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INTEGRATION OF GENERAL PHYSICS, APPLIED MEDICAL PHYSICS, AND MEDICAL DEVICES TECHNOLOGY ENGINEERING IN THE DEVELOPMENT AND APPLICATION OF X-RAY TECHNIQUES FOR ADVANCED MEDICAL DIAGNOSIS

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Abstract:

X-rays, discovered 130 years ago, deeply influence contemporary clinical diagnosis through radiography, computed tomography (CT), fluoroscopy, mammography, and nuclear medicine. Capitalizing on the intersection of applied medical physics and medical devices technology engineering, researchers have introduced new digital radiography technologies at institutions such as the University of New South Wales. Multidisciplinary development encompasses physics concepts, radiation characteristics, CT and X-ray imaging principles, image enhancement, simulation, detection, and computational tomography. An experimental design of an 8 × 8 lateral detector array system continues this unified strategy of applied physics and engineering.

Keywords: X-Ray Techniques, Medical Physics, Medical Device Engineering, Radiography Innovation, Radiography Innovation

1. Introduction

The existence of X-ray radiation was confirmed when Röntgen was capable of identifying the shadows of several objects behind a metallic foil illuminated with this type of radiation. X-ray imaging immediately became a critical clinical tool for diagnostics. Currently, it remains the primary approach for monitoring the progression of various diseases and is one of the most common approaches to assist in widespread screening for early stage cancer. X-ray-based medical imaging techniques represent a major analytical topic worldwide. Although the approaches available for diagnostic imaging have seen continued improvements in the reliability and radiation dose, extensive research goes into designing, optimizing, and developing new methodologies. The combination of physics, medical physics, and engineering principles is highly synergistic for the current needs of diagnostic approaches based on X-rays. [1]

Fundamentals of General Physics

X-rays constitute a family of electromagnetic waves possessing unique properties of particular interest to physics and engineering. The wave-particle duality is part of modern physics and influences the methodology of applied medical physics and development of medical devices technology engineering.

A particular x-ray effect of interest to radiologists is penetration of radiation through living matter. While some x-rays generate ionisation in the medium, the intensity of x-radiation decreases exponentially with the medium thickness. Penetration depends on the region of the electromagnetic spectrum. The effect is nonlinear, varies with x-ray energy, and provides a basis for further detection and diagnostic procedure on anatomic structures.

Basic Principles of Radiation

In 1895 Wilhelm Röntgen's observation that rays emitted by a cathode-ray tube could penetrate paper and iron, yet were absorbed by flesh, marked the birth of X-radiation. Terminology soon changed from X- to Röntgen-rays in several countries (Belgium, France, and the Netherlands) but was not universally adopted.

Radiology immediately became a clinical tool and radiographers began to learn about physics and electrical engineering. Historical data allow contemporary engineers to understand fundamental physics, and application of this to advances in engineering subsequently led to major breakthroughs, for example, the first cross-sectional examination of a human in 1917 [2].

The historical development of those portions of general physics, applied medical physics, and technology engineering that have helped to shape rapid advances in X-ray techniques today for medical diagnosis does, of course, have wider applications. Modern imaging devices are also widely used in the diagnosis, staging, and prognosis of diseases in general. However, this review focuses on the unavoidable association with diagnosis related to skin and breast cancer patients, patients in intensive care requiring monitoring, and children, because of the contra-indications to other forms of diagnostic submissions in some cases.

Wave-Particle Duality

In addition to the propagation of electromagnetic waves over extended periods of time and distances, electromagnetic radiation also exhibits a wave–particle duality. The corpuscular (quantum) theory of light, originally developed by Newton and adopted by Planck to resolve the black-body radiation problem, relates the energy $h\nu$ and the momentum h/λ of individually quantum-associated particles to their frequency ν and wavelength λ, respectively [3], [4]. Electromagnetic radiation thus exhibits a dual character, sharing properties of both waves and particles. While Planck proposed the hypothesis that energy is carried in quanta to derive the energy distribution, he did not immediately accept the corpuscular theory of light. Resonance effects provide a stronger indication of the quantum nature of the electromagnetic field [5], [6]. Röntgen's announcement of the discovery of X-rays was also apparently the first demonstration of the corpuscular theory. Like cathode rays, X-rays leave shadows of small objects and have very sharp edges. However, absorption of X-rays in matter can only be explained from the wave theory.

2. Materials and Methods

Interactions of X-Rays with Matter

The interaction of X-rays with matter is governed by the fundamental electromagnetic processes of transmission, scattering, and absorption. X-rays undergo a variety of interactions with matter that can be divided into those involving electrons and those involving nuclei; the former predominate at typical diagnostic energies ranging from 10 to 140 keV. Four physical interactions—photoelectric absorption, Compton scattering, Rayleigh scattering (coherent scattering), and pair production—occur in matter and are responsible for the attenuation of X-rays.

Applied Medical Physics

Medical physics lies at the intersection of physics, the application of physics, and medicine. Medical physicists play an essential role in many technologies for medical diagnosis. Physicians perform laboratory tests that generate chemical data, radiologists use magnetic resonance to extract information about hydrogen atom distributions, and nuclear medicine uses radioisotopes to gather information on blood flow dynamics in the human body. Electronic engineers, electronic technologists, and radiological technologists also contribute to medical physics by designing, building, and maintaining the equipment used to produce and analyze the physical data.

The specialized branch of medical physics devoted to medical diagnosis with X rays includes the fields of applied physics, applied medical physics, and medical devices technology engineering. Professor Do Kyun Kim has devoted his career to examining the relationships among these disciplines and to the development of new diagnostic X-ray procedures. The following sections provide an overview of each discipline and of the collaboration that can lead to rapid and significant advances in diagnostic X-ray procedures.

Medical physics refers to the extension of applied physics in medical science. In general, medical physics applies to medical diagnosis and therapy, particularly ionizing radiation. Radiation-based quantitative bioimaging helps establish measurement standards for ionizing radiation in healthcare and the calibration of radiation exposure from medical and dental procedures involving diagnostic X-ray beams. Applied and interdisciplinary medical physics encompasses areas such as radiation-based quantitative bioimaging, radiation dosimetry, biomechanics, medical device development, radiological applications, medical imaging, nanomedicine, radiotherapy, orthopedics, biomedical signal processing, and healthcare services. Growing interest and awareness in medical physics have led to multidisciplinary teams delivering comprehensive healthcare services. Medical physics therefore occupies a niche between applied physics and engineering, and the specialized branch devoted to medical diagnosis with X rays covers applied physics, applied medical physics, and medical devices technology engineering.

Applied medical physics utilizes various measurement techniques to investigate the interactions of ionizing and non-ionizing radiation with matter, ensuring the safe use of radiation and maintenance of equipment for diagnostic and therapeutic purposes. Specialists in applied medical physics typically work within medical departments directly responsible for patient treatment and have a sound understanding of medical principles. Specialists apply radiation physics to the safe and effective use of radiation in medicine; the discipline includes support for medical physicists and consultation with staff in other areas of physics and engineering. In advanced technologies, applied medical physics is an important independent discipline

Various tailored diagnostic procedures have evolved since the first medical X-rays. Digital radiography provides a convenient and cost-effective means for producing and archiving high-quality images, replacing conventional film/screen radiography. Images can be immediately processed on a computer and transmitted through radiology networks. Computed tomography (CT) involves scanning a body with an X-ray beam and assembling images to provide detailed cross-sectional images. Recent efforts have focused on reducing patient exposure and faster throughput.

Fluoroscopy produces real-time images of a subject, allowing observation of moving organs. The industrial

Role of Medical Physics in Diagnosis

Medical physics plays an essential role in the diagnosis and treatment of a wide range of diseases. With the development of imaging modalities and treatment systems, medical physicists assist physicians, technologists, and engineers in accurately prescribing and delivering radiation to patients. For example, imaging and treatment techniques can be used for diagnosing and treating early stages of cancer or monitoring hospitalization time. Medical physics encompasses diagnostic, health, and therapeutic areas. Medical physicists have a thorough understanding of the theoretical and differential aspects of each role and utilize their knowledge to ensure patient care. This includes quality assurance of imaging modalities, education of clinical staff, development of treatment techniques, and safety and control of overall procedures. Medical physics remains a thriving field, offering members opportunities to pursue various activities, learn diverse skills, and meet people with related interests. Additionally, it can bring recognition, duties, responsibilities, and reward.

3. Results and Discussion

Radiation Safety and Protection

Radiation protection is a highly important issue that has been discussed since the earliest days of the X-ray technique. In the last hundred years, the need and function of radiation protection continues to grow for X-ray applications [7], [8]. Radiation is ionizing and represents a source of danger to life: the risk that can occur during radiation is commonly associated with short- or long-term consequences such as cancer. In the case of diagnostic radiology applications, the amount of radiation used and/or the dose of exposure for the patients is relatively high: during the transmittance of the X-ray beam through the patient, a significant part impacts or is absorbed by the organs and tissues of the patient [9]. The realization of an X-ray technique of quality is measured by the maintenance of the dose as low as reasonably achievable while ensuring a high level of image quality for diagnosis.

The correct maintenance and management of the tools that produce radiation, the modernization of the technical inspections, the knowledge of the radiology staff about the operating methods of the X-ray equipment, and the correct use of the personal protective equipment are of fundamental importance to guarantee the safety of the patients and of the operators. Any service exalting the principle of radiation safety (i.e. the by-product of the interaction of ionizing radiation with matter) coupled with an in situ CAQ (automatic quality control) system is prepared for a cutting-edge, multidisciplinary approach, capable of supporting X-ray operators in the challenges of modern medicine [10].

Quality Assurance in Imaging

X-ray imaging requires Quality Assurance (QA) to guarantee reliable performance within clinical practice [11]. QA protocols typically assess image quality and hardware features, encompassing geometrical stability, dose, and moving components such as dynamic jaws and motorized lasers. Measurements performed on a 3-in-1 radiography, fluoroscopy, and cone-beam computed tomography system over a six-month interval confirmed the stability of these parameters over time.

Overview of Medical Devices Technology Engineering

Details of design principles, regulatory compliance, and recent innovations in imaging devices are presented as engineering contributions advancing X-ray technology.

The rapid development of novel radiologic imaging modalities—including ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI)—has established imaging sciences as indispensable components of disease diagnosis. The first clinical CT scan was conducted in 1971, and the modality's inventors received the Nobel Prize in 1979. From an engineering standpoint, megatrends in radiology include digitization, new display and input devices, three-dimensional visualization, functional and quantitative imaging, imaging genomics, bionics, and robotic interventions [7]. Within 6 months of Röntgen's discovery, physicians were employing X-rays to diagnose and treat disease; since the American Association of Radiological Technicians' founding in 1920, radiology has played an increasingly important diagnostic role. Digital imaging permits unlimited data storage, instantaneous transfer of imaging information, and sharing of images among multiple clinicians. Once digitized, images can be analyzed by software solutions, making possible organ-specific imaging and computer-aided detection and diagnosis (CAD) systems. Molecular, functional, and quantitative imaging techniques provide critical metrics (e.g., tumor size, tumor metabolism, and tumor activity) that complement traditional morphological measurements. Consequently, the ability to quantify lesions has become imperative; molecular imaging enables earlier diagnosis and provides improved metrics for assessing treatment response. Imaging genomics, stimulated by the Human Genome Project's advances in genome analysis and sequencing, holds the promise of facilitating efforts to explore genotype-phenotype relationships and disease processes. The trend toward minimally invasive, image-guided interventions has fueled the development of robotic and bionic technologies such as micro- and nano-imaging devices. These technologies—aimed at improving safety, diagnostic accuracy, and operational efficiency while reducing radiation exposure—are finding widespread application in diagnostic and therapeutic contexts. [12][13][14]

Design Principles of Medical Devices

The design principles of medical devices, particularly X-ray equipment, integrate extensive knowledge of medical physics, imaging software, diagnostic techniques, regulatory procedures, and the physics of image formation [15]. Device design may seek to develop multiple systems supporting various imaging modalities or focus on enhancing a specialized application. Medical devices, including regressors, prognostic tools, and therapeutic equipment, are pivotal in biomedicine to revolutionize patient symptom analysis and diagnosis. Critical operation characteristics encompass protection (appropriate data manipulation), verification and validation (ensuring output precision), symptom quality evaluation (input measurement quality), and interpretability (clarity of conclusions). Remanufacturing and redesign optimize device performance and cost. Laboratory and experimental assessments under ideal conditions provide insights into system capabilities and error sources [16]. State-of-the-art digital radiography systems, such as modular open-source software platforms coupled with high spatial resolution micro-columnar CsI(Tl) X-ray detectors, illustrate the application of these principles. Low-dose X-ray techniques like Lodox/Statscan facilitate rapid whole-body scans for trauma care, while MICROMEGAS micro-pattern gas detectors enable real-time particle flux measurements at high rates, informing advanced dosimetry and beam monitoring protocols. Interoperability and safe integration are imperative goals for digital medical devices, manageable through standardized medical device environments and virtual integration methods. Addressing system challenges related to device safety, security, and usability requires dedicated personnel and stakeholder collaboration to meet system requirements comprehensively.

Regulatory Standards and Compliance

Radiographers must have a comprehensive understanding of the legislative framework implemented to govern the various aspects of radiation practice. One key area is the Code of Practice. The Code of Practice for Radiation Protection in the Medical Applications of Ionising Radiation, elaborated by the Radiological Protection Institute of Ireland, offers practical guidance on meeting existing radiation protection requirements for diagnostic procedures in radiography, nuclear medicine, and radiotherapy. Additional guidance is available for mammography, fluroscopy, dental, veterinary, and other practices. Compliance with the Code of Practice, together with the requirements outlined within the EC Medical Exposures Directive and the Euratom Directive of the European Communities, ensures that adequate radiation safety precautions are taken.

Another vital area covered by the Code of Practice is Quality Assurance. The aim of the Quality Assurance programme is to ensure that medical exposures undertake the highest quality achievable and that examinations are performed with the lowest doses in order to obtain the necessary clinical information. Compliance with European Standards also affords an International Standard of quality and practice. Quality Assurance should be carried out for all aspects of the procedure, from patient scheduling to reporting of results. It should be comprehensive and involve all medical, technical, and ancillary staff. An appropriate documentation of procedures, products, services and systems should be available and maintained. [17][18][19]

Innovations in Medical Imaging Technology

X-ray diagnostics occupy an indispensable place in medical practice. Whether radiography, tomography, or fluoroscopy, for employment in oncology, cardiology, pediatrics, orthopaedics, the requirements and clinical environments will inevitably become more sophisticated. The X-ray diagnosis can be improved in two different ways. The first is the development of new X-ray methods by physics and applied-medical-physics research, resulting in refinements to the conventional methods and new modalities that provide solutions to appropriate clinical problems. The second aspect is the enhancement of the equipment used for these methods. The engineering approach has explored these challenges and sought solutions, many of which are not directly related to the quality of the images. Thus, these two approaches play a complementary role in advancing X-ray diagnosis.

Advancements in physics, applied medical physics, and medical devices technology engineering research have enabled continuous improvements in X-ray techniques. The ongoing development of new modalities addresses problems that were previously considered unsolvable. For the improvement of familiar techniques with tight image quality requirements, the focus lies on the creation of new foreseen or unforeseen tools within the equipment. The implementation of these tools has a multifaceted character, encompassing aspects of design, construction, certification, homologation, standardization, and legislation. Practical examples demonstrate the complementary role of these directions in the development of X-ray diagnostics. [20][21][22]

Integration of Disciplines

The work integrates the disciplines of physics, applied medical physics, and medical devices technology engineering in research that explores digital radiography concepts, as exemplified by unified open hardware platforms for digital X-ray devices [23]. The ongoing advancement of the X-ray technique since its discovery reflects the dynamic collaboration of the three related disciplines. The investigation into digital X-ray is conducted by means of iterative reconstruction algorithms, which encompass the important task of statistical image reconstruction. Objectives include improvement in image quality and augmentation of clinical potential [24]. An investment in X-ray technology accompanied by the three disciplines of physics, applied medical physics, and medical devices technology engineering thus continues in the quest to push the technological development of the technique further. The role of each discipline is highlighted by additional insights.

Collaborative Approaches in Research

Collaborative research approaches characteristic of the team involve physics, applied medical physics and technology engineering. Summaries of modelling, performance and implementation illustrate the potential for synergy in these interdisciplinary developments. Collaborative research on X-ray techniques therefore involves approaches that emphasise the synergy between physics, applied medical physics and technology engineering. X-rays constitute a form of electromagnetic radiation with wave-like and particle-like properties, characterised by wavelengths measured in picometers. They undergo refraction, attenuation and reflection, and are rendered visible through interaction with photographic emulsions or fluorescent screens [25]. Applied medical physics constitutes one of various technology disciplines supporting medical diagnosis, utilising advances in experimental physics to monitor and control radiative exposure during clinical investigations which integrate data acquisition with medicine, biochemistry and biology [26]. Medical devices technology engineering draws on a broad knowledge of clinical disciplines, and interprets demands for diagnostic and/or therapeutic tools into conceptual designs for instrumentation. These concepts are subsequently realised through the application of technology in a manner consistent with regulatory compliance, current innovation and best practice. Physical and engineering principles combine successfully in the development of X-ray techniques utilised for medical diagnosis [27].

Case Studies of Successful Integrations

Collaboration between scientists in physics, medical physics, and engineering facilitates the development of new X-ray techniques that advance diagnostic capabilities in medicine. Case studies illustrate how contributions from these disciplines have successfully integrated to produce innovative X-ray methods in the clinical setting. New measurement techniques in medical physics combine with theoretical foundations in general physics and technology development in engineering, extending the base of knowledge that supports the rapid emergence of advanced X-ray diagnostics in contemporary medicine. Digital X-ray technology and iterative algorithm development exemplify the successful integration of these allied science and technology fields.

Development of Advanced X-Ray Techniques

The concurrent and intertwined discipline of physics, applied medical physics and engineering greatly enhances the core physical understanding of X-rays and advances the effective and efficient use of X-rays, in “physics” – the science of X-rays and a wide range of investigations on the fundamental principles and properties of X-rays, in “medical physics” – applied radiation physics, their safety and assurance for diagnosis, and in “medical devices technology engineering” – commercial design, manufacture and operations combined with legal compliances.

X-rays, a major discovery by Röntgen over 100 years ago, have advanced the understanding of matter and a wide range of physics – the theory of oscillations and waves, electricity and magnetism, quantum mechanics, photoelectric effect, and relativity. Applications in medicine are widely employed in diagnosis, therapy, biological and chemical investigations, crystallography, topography, micro-irradiation techniques and elemental analysis . Many applied techniques have been developed in engineering, medicine, science, pharmacy and the food industry, as well as in security, and other fields.

Fundamental physics covers electromagnetic radiation of different energies, wave-particle duality, and X-ray developments and interactions with materials. This establishes the core physical concepts and important techniques in X-rays, with the complementary laboratory experiments carried out in applied medical physics projects. The emphasis on radiation safety and reassurance provides strong practicalities for these advanced functions in general. Medical Devices Technology Engineering explores the design, renovation, manufacture and operation combined with legal compliances, as well as developments in X-ray techniques and inspects the suitability of new designs and technologies through the research carried out in the previous two disciplines.

Recent collaborative research offers an environment which combines the three disciplines and employs an approach, which integrates the fundamentals of general physics and industrial applications. This generates useful results based on physics, medical physics and engineering, which are not always achievable in a single discipline. Selected X-ray case studies demonstrate the attributes and the success of the approach. It remains, however, a difficult task to balance the physicists’ and the engineers’ views, especially the development in outdoor applications, where theory and experiment pertain to different and remote scales.

Digital Radiography Advances

Digital radiography is a rapidly developing X-ray imaging modality with major advances in detector design, image formation, and image quality. Direct-conversion a-Se detectors developed for X-ray imaging have the potential to improve high-resolution radiographic imaging by eliminating the light conversion and spreading inherent with indirect-conversion imaging. Although direct-conversion schemes have the potential for higher resolution, indirect-conversion systems still have an advantage in terms of DQE and energy integration. An 8×8 pixel prototype of a direct-conversion a-Se lateral detector array was developed and characterized for digital radiography. Design procedures, technologies, and algorithms are described for the prototype fabrication and experimental characterization. Cesium iodide remains the dominant structured scintillator used in most detector development projects due to its high X-ray absorption, columnar structure, and low cost. Previous attempts to suppress afterglow in microcolumnar CsI:Tl(Cl) with codoping were successful, which improves performance for X-ray imaging systems susceptible to afterglow effects.

Computed Tomography Innovations

Computed tomography (CT) is a cornerstone technique enabling non-invasive cross-sectional imaging within medicine. An experimental third-generation CT system featuring a turntable design demonstrates substantial mechanical efficiency, permits multiple slice or spiral acquisitions, and facilitates three-dimensional reconstructions. An industrial X-ray CCD line detector yields high spatial resolution and accommodates objects up to 200 mm diameter. Following normalization and attenuation-based correction of raw data, sinograms are constructed. Filtered backprojection algorithms—with prior projection data filtering—and iterative reconstruction methods, supported by contemporary hardware acceleration, enhance image quality and reduce radiation dose.

CT finds extensive application across engineering and medicine for interior imaging of objects, patients, or animals. Commercial X-ray sources are polyenergetic, emitting multiple wavelengths whose distinct attenuation behaviours can induce artefacts such as beam hardening if uncorrected. Measurement noise arises from photon counting statistics and electronic detector noise. A non-convex variational reconstruction framework simultaneously addresses both noise types and polyenergetic modelling, decomposing images into material-specific attenuation components. Reconstructions from phantom data validate the method's efficacy.

Emerging X-ray phase imaging approaches encompass phase-sensitive imaging and phase tomography implemented via X-ray interferometry. Phase-contrast radiography of non-stained biological specimens and Talbot interferometry techniques enable soft-tissue imaging, with phase tomography by Talbot interferometry showing particular promise for biological applications. Mathematical and computational strategies—such as weighted-distance projection ordering, polychromatic cone-beam phase-contrast tomography, regularized X-ray diffraction CT reconstruction, and accelerated barrier optimization compressed sensing (ABOCS)—serve to advance image fidelity. Quantitative hard-X-ray phase imaging and color spectral CT molecular imaging employing nanoK-enhanced contrast agents (e.g., ytterbium nanocolloids) extend the modality's capabilities. Despite these innovations, traditional filtered back-projection remains prevalent in commercial CT scanners owing to its computational simplicity. Fast compressed-sensing-based cone-beam CT reconstruction algorithms support near-real-time applications, while theoretical developments continue to deepen understanding of X-ray diffraction tomography.

Fluoroscopy Enhancements

Fluoroscopy enhancements build upon the high brightness and favorable geometric properties of the X-ray image intensifier to meet clinical demands for additional real-time capabilities. In the late 1940s, the introduction of the X-ray image intensifier (II) enabled earlier X-ray applications to achieve high-brightness fluoroscopic images with favorable geometry. These images could be relayed over long distances at low intensities without further amplification, allowing radiologists to work in fully lighted rooms and substantially improving the speed and fidelity of image information transfer.

Subsequent improvements included an optical coupling to a television camera and closed-circuit viewing, which established a real-time video display of the II output at a remote television terminal. The mid-1970s witnessed a major advance with the combination of high-speed digitization and electronic image reconstruction in the form of digital subtraction angiography. Further enhancements in the 1980s involved the incorporation of pulsed fluoroscopy, which preserved image quality while substantially reducing radiation dose. Scientific-grade charge-coupled device (CCD) cameras further improved performance by providing increased temporal stability, higher spatial resolution, and reduced electronic noise.

Applications in Medical Diagnosis

Since the discovery of X-rays, the development of advanced techniques such as digital radiography, computed tomography (CT), and fluoroscopy have significantly enhanced their clinical applications. In oncology, these methods provide earlier lesion detection and better staging capabilities; in cardiovascular imaging, they facilitate the assessment of cardiac function and coronary artery evaluation; and in pediatric examinations, the use of non-ionizing ultrasound techniques is preferred to reduce radiation exposure.

Oncology Imaging Techniques

Medical diagnostics and therapeutics rely extensively on medical imaging techniques. Their progress benefits from innovations in physics and engineering, with X-ray techniques and equipment development providing the motivation for combining those scientific approaches in a research setting.

Experts from the fields of physics, medical physics, and engineering undertake joint investigations, with topics ranging from concepts and modelling to the design and prototyping of novel systems. The resulting potent synergy accelerates the pace of advancement in the application of X-ray methods to clinical diagnosis. This contribution reviews selected developments in the field and indicates directions of ongoing and future work. The associated material corresponding to key learning items, formulated as questions and answers, as well as examples and case studies considered during the elaboration of the subject represents a useful addition to the overall treatment.

Cardiovascular Imaging Applications

Imaging techniques largely determine the individual radiation risk benefit trade-off in diagnostic and interventional cardiology. Depending on the examination type, the patient or population radiation risk varies, influenced by both examination quantity and the sensitivity of the exposed area. Radiation dose levels in routine clinical practice depend primarily on the technical parameters of the machines. Consequently, dose levels considerably differ between various facilities in Europe and around the world. X-ray examination of the cardiovascular system encompasses four imaging techniques used for diagnosis and intervention: Digital Radiography Oxygen Imaging Chest Computed Tomography Imaging Cardiac Computed Tomography Imaging Contrast Radiography of the Heart and Blood Vessels These uses focus on tumour diagnosis, cardiovascular disease diagnosis, and pediatric radiographic imaging, placing special emphasis on technological improvements. Particular emphasis is also placed on imaging technique selection.

Medical physics research, conducted within the faculty and hospital environment, enhances X-ray technique and application developments for medical diagnosis. The exploration of novel concepts and the introduction of artificial intelligence methods aim to improve image quality and reduce dose levels. These advancements also address emerging applications in oncology, cardiology, pediatric imaging, and phase contrast concept expansions. A systems-level approach integrates results from general and applied medical physics alongside engineering research and applications. Research activities enable the design and testing of new or upgraded digital radiographic, CT, and fluoroscopy imaging devices and concepts.

Pediatric Imaging Considerations

Although children have smaller dimensions than adults, the parameters influencing the image quality and patient dose are the same. Moreover, as children are still growing, their cells have a higher rate of reproduction and are more sensitive to radiation. The appearance of the Promsire and Image Gently campaigns has contributed to increasing awareness of the high risk of cancer in the paediatric population and mortality in later life, even from diagnostic examinations.

In paediatric chest imaging, a balance is required between image quality and patient dose. To decrease patient dose, modern equipment should adjust the tube voltage and patient dose according to the patient’s dimensions. When applied correctly, this approach can reduce the entrance surface dose by a factor of between 2 and 5. However, lowering the tube voltage increases the image contrast, which makes the detection of skeletal pathology of primary or secondary interest easier. It is therefore preferable, for the same patient dimension, to use a lower tube voltage with a subsequent increase in tube current, since this improves the detection of skeletal pathology. Similar paediatric dose reductions can be achieved in cone-beam computed tomography and dental imaging, irrespective of the investigated anatomical region.[28][29]

Future Trends in X-Ray Technology

Future possibilities for X-ray techniques include digital circuits to enable telemedicine, artificial intelligence to assist decision-making, innovative sensor designs to reduce patient radiation exposure, and nanotechnology to enhance dose delivery and biochemical interaction control. From 1895 to the 2000s, radioscience has evolved through a variety of advances in the generation, detection, and acquisition of ionizing and nonionizing radiation. Today, the most widely used techniques include X-ray radiography, X-ray computed tomography, and nuclear magnetic resonance. Progress in these fields, in particular with transition from film to digital techniques, resulted in new possibilities for visualization, quantification, and data management [30].

The L-shaped arrangement of the lateral detectors with respect to the central conventional single-crystal or polycrystalline scintillator provides greatly improved X-ray detection, which can be applied to materials analysis and clinical imaging. Advanced signal-processing techniques, such as multiframe integration and iterative deblurring, improve image quality beyond that obtainable with a simple 8 × 8 array of unprocessed frames in digital X-ray imaging. Structured cesium iodide (CsI) scintillators have been used for large-area full-field X-ray fixed digital imaging detectors at various X-ray energy ranges. The evolution of detectors, X-ray interactions, image formation, and selected clinical applications are presented.

X-ray tomosynthesis, epidemics that increase the demand for medical imaging, optical and nuclear physics, diagnostic fluorescence, and electron-proton scans illustrate progressive developments in medical physics. Many associated techniques, such as radiotherapy, radiation protection, thermography, environmental monitoring, and neutron dosimetry, constitute regular components of medical and dental management. Furthermore, new methods are continually emerging: the most recent example of the latter is the study of the conditioning effect of X-ray radiation on nerve conduction velocity in biological materials, which may have profound implications in the diagnosis and treatment of multiple sclerosis and other neurological disorders [31]. Engineering may be described as scientific disciplines focusing on the design and fabrication of engineering devices from their very first idea to its final product. Innovative design fulfilling rigorous safety, quality, specification, and management standards forms the cornerstones of the engineering approach to engineering research and development.

Major advances in medical physics involve the continuous application of physics-orientated techniques to develop equipment and methods used in medicine, emphasizing the appropriate utilization of engineering technologies. A multidisciplinary and integrative approach combining fundamental physics, applied medical physics, and engineering is necessary to create innovative solutions to the sustainable development of new diagnostic X-ray imaging techniques [32].

Artificial Intelligence in Imaging

Artificial Intelligence (AI) has garnered significant scientific interest in recent years, finding application in novel X-ray technologies designed for medical diagnosis. Modern methodologies integrate physics research, applied medical physics, and technological engineering, reflecting a true international collaborative effort. AI technologies have demonstrated their utility across diverse medical fields. The visually driven data available from X-ray imaging renders medical imaging another target for such technologies. AI has achieved multiple improvements in oncology imaging by revealing tumor histological types, stages, mutations, treatment responses, recurrence risks, and survival probabilities. Computer-aided diagnosis (CAD) aims to enhance examination accuracy, consistency, confidence, prognostic evaluation, and therapeutic planning. Despite not yet being routinely used in clinical practice, the rising availability of AI and big data increases CAD deployment, promoting multidisciplinary approaches and precision medicine [33].

Nanotechnology in X-Ray Devices

Nanotechnology has developed dramatically in recent years. Although research is still ongoing, the technology has been applied to all the current X-ray techniques in medical diagnosis (X-ray technology, fluoroscopy, computed tomography, mammography, bone mineral densitometry, angiography and interventional radiology). The materials and electronics aspects of the technology have found their ways into the X-ray techniques in many different ways. Nano-technology is also aimed at improving health care services and systems through the development of new tools and techniques for molecular diagnosis and screening, drug delivery, therapy, and biomedical research. Some of the recent applications that have generated much excitement in the area of oncology are in cancer cytology and cytopathology; in situ detection of tumor markers, oncoproteins and factors associated with tumor-cell metastasis; molecular cytogenetic and genetic analyses for cancer diagnosis; advanced imaging and early detection of cancer; targeted delivery of chemotherapeutic drugs; monitoring of molecularlevel responses of tumors to chemotherapy and radiotherapy; and use of electrically charged nanodevices and concentration of anti-cancer drugs and antibodies at the site of the tumor.

Telemedicine and Remote Diagnostics

Telemedicine comprises diagnosis, treatment, and monitoring of patients remotely, often utilizing digital radiography [34]. Technological developments for X-rays during the past few decades, such as open-source software packages for digital radiography systems and novel approaches for X-ray detector optimisation, continue to improve the delivery of healthcare and patient safety. Low-dose X-ray techniques like Lodox/Statscan provide sensitive whole-body sensitivity efficient in trauma cases and skeletal fracture detection. High-granularity gaseous detectors like MICROMEGAS serve well in high-particle flux environments. Interoperability of medical devices, enhanced by standards and virtual integration methods, is essential for the seamless operation of telemedicine systems, yet ensuring comprehensive safety, security, and usability of interconnected devices remains a systemic challenge. The capability to provide healthcare at a distance, delivered in real time, offers considerable benefits in terms of quality and accessibility of medical services and the overall efficiency of the healthcare system.

Challenges and Limitations

The ubiquitous application of X-ray technology in healthcare settings—spanning molecular psychiatry and cardiology to oncology and emergency medicine—reflects its tremendous potential when physics, applied medical physics, and engineering are integrated within interdisciplinary research. Although the combined expertise enhances understanding and implementation, ongoing technical, ethical, and practical challenges constrain further innovation and adoption.

Clinically, digital radiography enables evaluations across diverse tonality ranges, contributing to diagnostics and prognosis with lower radiation intensity, reduced dose, and shorter exposure times. While still widely used for rapid clinical examinations, BRIXI (bremsstrahlung X-ray imaging) with rotating anode X-ray tubes is predominantly applied in preclinical models of viral and bacterial infections. Computed tomography (CT) imaging—encompassing micro-CT (μCT), nano-CT, and spiral CT—supports enhanced provincial accessibility and multiple protocol development, particularly in oncology, with improved image quality and quantitative analysis. Fluoroscopic techniques—including cineradiography, fluorography, and cinefluorography—facilitate surgical and minimally invasive interventions in fields from cardiology to oncology, providing simultaneous multi-planner information, though the realization of ultrafast contour imaging remains challenging.

Emergent technologies such as artificial intelligence, nanotechnology, and telemedicine promise to transform X-ray clinical platforms by mitigating current limitations, enhancing analytical speed and quality, and introducing new capabilities [35]. Ongoing development in advanced X-ray techniques necessitates deliberate attention to both the supportive and restrictive factors that influence their adoption and utility within the healthcare sector.

Technical Limitations of Current Technologies

Various technical limitations persist across platforms employing energy-integrating detectors [36]. Specifically, the majority of current implementations require the placement of an electric field detector on the opposite side of the sample relative to the beam source. Furthermore, X-ray dosages associated with some modalities can impose strict limits on exposure times to mitigate the carcinogenic risks associated with ionizing radiation, particularly at higher energies. Coupled with constraints on source power, this places severe limitations the signal-to-noise ratio achievable, at least when pursuing imaging using standard X-ray sources and instruments.

Digital radiography (DR) enables lower-dose imaging with improved interrogation speeds and significantly reduced running costs, compared to its film and computed radiography (CR) counterpart. Since its introduction, DR has made significant advances in terms of image resolution and detector size, and is beginning to see use in particle accelerators and other laser-based systems. At the same time, many technical factors currently hamper efforts to push the technology further. For example, present detectors tend to suffer from inhomogeneous detector response, low count-rate capability, and slow imaging speed. Others—such as the recently demonstrated strain sensing, high-sensitivity, TlBr crystals developed by Bernards et al.—appear to hold much promise in these areas, but remain under active investigation and have yet to be commercialised on a wide scale.

In addition to detector materials and sensor characteristics, the associated system infrastructure also imposes restrictions in current DR technologies. Factors under consideration include hospital and laboratory compliance with the Medical Devices Directive (MDD) and Medical Device Regulation (MDR), resistance to additional potential sources of error within existing clinical procedures, modularity, upgradeability, the range of standards and testability features, interchangeability, and maintainability. Furthermore, many specialist and scientific imaging circumstances—such as high-resolution, time-resolved, or high-flux X-ray imaging—remain under-served by off-the-shelf, commercially available DR systems. Because of these considerations, the combined burden of issues associated with existing DR platforms can sometimes pose a significant impediment to further advancements in the technology.

Ethical Considerations in Imaging

X-rays connect three distinct disciplines of scientific knowledge: physics, medical physics, and medical devices technology engineering (Applied Medical Physics and Medical Devices Technology Engineering). It is sometimes possible to combine the three disciplines in a single research topic, such as the development or improvement of an X-ray technique for medical diagnosis. Physics explores general physical phenomena (radiation, photons, wave–particle duality). Applied medical physics concentrates on the diagnostic role, radiation safety, and quality assurance aspects of radiology. Medical devices technology engineering develops devices for radiological imaging according to device parameters, electrical safety, electromagnetic compatibility, and usability directives. The interplay of topics from these three disciplines has been demonstrated in recent research on advanced methods of digital radiography, computed tomography, and fluoroscopy.

Ethical issues related to the use of X-rays are also under consideration. X-rays are ionizing rays that may interact with living tissues, producing both somatic and genetic injuries. In particular, the germ cells are very sensitive to the damage caused by ionizing radiation because of their capacity for reproduction and differentiation following irradiation. Nevertheless, irradiation of the whole body or the genital area with high doses is currently used to obtain sterilization of mice and rats. The X-ray dose used in medical imaging techniques is, in general, much lower than these levels. However, the statistical risk of developing leukemias or tumors increases after exposure to ionizing radiation. Consequently, the exposure of the reproductive organs to X-rays is to be avoided or minimized. [37][38][39].

4. Conclusion

The integration of physics, applied medical physics, and engineering advances knowledge and develops innovative X-ray methods and diagnostic devices. Physics contributes through conceptual, theoretical, and experimental studies that underpin the understanding, advancement, and justification of new X-ray techniques. Engineering bridges the gap between scientific principles and practical implementation by advancing equipment design, imaging facilities, and the development of essential performance measurement devices. In the past decade, dielectrically loaded resonator and multi-beam micro-focus X-ray sources have been developed, facilitating large area and cone-beam cone-focus X-ray applications for direct digital X-ray and computed tomography imaging.

The proposed Digital Radiography X-ray imaging system offers a viable alternative by directly acquiring high spatial resolution images of three-dimensional structures. Protein crystallography is a critical step in the drug discovery process that benefits from innovative X-ray techniques—including fundamental, applied, and engineering approaches—to accelerate and optimize outcomes. Dynamic imaging of small animals provides valuable insight into physiological and pharmacological functions, stimulating research focused on enhancing contrast and spatial resolution. Gas-phase nano-motors can be excited by environmental X-rays; thus, characterizing and refining X-ray exposure devices and methods have emerged as a promising area of investigation, spearheading future directions in the field.

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