a maximum energy in the range of 20–50 keV [97].

Electronic brachytherapy is a medical treatment method that employs a miniaturised X-ray tube or source, which is capable of generating X-rays with energies ranging from 20 to 50 keV. This technology presents several principal advantages for healthcare professionals and patients alike. One of the most significant benefits is the reduced need for extensive shielding, which simplifies the setup and operational requirements in a medical environment. Furthermore, it eliminates the complications associated with radioactive waste management, making the process safer and more efficient. Another key advantage is that there is no radiation emission when the source is powered off, which enhances the safety protocols in clinical settings. On the other hand, traditional radionuclide sources offer their own set of advantages that are well-known and have been established through decades of clinical use. These sources come with well-defined treatment protocols that have been clinically proven to be effective over time, providing a sense of reliability for practitioners in the field. Additionally, predictable source decay characteristics are an important feature of radionuclide treatments, simplifying the planning and administration processes. However, these traditional methods are not without their own challenges. Radionuclide sources can pose risks such as potential radiation leakage, which can impact patient safety as well as that of the medical staff. Moreover, the inherent radioactive waste generated from their use presents a significant concern, necessitating careful handling and disposal. Radionuclide sources also require frequent replacements, which can lead to logistical complications and additional costs. In contrast, electronic X-ray sources provide greater flexibility thanks to adjustable energy settings, allowing tailored treatments based on individual patient needs. The output stability of electronic sources enhances treatment precision, which is crucial in targeted therapies. Another noteworthy benefit is the diminished exposure levels for staff who administer these treatments, thus promoting a safer work environment. Nonetheless, this technology does have limitations, such as its less extensive applicability in various treatment sites and a narrower base of clinical experience compared to traditional radionuclide options. Ultimately, both electronic and radionuclide methods have their unique advantages and challenges, making the choice of treatment dependent on specific clinical scenarios. [98, 99, 100]

9.3 Emerging Therapeutic Technologies

The x-ray systems engineering community is increasingly working on advanced therapeutic irradiators. These innovative systems enable the development of new therapeutic approaches that not only complement traditional radiation therapy but also deliver highly localized radiation to targets that are otherwise inaccessible with conventional techniques. By developing real-time control over various parameters such as flux, energy, and spectrum, the field could see significant advancements with this enabling technology that would greatly expedite the calibration processes essential for effective treatment. Moreover, the familiar footprint of x-ray technology plays a critical role in significantly reducing barriers to integration within clinical environments. For instance, the design of a familiar treatment room can be easily reused when transitioning from typical diagnostic functions to more advanced therapeutic functionalities. This adaptability ensures that elements of existing standard wall designs, such as lead-lined gypsum board and existing shielding materials, can be directly and effectively incorporated into newly established treatment rooms specifically designed for radiation therapy, enhancing efficiency and safety during patient care. This integration not only streamlines the transition but also ensures that the infrastructure meets the necessary regulatory and safety standards in a cost-effective manner. [52, 15]

Chapter - 10

Advancements in X-Ray Technology

Technological innovations instigate ongoing enhancements in diagnostic imaging and therapeutic applications. Mammography benefits from reduced radiation doses while maintaining the capacity to capture detailed breast-tissue features, enabling early detection of breast cancer. Recent improvements in dental radiography enhance visualization of teeth and jaw bones through intraoral and external imaging, as well as panoramic and computed tomography (CT) examinations. CT systems have progressed to three-dimensional representations using a rotating tube and detectors, with devices classified into five generations-a distinction based on detector count, beam geometries, and the relative movements of tubes, detectors, and patient tables.

Emerging sources such as pyroelectric X-ray generators constitute incredibly promising and innovative developmental directions within the field of X-ray technology. Pyroelectricity, a fascinating phenomenon, entails the generation of an electric voltage in certain specialized crystals when there is a change in their temperature. Materials such as Lithium Niobate and Lithium Tantalate exhibit strong and reliable pyroelectric characteristics. These properties have been effectively exploited in a variety of multifunctional applications, including but not limited to ultrasound generation, terahertz radiation, neutron emission, and ion acceleration. Due to their unique capabilities and performance, pyroelectric X-ray emitters hold the potential to serve as efficient and effective alternatives to traditional X-ray tubes. Conventional X-ray tubes, while widely used, are surrounded by numerous constraints and limitations that often hinder their effectiveness and versatility in different scenarios. [52, 101, 75, 102]

10.1 Digital Imaging Innovations

Digital imaging, particularly digital X-ray imaging, has become a major focus in the development of diagnostic X-ray systems [14]. Image quality, dose efficiency, and speed continue to improve, opening new possibilities for diagnosis and therapeutic guidance. Components in these digital X-ray systems include detectors, X-ray tubes, high-voltage generators, and image-processing units. Integrated systems provide stable operation and high reproducibility.

Single-energy digital radiography directly measures attenuation, yet organs and structures overlay one another. Computed tomography (CT) generates 3-D images but with considerable dose and expense. Dual-energy methods use differing attenuation at two energies to separate materials of different atomic numbers. While dual-energy radiography has existed for many years, new developments in pulsed sources and detectors that can operate at different energies are stimulating renewed progress.

High-power X-ray tubes are undergoing significant evolution with innovative designs aimed at enhancing their longevity and ensuring stable operation. Several new considerations have come into play, especially regarding the impact of different material choices that affect focal spot stability and the presence of contaminant elements, which can significantly influence the quality and accuracy of X-ray output. As long as the source and detector maintain a stable configuration, the measurement of attenuation can provide valuable insights into the body being examined, delivering information with not only improved quality but also potentially reduced radiation dose to patients. This progress marks a crucial step in advancing the safety and effectiveness of diagnostic imaging technologies. [103, 73, 104, 105]

10.2 Artificial Intelligence in Imaging

Artificial Intelligence (AI) has garnered significant attention, particularly with the advent of deep learning algorithms applicable to medical imaging. AI effectively manages data overflow, reduces interpretational bias, accommodates rare diseases, and enhances robustness across centers and operators. In molecular imaging and radiation therapy, ongoing developments include improvements in positron emission tomography (PET) instrumentation, image reconstruction, quantification, segmentation, and denoising. AI further facilitates radiation dosimetry and supports computer-aided diagnosis (CAD) and outcome prediction for malignant lesions; however, full clinical integration remains a challenge [106]. Similarly, AI has markedly advanced oncological imaging, enabling analyses that extend beyond benign-versus-malignant distinctions to reveal tumor type, stage, genomic mutations, treatment response, recurrence risk, and survival. CAD systems are designed to enhance diagnostic accuracy, consistency, prognostic evaluation, and support therapeutic decisions. Although limitations persist, the expansion of AI and big data resources promotes standardization and encourages multidisciplinary, personalized approaches. Digital medical images consist of pixel matrices representing gray-scale information, with volumetric techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) producing multiple slices interpretable as voxels. The transition to filmless radiology hinges on picture archiving and communication systems (PACS), which facilitate the storage, retrieval, and exchange of imaging studies within healthcare environments and underpin the clinical integration of AI tools [107].

Chapter - 11

Challenges in X-Ray System Development

In addition to the many physics and engineering aspects of X-ray systems that have been previously discussed in detail, there are a number of significant technical, ethical, and legal challenges that continue to remain unresolved and urgently need to be addressed. The development process of medical X-ray devices and their multiple components must take into careful consideration various scientific solutions, industrial constraints, and the wide-ranging healthcare needs of patients, all while making diligent efforts to improve patient outcomes and to minimize any potential risks and discomfort that may be associated with these procedures. As autonomous support programs for clinicians are increasingly integrated into the future design of medical devices, a multitude of critical questions regarding issues of responsibility, accountability, and ethical considerations will inevitably arise and demand careful examination. From a technical perspective, the various components that are commonly found in medical X-ray imaging systems can significantly complicate the overall design and integration process. For example, motorized or fixed collimators play a crucial role in guiding and narrowing the X-ray beam precisely onto the target area, which is essential for ensuring focused imaging capabilities. Furthermore, automatic exposure control (AEC) systems are vital, as they adeptly adapt to exposure variations in real-time, thereby maintaining high image quality based on the specific radiation levels that are detected passing through various types of detectors. Dose area product (DAP) systems serve an important function by measuring the precise amount of radiation exposure that a patient receives during imaging sessions. Concurrently, workstations are responsible for the critical tasks of digitally controlling, monitoring, and acquiring important imaging data, thus significantly enhancing the overall workflow in medical facilities and institutions. The successful integration of all these integral components is of utmost importance for creating a fully functional and effective radiography scanner that can reliably serve its purpose. Traditionally, vendors construct radiography scanners by carefully selecting components that are available off-the-shelf, meaning they are readily acquired from manufacturers for ease of access. However, the challenge arises from the glaring absence of widely accepted standards for component connectivity, which complicates and makes the integration process not only time-consuming but also quite complex and arduous. This complexity can ultimately compromise both safety and efficiency in clinical settings, leading to considerable concerns among healthcare providers regarding the potential implications for patient care. Moreover, whenever there is a necessity to replace parts in these intricate imaging devices, it invariably triggers stringent requirements pertaining to efficiency, safety, and rigorous regulatory review, which can further complicate the situation. Following the need for replacements, extensive testing and calibration become necessary-processes that often incur considerable time and financial costs, creating additional burdens for healthcare institutions and providers. Researchers who are deeply engaged within this field also face significant challenges arising from limited accessibility that results from vendor-imposed restrictions on user access levels and the capacity to intervene with hardware components. This limitation effectively constrains the possible avenues for advanced research and development, ultimately impeding innovation and progress in the area of medical imaging technology. To effectively respond to these multifaceted challenges, a proposed conceptual model and an accompanying open-source hardware platform known as "SyncBox" have been introduced and developed. This innovative model adheres to a Plug-Integrate-Play paradigm, which aims to significantly enhance both the integrability and extensibility of digital X-ray scanners, thus facilitating easier configuration and improvement. By addressing the existing limitations head-on, the development of next-generation X-ray systems can therefore progress at a much more rapid pace and in a significantly more effective manner. Consequently, this advancement ensures that the ongoing interplay between physics and engineering continues to propel meaningful advancements in both diagnostic and therapeutic modalities, ultimately resulting in substantial benefits for patient care and improving treatment outcomes across the board. [53]

11.1 Technical Limitations

The extensive clinical application of X-rays for nondestructive testing and medical diagnostics, combined with the design and manufacture of related equipment, requires a complex synergy of general physics, applied physics, medical physics, and engineering principles. The following example illustrates integration principles that can guide collaborative efforts in developing X-ray systems for diagnostics and therapy. [108, 75, 109, 110]

Modern industrial and medical X-ray equipment must operate under demanding conditions that highlight a range of technical limitations. Conventional design approaches address incident power using quantity parameters such as penetration, transmittance, and contrasts related to tissue thickness and atomic composition. Determining appropriate components for an X-ray system based on these parameters is a highly specialized activity that depends on expert intuition supported by theoretical formulas. [1] provide a detailed overview of the selection criteria for X-ray optics components, such as the tube and detector, which are critical to designing effective tomography systems capable of investigating internal structures with micron-scale resolution at tube voltages ranging from 10 to 160 kV. The design stage remains pivotal for specifying key parameters and developing configurations that meet application requirements. [11, 111, 112]

11.2 Ethical and Legal Considerations

Many medical physics guidelines, standards, and safety recommendations coexist with regulations for engineering design, manufacturing, and testing of medical devices. Although the primary objective of engineering regulations is patient safety and risk reduction, these regulations also form the foundation of business ethics in the healthcare industry. With the increasing complexity of healthcare delivery and the diversification of business relationships, ethical concerns may represent additional constraints during the development of medical devices.

All stakeholders involved along the comprehensive supply chain, which includes healthcare providers, manufacturers, sales and marketing agencies, maintenance groups, as well as patients, must ethically assess and consider aspects such as cost reduction strategies, the efficient offering of products, proper application of these products, and the necessity of periodic maintenance of the equipment and therapy provided. These ongoing executive responsibilities in their entirety constitute significant ethical concerns when it comes to the development of medical devices. Within the various stages of development, ethical considerations that encompass the activities and responsibilities of engineers, designers, programmers, contractors, and managers predominantly involve numerous management and legal concerns that must be carefully navigated. It is crucial for all parties to maintain a strong commitment to ethical practices throughout every phase of product development and delivery, ensuring that the highest standards are met while addressing the needs of all users effectively. [113, 114, 115]

Chapter - 12

Future Directions in X-Ray Systems

Emerging trends and ongoing research efforts have continued to drive the significant expansion of both diagnostic and therapeutic capabilities associated with X-ray systems. The development of new materials, in conjunction with innovative codoping techniques, worked to effectively suppress afterglow effects in structured cesium iodide scintillators. Furthermore, novel architectures for direct-conversion detectors have been meticulously designed with the aim of improving temporal resolution and overall image quality. Notably, improvements in tube design and careful manufacturing processes have focused primarily on enhancing efficiency while simultaneously reducing patient radiation dose. Significant advances in hardware and software technologies, such as digital tomosynthesis and turbulent flow particle image velocimetry, have enabled much faster image acquisition, leading to improved lesion detectability and more accurate simulations of X-ray sources. Additionally, the integration of X-ray systems with various other imaging modalities, along with the thorough exploration of emerging detector electronics, sought to enhance versatility and the overall functionality of these systems. In parallel, innovative techniques in astronomy have greatly expanded our understanding of X-ray phenomena as they occur in the vastness of space. The development of an open-source hardware platform boasting a plug-integrate-and-play architecture has effectively addressed challenges surrounding device accessibility, extensibility, and the high costs typically associated with extensive testing and calibration necessary for component replacement. The integration and application of these prevailing trends required a comprehensive and multidisciplinary approach that artfully combined fields of study such as physics and applied physics with medical-device engineering in order to create advanced capabilities essential for modern medical operations. [14, 116, 117, 29, 118]

12.1 Trends in Medical Imaging

Medical imaging plays a central role in modern healthcare, permitting physicians to both rapidly and safely gather critical information about a variety of medical conditions. X-ray systems, in particular, have long been employed for locating broken bones and more recently for tracking cancer, monitoring heart disease and assessing brain injuries.

Traditionally, the development and manufacture of medical X-ray systems is separated between physics and engineering. The role of physics is to understand the physics underlying the various processes of a device, while engineering is charged with creating robust, repeatable and stable medical systems that meet the required engineering specifications.

12.2 Potential Research Areas

Using high-energy-density physics (HEDP) experiments to illustrate the comprehensive methodological integration of physics and engineering in the development of advanced diagnostic and therapeutic X-ray systems, the relevant fields from broad general principles to specific applied techniques and from theoretical physics to practical engineering approaches have been effectively identified and examined. Within this robust methodology, the remarkable synergy of physics and engineering to identify potential cutting-edge research areas has proven to be particularly productive and fruitful. First, in the cutting-edge realm of HEDP, complementary X-ray backlighting techniques enable K- and L-shell radiographs to be acquired simultaneously in an efficient manner. In ongoing X-pinch research, the doubly cascaded emission of large-area K-shell X-ray sources is now achievable through an innovative staged wire array loading scheme, showcasing the ingenuity of modern engineering. More generally, a high-resolution imaging system that combines X-ray backlighting with a Lithium Fluoride (LiF) detector yields an impressive 2-μm spatial resolution over a significantly large field of view that exceeds 2 mm2, underscoring the precision that modern technology can achieve. A well-designed staged array featuring low wire numbers per array can produce stable, efficient implosions as well as multi-keV X-ray radiation, which is crucial for numerous applications. Meanwhile, a versatile platform that effectively combines an XFEL backlighter with an LiF detector delivers exceptional high-contrast single-shot images with 2-μm spatial resolution, demonstrating the versatility and effectiveness of this approach. This high resolution is absolutely indispensable for many diverse HEDP experiments, enabling researchers to probe the intricacies of physical phenomena with unparalleled clarity and precision. [119]

Chapter - 13

Conclusion

The increasing use of X-ray systems for medical diagnostics and therapeutic applications highlights the synergy between general, applied, and medical physics and engineering principles. The successful combination of physics and engineering techniques for developing diagnostic and therapeutic X-ray systems is demonstrated at a foundational level. X-ray systems form the basis for medical applications such as imaging and radiation therapy. A basic understanding of X-ray physics is provided, along with introductory principles of engineering and device design. Several examples demonstrate how general, applied, and medical physics can be integrated with engineering to develop X-ray systems for clinical use. Future work should build on these concepts to develop more advanced systems.

Modern digital radiography devices constitute the gold standard for diagnostic or therapy guidance in medicine. During the development phase of innovative X-ray devices, researchers and emerging companies encounter significant challenges, as individual components are manufactured independently and global standards for device integration are lacking. A plug-and-play (PIP) conceptual model for X-ray imaging systems, implemented as an open hardware platform called SyncBox, enables the selection of device components from different vendors based on application and performance criteria. The first implementation is a full-body, high-resolution radiographic scanner employing a novel time-delay integration (TDI) digital detector. SyncBox has the potential to introduce an open-source hardware platform to X-ray equipment design.

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