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The Role of Medical Physics in the Design and Optimization of Diagnostic Imaging Devices

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Annotation: To explore the role of medical physics in the design and optimization of diagnostic imaging devices, it is essential to focus on physical aspects of these devices. The focus here is on physical optimization of digital x-ray detection systems primarily because of the extensive background and experience in this area and also because of current interest in clinical applications of x-ray tomosynthesis with systems still being manufactured and marketed based on experience accumulated in a different area – digital x-ray radiographic systems.

Others have examined other aspect of such devices and their use. Varied aspects of digital radiographers have been thoroughly examined so breadth of coverage would be a huge task. Already substantial content has been collected and organized into 30-papers on complementary topics covering the many areas of interest and need.

Digital x-ray imaging has several important advantages over conventional analog systems. Instead of film and screen detectors, cost-effective, image intensifier and video cameras, lattice photo-diodes and video, and separate image processors, these imaging devices are being replaced simply with a digital detector, a computer workstation and a printer. Illumination and handling of the films, film-screens,

and their storage and retrieval are no longer worries. The film also becomes a permanent image without any risk of patient privacy breach from wrong storage and retrieval. The latest advantage, increased diagnostic confidence, is in part a consequence of the variably enhanced imaging performance and optimized parameter settings made possible by digital systems. Interesting and promising applications are also appearing.

The digital x-ray exposures depend on the x-ray beam describing a specific view through the imaged volume of tissue. Unlike film, the electronic detectors are capable of capturing in real-time the intensity of the incoming x-rays composing this view with either some or no geometrical compression in storage depending on individual devices. Instead of silver grains, x-ray quanta interacting with these grids excite free charges in the solid or transferred through scintillation. The quanta intensities are captured as either real "analog" pixel corresponding to their locations or as grayscale values of discretely defined finite elements in the grid while weights are more instructively shown rank-wise.

1. Introduction to Medical Physics

The application of physics to medicine is usually termed medical physics, although it is often referred to as physics in medicine, and it can be subdivided into radiation oncology, diagnostic imaging and health physics. It can also include a small portion of administrative duties [1]. The field of medical physics is interdisciplinary. Medical physicists find employment in hospitals, private practice, research facilities, industry and academia. Medical physicists receive a long period of training and education including a Ph.D. degree in physics or mathematics, training in a medical or clinical specialty, and two to three years of supervised residency. A medical physicist is usually required to present a record of on-going professional development, which can include, for example, items such as publishing in the refereed literature, attending professional conferences, maintaining technical certifications, consulting, providing lectures and disseminating knowledge through continuing education seminars and teaching. Medical physics consists of services provided by physicists or trained science personnel on the implementation, maintenance, and quality assurance of any device or apparatus supporting medical and healthcare practices that involves radiation or adverse electromagnetic or mechanical phenomena. Medical physics encompasses radiation physics, health physics (radiation safety), diagnostic radiology physics and medical imaging, radiation protection, radiation therapy and the physical treatment of diseases, and the physics of rehabilitation and therapeutic devices among others. More specialized areas include MRI, ultrasound imaging, photonic imaging, and a few emerging modalities. [2][3][4]

2. Overview of Diagnostic Imaging Devices

Today diagnostic imaging is one of the fastest growing fields in health care. Advances in therapy methods, instruments, and technology have changed the ways in which physicians diagnose a disease and monitor its progression. Similar advancements in imaging have had a great impact on the methods by which radiologists read and interpret diagnostic images. Medical imaging is an effective assessment tool and facilitates detection of diseases at very early stage. It can assist in treatment planning, treatment evaluation, and long-term monitoring [5]. X-ray is the most widely used imaging technique; however, the safety issue and harm can only be minimized by using the appropriate protocols. To get relatively large images from small sample sizes, some sort of imaging system is needed and CT is one of the most widely used. MRI is one of the most rapidly advancing imaging techniques and is now one of the most commonly used devices for imaging the human body. Nuclear imaging starting from SPECT gamma camera to the invention of PET has increased the quantitative functional imaging capabilities. On the other hand, Ultrasound has been the most commonly used imaging modality for monitoring pregnancy, Hemodynamic/CV anatomy, and lesion ablative therapy related imaging. In the last decade, the use of ultrasound in evaluation of neurosurgical applications has gained interest. The ultrasound Zeitgeber has been used for imaging neurophysiology, Tumors, Hydrocephalus, and Cerebral blood flow. With other well-established imaging techniques, there has been a surge of interest over the past couple of decades to use Electrical Impedance Tomography in biomedical applications too. Emerging technologies like photoacoustic imaging, Magnetic Particle Imaging, Temporal Bone Imaging, and Arc-CT have also been proposed and being researched a lot, though not widely available yet [6].

Reading and interpreting medical images by radiologists is tedious and difficult. Due to the large heterogeneity of a number of diseases, it is not possible to build a scanning and processing pipeline customized to any one single disease. A crack in an image can have very different appearances based on a patient's biology, imaging techniques, variations in protocols, and many other factors. The limitation of image quality or resolution is another major source of ambiguity in the visualization of a disease. Availability of large imaging datasets is a major obstacle to the development of intelligent systems. Many machine learning systems for exploration, analysis, and classification of images have been recently developed, but the large variance in how a single disease is manifested limits the use of such systems. A vast amount of medical imaging data is generated on a daily basis, but accessing such data for further analysis is a huge challenge. Even if properly indexed, a vast majority of those data are in images that are not searchable. Text-based searches are ineffective because common key-words may not be present in reports due to the interdisciplinary difference in medical knowledge, terminology, and abbreviations.

3. Fundamental Principles of Medical Imaging

Imaging techniques in medicine, collectively referred to as medical imaging, have become indispensable tools in the diagnosis and treatment of various diseases. Medical imaging is not only being used to produce images of anatomical structures but has also been further extended in many applications targeting physiological, chemical, and functional properties. Several different imaging modalities, including X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Nuclear Imaging, Ultrasound etc. treatment have been proposed and quite widely used in today's healthcare [5]. X-ray images are now routinely reconstructed in tomographical images both in two and three dimensions. The concepts and the terms of nuclear imaging were proposed in the early 1940s. Radioactive chemical tracers that emit gamma rays or positrons are used to image the distribution of a radiopharmaceutical in human anatomy with single photon emission tomography (SPECT) or positron emission tomography (PET).

The potential of ultrasound as an imaging modality was realized as early as the late 1940s. The ultrasound-based imaging modality has become a widely accepted diagnostic tool to visualize structures such as muscles, joints, internal organs, and even the fetus [7]. MRI is one of the most powerful diagnostic imaging tools. Although MRI cannot penetrate bony and air-filled structures with negligible attenuation and artifacts, it is the only imaging modality widely used to assess soft tissue contrast. On the other hand, MRI has several drawbacks because it is time-consuming, expensive, and not available in all hospitals. In contrast, x-rays are widely used to visualize anatomical structure such as bones and joints at a lower cost. However, X-ray imaging exposes the patient to ionizing radiation, and with a longer exposure time, multiple images are needed to visualize the pathologies clearly. This chapter presents some fundamental principles of several medical imaging modalities. First, general principles of modalities are explained. Then, other abstracts of more specific modality principles follow, including the generation and interaction of ultrasound with tissues, physical effects of radiation and its detection, fundamentals of MRI, and so forth. [8][9][10]

4. The Role of Medical Physicists

A Medical physicist is a scientist with advanced knowledge in physics and medicine, dedicated to the development and application of radiation-based technology in the clinical environment in combination with clinically relevant radiation/physics knowledge. Medical physicists play a critical role in the development of diagnostic imaging systems, and for optimizing their performance. Medical physicists' active participation in the design process of new systems influences the success of the installation of the devices and the performance of all imaging settings, departments and QA protocols associated with them. Since the introduction of x-rays, the most widely used form of diagnostic imaging in medicine, at the end of 20th century, medical physicists have been professionals responsible for researching, designing, writing and implementing the QA protocols ensuring the daily adequate and persistent high quality performance of these systems as well as for the decision making on the purchase of new devices [11]. In this role they've been responsible for regular tests with formalisms guaranteeing their efficiency for the clinical studies performed. This made them the doctors of the x-ray equipment in hospitals, as radiologists are the doctors of patients (and images, if deemed necessary) in the x-ray environment.

In the 1980s, a level of commissioning of once-in-a-technical-lifetime systems and often of each new manufactured system by external organizations (occasionally including the developer) was introduced which brought an abrupt change in the profession partly facilitated by taking the licensure exams and the Indian market. Because these packages are often not an off-the-shelf product, there was little or no knowledge for their understanding and optimization, 3D QA protocols, clinical optimization, report writing and digitization, full-digital hospitals, PACS, multi-view multi-input devices, triage systems, an MRI-compatible therapy couch etc. became major 'new'-domain research areas. Furthermore, medical physicists started modeling codes for diagnostic imaging systems, often with the aim of optimization of their design and use.

5. Design Considerations for Imaging Devices

Individual detector modules must be optimized before integrating them into a full detector system. Ideally, a perfect detector consists of a large slab of high atomic number material optically coupled to an array of MPPC. The optical coupling is often via tapered light guide structures, fabricated from transparent plastic with appropriate index matching, since these designs enhance detector efficiency. Tapered structures minimize the chances of photons being transmitted to a non-sensitive pixel during propagation through and turns, thereby preserving the naturally isotropic light collection response of scintillator blocks. Each module readout consists of a pixel-to-pixel at the end of the guide that converts the scintillation emitted onto single MPPC, this at the designer's LightGuide FTL. The diameter of the holes, the spacing between them, and their arrangement are free to be chosen, while accounting for material budget for particle tracking. Tuning these parameters provides an optimization of the readout for factors such as opacity to scintillation light and transparency to number of photons traveling within the guide, rigidity, alignment, etc.

Imager specifications depend on the imaging modality, which can be classified as radiographic or tomographic. Effects of interest in radiographic devices include transmittance, spatial resolution, and detective quantum efficiency (DQE). Reduction in x-ray dosage while keeping speckle noise below perceptual limits is a design goal. For tomosynthesis, vertical resolution, speckle noise, and maximum number of sources are critical. Validation of apparatus is the first step in the design process, pattern recognition and quantification in the second, with the result being decision variables for the optimization stage. Optimization can define a design for an imaging device that minimizes material usage while maximizing performance with respect to tissue contrast and user-specified design goals [6].

5.1. User Requirements and Specifications

User requirements are the basis for systems specifications but do not provide sufficient information for a work package to proceed to tender. The work package will develop the systems requirements specification (SRS) in accordance with a model shared with the SRS focus group. Prototype specifications will be developed for the SRS. The design of the analysis will include surveys of the needs of the target groups and participants from other countries which have demonstrated interest in moving to the next stage of the project. In-house mock-up designs will be used and evaluated using a single day workshop and scenario-driven tests with potential users and content providers. The focus will be further developed and prototypes constructed. A quantity and quality assessment will be made of existing resources and the state of the art. All prototypes will be evaluated by users from business, education and public services with representation from all regions. A conceptual design will also be produced for a user needs analysis relevant to all member States. This will include attendees from member states and nominated experts to establish, validate and recommend priorities for a user needs analysis.

The initial analysis and specification are described on the basis of existing designs that have been used or studied for use. The written specification is accompanied by a graphic representation of the hardware which this specification has inspired. The intention of this report is to disseminate the design progress to other work packages and service providers to encourage debate and generate refinements to the specification and design. Candidate hardware for the systems requirements specification has been selected on the basis of features, cost and availability. Five systems have been selected. Systems selected for investigation include workstations, the operating system, a Java environment, and a database. The recommendations derive from the analysis of the preceding systems selection trials and experimentation.

5.2. Safety Standards and Regulations

Manufacturers and purchasers of diagnostic radiological equipment are legally responsible for the safety features of the equipment. Safety standards assure necessary safety regulatory requirements related to the production, installation, and commissioning of the devices. Professional organisations develop safety codes and guidelines. National/International agencies issue regulations based on the safety code to implement it. Each country ensures compliance with safety codes as per national policies and regulations. Special safety regulations with minimum requirements for safe operation are developed for critical installations commonly used medical diagnostic radiological equipment. The safety standards, codes, safety guidelines, and bulletins relevant to the design, development, operation, and safety features of diagnostic radiological devices are discussed.

International safety code in medical physics, patients, health physics, and occupational and public safety in health care are highly expected. A well-designed and safe installation with equipment complying with regulations can avert the occurrence of accidents, unintended exposures, and unsafe operating conditions. A safe installation will reduce the need for painful and repeated examinations for patients, which should be promoted by the medical physics community. Health physicists stop and shut down the installation in emergency conditions. Hence, health physicists also play a crucial role in patient safety before delivering the safe device and training the operation of the device.

Design and development of safety features and improvised versions complying with new safety features in existing devices is a challenge and challenge duty for medical physicists [12]. An expert safety code can provide necessary assistance and improvement to safety and entry documentation for recent devices imported into the country. Inputs regarding compliance with safety codes are to be submitted to the safety regulatory authority. Compliance with safety code documentation is also essential to avoid accidental exposures, loss of insurance cover, and punitive actions from regulatory authorities. The absence of safety safety committees and safety codes can result in preventable death. [13][14][15]

6. Optimization Techniques in Imaging

The imaging process involves the interaction of electromagnetic waves and matter including one's body. In this process, the transmitted, refracted, absorbed, and scattered radiation forms an image of the distribution of the matter inside the object. The most important step that creates the image is the processing of the data from the imaging device, and this is termed image reconstruction. Reconstruction algorithms need to be developed to convert the projection data in the image domain and in many imaging devices modern image reconstruction technology is applied. There are various mathematical models that describe an imaging device and the task of the optimization is to estimate the parameters of the model so as to obtain the best match between the data and the model prediction [1]. An imaging device may be described as a mathematical model of the imaging process. The model usually consists of both deterministic physical models and stochastic ones reflecting the apparatus imperfections or the physiological variations in the object image. The deterministic predictive model describes the formation of the projection process that transforms the object from the image space into the data space. The common deterministic models widely used in the imaging community are includes Ray Tracing Model, Finite Ray Tracing Model, Finite Difference Model. The Ray Tracing Model: It takes into account that rays propagate in a straight line from the source to the detector along the three-dimensional space in a homogeneous medium. The trajectory of each ray is defined by the point of the origin source, ray direction, and the distance to the detector. Given an intensity distribution in the object space, the detected intensity in the data space can be calculated. The Finite Ray Tracing Model: It is an extension of the ray tracing model to include scattering phenomena. In this model, a number of rays are released from the source into the object. Instead of a single ray, each zero-th order (primary) ray then propagates through the object to the detector and generates a number of scatter rays of higher order, which imitate the spread of the radiation due to scattering. Each transmitted ray either contributes to the detected projection if it hits the detector or is attenuated if it leaves the detector's sensitive area. The intensity distribution in the object domain is related to the detected intensity distribution in the projection domain via the transformation termed the forward operator. [16][17][18]

6.1. Image Quality Enhancement

The advent of advanced technologies and the emergence of highly effective diagnostic imaging devices in clinical practice have enhanced the diagnosis and treatment of diseases, enabling better patient outcome. To immerse into the new area of research, the widespread utilization of imaging devices resulted in images growing increasingly complex. Examining the finer nuances in such images required a thorough understanding of the significant factors playing a role in image formation. This knowledge base is also essential for the design and optimization of the widely used diagnostic imaging devices. The proper understanding of physics phenomena such as interactions between radiation and matter resulted in techniques that significantly improved the image quality and usability of the imaging devices. An overwhelming majority of diagnostic imaging devices are operated on the principles of the electromagnetic spectrum. Thus, this article primarily highlights the research activities informed and conducted by medical physicists in the field of diagnostic imaging.

This also provides a succinct overview of the research inputs in emerging techniques such as computed radiography and digital radiography. Diffuse scattering from the breast parenchyma, which fundamentally limits the spatial resolution of mammography systems, was investigated. A model-based method of analysis was developed, characterizing the physical properties of the breast, subsequently estimating the modulation transfer function of the mammography system. Other significant research works include improvements in image quality in both digital and traditional modalities [19], the design of beam filters in mammography systems, anti-scatter grids, x-ray optics, and collimators for nuclear medicine imaging systems, the computation of an automated AI-based mammography reading system for computer-aided detection, and the design of a columnar-detecting scintillator for digital radiography. While the educational impact has mostly been in the form of classroom teaching, the research also has had some exposure to undergraduates, medical physics, and applied physics master's students, as well as residents, radiologists, and technologists through seminars.

6.2. Dose Reduction Strategies

High-radiation doses from medical X-ray use to both patients and staff are increasingly undesirable, particularly when evidence arises over adverse health consequences. Radiation dosimetry can be used to infer links between high doses and stochastic events like cancers and hereditary effects if the doses are reconstructed or estimated. Action thresholds are dose limits above which users must investigate potential dose-reduction measures where it is improved. As the pressure to improve efficiency and output shortens, the impetus is on the equipment team to ensure medical devices' performance and patient equipment designs contribute to their diagnostic efficacy and safety. There are also design characteristics and protocols more common to one CT scanner than another that impact overall output dose and distribution of tissue doses across the patient anatomy. The cumulative contribution to collective dose from conventional X-ray-type basic and advanced fluoroscopy systems is increasing, as is the subsequent scrutiny as to the justification of their use and dose distribution characteristics. Lowering fluoroscopy pulse rates to reduce radiation dose during cardiac procedures is advantageous to both patients and staff where X-ray systems with lower multipulse rates are available. Fluoroscopy pulse rate reductions are a crucial dose reduction technique during electrophysiology and vascular intervention procedures. The need for these procedures continues to grow worldwide, as does the social and medical cost. Most radiation exposure to patients during fluoroscopy procedures comes from fluoroscopy, and fluoroscopy pulse rates can be decreased to benefit patients and staff. A modern X-ray system with low fluoroscopy pulse rates can significantly reduce DAP and patient exposure during electrophysiology procedures. Data showed the DAP could be reduced, with an average of over 17% reductions based on the procedure type, less for some of the simplest, and up to 100% when not needed. It would be prudent to ensure a procedure protocol was comfortable from a clinical perspective and did not extend the exposure time unnecessarily, as was demonstrated on the capless cases [20].

7. Quality Assurance in Diagnostic Imaging

The quality assurance (QA) of the images emitted from diagnostic tests is a requirement for the evolution towards the concept of the client-oriented diagnostic imaging service. The QA of these images is based on development methods and procedures that test the equipment operating condition. For a technical evaluation of the equipment conditions of a service in a Health Institution, it is required to set a QA program based upon the technical requirements of the testing procedures. A QA program specifies the QA methods and procedures of a given test. In Brazil, two QA programs were proposed, the first titled "Radiographic Quality Control" was designated for radiographic equipment, while the second program "QA of Mammography" was aimed at testing the mammography equipment. These QA programs consist of Technical Reports that specify the testing procedures, the description of the methodology of applying the procedures, equipment to be used, the registration forms, and results interpretation criteria. The information produced by the Health Institutions QA program implementation is an indispensable aid for the learning about the acceptability limits of the parameters that characterize the operating condition of mammographer X-Ray equipment, gamma cameras, conventional and digital fluoroscopy equipment, and cone-beam computed tomographs. This, in turn, is expected to effectively improve the quality of these services in Brazil [19].

A QA program has to be effectively implemented for the operation of a diagnostic imaging service. Several workflows, tests, procedures, result forms, and report formats should be developed and used by the clinical qualified medical physicist (CQMP) to implement a QA program. The effective implementation of a QA program of a diagnostic imaging service (DIS) can be supported by a computerized management system called the Quality Assurance Manager for Diagnostic Imaging Services (QAMDIS). This management system has four modules: (i) the knowledge-based module, (ii) the administration module, (iii) the QA workflow module, and (iv) the image database module. This management system enables the CQMP to simplify, automate, and keep the reports to be issued and the registration of the repeated procedures, and explicitly used templates [21].

7.1. Routine Calibration Procedures

To ensure high standards of isocentricity and spatial accuracy for both kV and MV systems, it is recommended that calibrations be performed once every 2 months during routine QA. If either calibration fails, a full geometric calibration check should be performed [22]. Acceptance testing should consist of a full path test to confirm correct operation; a geometric calibration test to ensure that the system has sufficient spatial accuracy for the required clinical tasks and that the calibration procedure has not been run out of sequence; and a center of rotation test to confirm that the kV system has sufficient volumetric imaging accuracy and, if necessary, find any significant error. Other tests, such as resolution and dose rate measurements, may be necessary for satisfying commissioning of specific services. These tests should generally be performed by the medical physics department. However, the routine calibration currently takes a significant commitment on the part of the medical physics department. In order for the service to be sustainable, the dose rate measurement and calibration procedure should be simplified and the transferred microCT calibration equipment validated for use by radiographers.

Quality assurance methods for the ExacTrac localization system were developed based on the reproducibility of the uncalibrated positioning in both the horizontal and vertical directions. Calibration checks on an image translation system were added, and tests of the reproducibility of each room's preparation were incorporated. Ongoing checks confirmed that image quality remained within expected limits and deviations were due to a change in the imaging system [23].

7.2. Performance Testing Protocols

The development of performance testing protocols in diagnostic imaging is being carried out in developing countries such as Egypt, building on essential methods. The purpose of this work is to produce standard protocols together with a training program for medical physics staff that are relevant to developing countries. The design goals of these protocols and training programs necessitate the preparation of procedures suitable for education, further training and quality control of CT, MR, radiography, fluoroscopy and mammography devices in light of local capabilities. Wherever video surveillance is available for a modality, it is also suggested that while defining standard protocols, video files demonstrating essential tests be recorded during their execution, especially for advanced tests that need only basic medical physics education. Acceptable qualities given in the protocols must be selectable according to existing equipment and capabilities, and protocols must be adjustable to local situations and periodicity. Besides periodically repeated standard measurements, it is also recommended that the capability to carry out supplementary measurements requested by clinicians be built. This necessitates cooperation with clinicians, further training in audit planning and analysis, and the acquisition of additional equipment over time [24]. It is an undeniable fact that large-scale nuclear facilities, be it research reactors or nuclear power plants, need to be subjected to performance audits. The Type C1 audit proposed establishes a comprehensive audit. It is however also easily imaginable that it would be better to keep dedicated smaller audits, termed mini-audits here, focused on given areas while moderate in scope and effort, as such audits can be performed much more frequently and be more easily accommodated into the audit calendar. There can be many avenues of mini-audits such as focusing on the performance of individual systems or the range of factors affecting individual systems. It would be very hard if not impossible for one audit team to cover everything, as is demanded by the audit protocol of Type C1 audit [25].

8. Emerging Technologies in Medical Imaging

The focus of research and development in medical imaging over the next decade is shifting to systems that exploit collapsible arrays, enabling portable instruments and large-scale systems, especially for 3D arrangements. Guidance of treatment delivery, course-matched imaging, and imaging probes with small footprints in thick samples lead to new image guidance concepts. Reconstruction techniques and instruments benefiting from constraints become more important, including instrumentation exploiting hybrid imaging agents. The high learning volumes and variable image quality of imaging devices create challenges and opportunities for high-performance, low-cost in situ calibration and verification systems. These developments may virtualize the acceptance and quality assurance of imaging devices. Instruments with compact and collapsible designs may alleviate hard-to-access locations of fixed imaging devices, such as the lung surface in small animals. Collapsible instruments may also take advantage of object scale. Detecting secondary emissions from a colliding particle beam may involve combinatorial arrangements of thousands of detectors, or an array that collapses into a violin type arrangement. Collapsible and flexible arrays are needed for magnetic resonance and ultrasound imaging. For magnetic resonance, racks with arms that grasp all detectors over time may be considered. For ultrasound, collapsible arrays or swiveling rotating arms are needed over large angles of dispersal. Researchers continue building in vivo systems with framed detectors that permit zooming in and out of focus. This work increases deformed arrangements of large camera systems, resulting in a large estimation of optical blur and reconstruction regularization paths. Arrays with stitching or filtering components are also being explored. Multi-slice Spiral Computed Tomography continues increasing its azimuthal coverage, while developing stage elements close to the beam path. These stages include high-accuracy rotary and linear axes, and a clever arrangement for the rotation to follow the subject spiral as the volume is filled. Imaging devices with flexures are also developed for applications such as surgery, dental implants, and self-charging pacemakers. This elastic arrangement, exploratory low-cost MEMS systems, and inexpensive 3D printed designs with high precision become potentially widely used. Experimental and computational modeling of imaging devices becomes more important in the light of learning and estimation. The high learning volumes of large installations, the wide variety of imaging paths in very high dimensional parameter spaces, and changes to the imaging conditions and instruments necessitate emphatic and online modeling. Attention is given to the optimization of instruments before and during capture. Responding to a need for changing image and instrument conditions in reconstructions, established techniques in geophysics and related fields are adapted to estimate regularizing constraints in difficult situations. [26][27][28]

8.1. Artificial Intelligence in Imaging

Digital X-ray, CT, and MRI images are subjected to subsequent processing and interpretation by image analysis methods and algorithms. To process digital images, two types of mathematical operations are used: point-wise operations in which the operation is applied to each pixel, such as gray level transformation and histogram equalization; or spatial operations in which the gray level of each pixel is calculated based on its neighborhood area, such as filtering and convolution. Extraction of numerical parameters and their interpretation is carried out in image analysis methods and algorithms. These parameters are termed as textures and may provide relevant information for the diagnosis of different diseases. Image analysis is important in diagnostic imaging since it can enhance the visibility of the diagnostic information, is essential in dose-compliance algorithms between diagnostic images, and it provides radiologists with quantitative information. Nowadays, AI is applied to medical imaging where it can play an essential role in image analysis, detection and diagnosis, treatment assessment, quantitative assessment, and characterization of disease.

AI can be classified depending on the study objective, explicitly supervised, semi-supervised, or unsupervised classification. The usual types of neural networks are Convolutional Neural Networks that are principally used for imaging applications. Functional MRI is used for capturing the brain activity indirectly through measurement of the blood-oxygen-level-dependant signal. For fMRI, the hemodynamic response to a stimulus was compared to a selected time course by computing a correlation coefficient. PMUs estimate the remained load of faulty capacitors as imprecise inputs for ANN. Tests show that ANN produces better results than commonly used algorithms and statistical methods. Write a hierarchical biomedical knowledge graph based on ontologies. Incidence is an association between a disease and an anatomical site that is denoted by a range of different code systems in a multidimensional manner and it is associative with various information including epidemiology and preventive strategy.

8.2. Advanced Imaging Modalities

The advancement of technology has led to the introduction of new modalities of imaging. These modalities have unique design and operating principles, but the requirements for imaging performance are common for tomographic, planar, or hybrid imaging techniques. In particular, the early and late image quality (noise and distortion) and reconstructed (after correction) image quality (CT accuracy and spatial resolution) should be considered in the design and acceptance of a new medical imaging modality. One of the advanced modalities is digital tomosynthesis (DTS) viewing, which offers x-ray images of a target object in reconstructed slices for improved visibility of an object, and has already been used in clinical breast cancer imaging. In such imaging, the x-ray beam source and detector are rotated acutely around a fixed θ-axis of a patient support table (or object), capturing a sequence of low dose projection images that are processed to generate reconstructed 3D slices. The DTS systems currently in use extend the orthographic projection by performing the additional 2D image restoration and interpolation, and have improved the speed in obtaining planar images. However, the DTS systems do not provide the true projection needed for the implementation of the conventional image reconstruction algorithms owing to the non-Fourier projections caused by the detour lens using a tilted focal plane. In addition, the 3D image viewing range is limited because of the view angle restrictive considerations of the round cover.

The development of new imaging modalities usually starts with a prototype and sometimes with a mock-up rig to test the feasibility, reliability, and performance of the proposed novel concept. Mock-ups may also be used to test some preliminary effectiveness of a new component or material before further serious investment is made. Experts in medical physics, scientific instrumentation, and/or preclinical imaging are thus consulted for the construction of a prototype. Design and optimization of some new imaging modalities may also be considered as a major research project till a comprehensive feasibility study is completed. Eventually, the modality may be commercialized or licensed out to the system manufacturers or service providers [5].

9. Clinical Applications of Diagnostic Imaging

Diagnostic imaging has advanced significantly in the last decade and plays an indispensable role in healthcare. It is commonly used to visualize the anatomy and functionality of organs and blood vessels inside the body for the diagnosis, treatment, and follow-up of various diseases. In diagnostic imaging, numerous applications have emerged from high-end scientific and engineering research and development. These applications may help aid and sometimes replace cumbersome manual reading and interpretation of images by expert radiologists. A wide range of approach types, including hardware enhancement, software augmentation, and learning-based algorithms, have been or are being developed to provide a lot of clinical outcomes [5].

Fluoroscopy is one of the widespread radiological modalities in hospitals and clinics that provides real-time imaging and monitoring of anatomy. However, reading and interpreting fluoroscopy images on screen is very time-consuming and tedious, especially in pediatric patients. Due to the ineffectiveness of dose optimization regarding system and procedure design, very high doses are often applied in fluoroscopy to avoid unwanted motion such as respiration. Non-interpretation of readings is another leading cause of the over-dosage of fluoroscopy in children. In most such cases, even if the fluoroscopy imaging has been performed, automatic detection of gross abnormalities is hardly achieved and the imaging still needs to be interpreted by an expert image interpreter such as a pediatric radiologist at a pediatric hospital. These often lead to severely under-detection rates of serious congenital diseases which lays the foundation of how diagnostics are made and how treatment procedures are early deployed. For this reason, automated interpretation of fluoroscopy images should be performed to avoid and/or minimize the impact of these sound concerns in clinical settings.

Interpretation of CT datasets is also time-consuming. The speed of examining a whole-body CT dataset is within half a minute. It takes much longer to spot and interpret hundreds of regions of interest from those abnormalities. For this reason, significant efforts should be done to detect, visualize, and segment identifiable organs and blood vessels. For CT, there are commercial solutions to spot the abnormality and commercially available ones using software packages with high-speed graphic processing units with a license fee. The flexibility of the software package should be arbitrarily controlled by an engineer and it is powerful. However, due to its greater independence, it might not be the most suitable solution in a CT lab without IT personnel or information technology knowledge. Hence, a simple routine with guaranteed speed and accuracy should be developed to locally visualize vessels interactively for better imagery interpretation. [29][30][31]

9.1. Radiology

Diagnostic imaging is a set of medical procedures utilizing specific devices for imaging. Radiology, a branch of medicine, deals exclusively with medical images in which physical parameters are detected and presented in meaningful forms. A simple device for medical imaging consists of a source of radiation, a detector, and two containers, the patient's body being in one container and a film in the other container. Medical imaging is of two categories, viz. medical photography and measurement of medical parameters. Medical photography includes visible light imaging of a living or dead body in which the visual light spectrum is utilized. On the other hand, measurement of medical parameters includes all other imaging in which parameters, and hence radiation emission, other than the visual light spectrum are utilized. Below the X-ray imaging, devices employed for medical photography, to greater and greater extent, utilizing specific available imaging devices produce and patent other medical imaging involved in thermal, sonic, electromagnetic and subatomic particles which may or may not be of ionizing range. A physicist specializing in devices producing and utilizing radiation for medical imaging is termed as a medical physicist.

Radiology is currently undergoing a rapid evolution characterized by demographic and technological changes. The new environment places unprecedented challenges on radiologists and medical physicists to ensure quality and safety in imaging. Progress in regulatory aspects, quality management systems, risk assessment practices, and safety in operations are ongoing [32]. Some recommendations for good practice in the medical physics department are provided and relevant aspects are discussed. Measured dose indices and image quality test patterns for the detector slices of a newly installed computer tomography (CT) scanner in a local hospital are presented. Sensitivity of column-wise image-reconstruction filters in development of a digital mammography radiography screen film imaging unit are discussed. Image processing and rate analysis systems used for acceptance tests of a computed radiography system and a mammographic equipment fixture are also described.

9.2. Nuclear Medicine

Nuclear medicine is a rapidly growing discipline that employs advanced novel hybrid techniques that provide unique anatomical and functional information, as well as targets for molecular therapy. There has been an increase in the attention paid to medical radiation exposure. A radiological justification for the practice of nuclear medicine has been implemented mainly through referral guidelines based on research results such as prospective randomized clinical trials. The International Commission on Radiological Protection recommends diagnostic reference levels as a practical mechanism to optimize medical radiation exposure in order to be commensurate with the medical purpose. The Korean Society of Nuclear Medicine has been implementing radiological optimization through a survey of the protocols on how each hospital determines the dose of administration of each radiopharmaceutical. In the case of nuclear medicine, radiation exposure of caregivers and comforters of patients discharged after administration of therapeutic radiopharmaceuticals can occur; therefore, optimization has been implemented through written instructions for patients, based on international recommendations. The development of patient-radiation-dose monitoring software, and a national registry and management system of patient-radiation-dose is needed to implement radiological optimization through diagnostic reference levels. This management system must work in agreement with the "Institute for Quality Management of Nuclear Medicine", and must take into account the medical reality of Korea, such as low medicine fee, in order to implement reasonable radiological justification and optimization. Medical practice gets significant benefit from molecular imaging procedures such as single-photon emission computed tomography (SPECT), positron emission tomography (PET), and from novel hybrid techniques such as single-photon emission computed tomography/computed tomography (SPECT/CT) and positron emission tomography/computed tomography (PET/CT), which provides unique functional and anatomical information relevant for patient management. Molecule-targeted therapy is also growing fast, with continuous development of approaches aimed to fight several forms of cancer [33].

Treatments should be optimized for the individual patient between what is tolerable and whatever good is required for efficacy. In radiotherapy, it is an unquestioned paradigm to perform patient-specific treatment planning prior to any course of treatment with external beams or brachytherapy sources. This optimization principle has been formalized in the EC Directive 2013/59/Euratom, laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation. Specifically, article 56 states: "For all medical exposure of patients for radiotherapeutic purposes, exposures of target volumes shall be individually planned and their delivery appropriately verified taking into account that doses to non-target volumes and tissues shall be as low as reasonably achievable and consistent with the intended radiotherapeutic purpose of the exposure." Nuclear medicine therapy is explicitly included by the definition of "radiotherapeutic" to mean pertaining to radiotherapy, including nuclear medicine for therapeutic purposes. Furthermore, the level of involvement of a medical physics expert is specified in three categories: (i) In non-standardized therapeutic nuclear medicine practices, a medical physics expert shall be closely involved. (ii) In standardized therapeutical nuclear medicine practices, a medical physics expert shall be involved. (iii) For other medical radiological practices, a medical physics expert shall be involved for consultation and advice on matters concerning radiation protection for medical exposure. The member states had to put into force the laws and regulations necessary to comply with the BSS by at latest 6 February 2018 [34].

9.3. Ultrasound Imaging

Ultrasound imaging is an essential technique in various clinical settings, providing the medical professional with a real-time image of internal soft tissues and fluids. Moving images are displayed in a cross-sectional slice corresponding to a plane illuminated by the transducer using the echo sequence of ultrasound from the tissue. This technology is widely available and has many applications, including obstetrics and gynecology, urology, cardiology, gastroenterology, musculoskeletal medicine, and vascular imaging [35]. Highly trained ultrasound professionals routinely conduct studies on intravenous ultrasound systems, handheld ultrasound systems, computerized ultrasound systems, and other advanced ultrasound detection equipment. Depending on the standard made available to the general public and the thoroughness of procedure adherence, this equipment can provide very high-quality images. However, due to the difficulty in quantifying the quality of sonographic images, it is impossible to know whether the procedure validity conducted with this equipment is high enough. Machine-processed imaging is particularly difficult to gauge the interpretation validity, as similar image sequences may pose different challenges for the analytical algorithms.

An objective measure of imaging quality cannot be based solely on the signal level, and any such measure must first consider the aspects of the imaging task. As human visual interpretation is the main use of sonographic imaging, a model of visual detection for tonal patterns [36] is employed. This model includes parameters of echo fluctuations that produce conflicting effects on information detection. Each of these parameters can be varied by changing either the imaging instrumentation or the scanning approach, providing a rationale for hardware and software optimization. Up to four levels of potential adaptation are considered: off-line design, automatic adjustment during scanning, multi-scan integration, and on-line uniformity assessment. The latter two adaptations can provide significant gains in imaging performance, and methods for both improvements are introduced. The results make it possible for the first time to quantify and further understand the performance of ultrasonic imaging systems.

10. Interdisciplinary Collaboration in Medical Physics

Since its inception, the field of Medical Physics has been at the interface between Medicine and Physics. Today, there are emerging trends and forces of change that will shape the continued evolution of Medicine, Medical Devices, Imaging Systems, and Medical Physics. Much of this change will not be driven solely by the field of Physics, but instead by other disciplines. As these changes develop, it is important for the field of Medical Physics to understand them, and in particular, to understand where it will have influence in the future, and what this influence will be. The following subsections provide some examples where different disciplines and their respective strengths come into play in the Medical Physics landscape.

The field of Biology has made great strides in the area of understanding malignant behaviour at the cellular and biochemical levels. Eventually, this understanding will facilitate the identification (in time) of cells that are on the verge of becoming malignant. The scientific challenges are here focused on what is the image the Medical Physicist will eventually be given for interpretation, and how this image will be exploited to identify Pre-cancer or Cancer [1].

Recently, advances in sensor technology have led to ubiquitous “active pixels” even in compact configurations where use was previously thought impractical. These new compact pixels have the promise of greatly improved spatial and temporal resolution, and increased detection/recognition speed. The challenge is how to harness this technology into a practical, cost-effective system [11].

The field of Engineering has made tremendous advances in the areas of three-dimensional modeling techniques. On the material side, much progress has been made in the area of polymer science, which have explosive accelerated rates of polymer grafting, cross-linking, swelling, etc. These developments will have profound influence on the design of introducers, catheters, coils, etc. The scientific challenges here are whether such models will be long-lasting, how practicality/safety will be incorporated into designs, and how optimal designs will really be realized in prototype and in production.

10.1. Working with Radiologists

Many medical instruments exist in the modern medical field, and each one has its own unique purpose. Some of these machines are more famous, such as Magnetic Resonance Imaging (MRI) scanners, while others are less popular, such as ultra-sound machines or CT devices. No matter the instrument, physicians and medical physicists must cooperate to generate the best machine and most beneficial policy possible. The design of a new magnetic resonance imaging device is a lengthy and careful process repeating many cycles of building, testing, and analyzing. An MRI device generates a magnetic field that goes through the patient. Next, Radio Frequency signals are used in order to angle the tissue nuclei away from equilibrium. The speed of angular return to equilibrium is different for every tissue. The generated signal is proportional to the speed with which the tissue returns to the equilibrium position. A Critical Reading task generates useful information about the tissue, and another set of designs generates the images. This task of image design requires particular cooperation between physicians and the designer(s), who are usually medical physicists. There exists a certain task specifying the macroscopic aspects of the desired design; this task refers to the main question to be answered by the images. The computation of the desired images is generally complex and lengthy, based on complicated computations; this step usually requires a substantial amount of time. Introduction of suggestions and improvements is lengthy and may require resorting to methods of considerable re-implementation of parameters. Only a professional designer can carry out this task. Indeed, part of the task is strictly professional; it is based on years of accumulated practical experience with the machine and its parameters. Medical physicists (and of course engineers) have a critical role to play in any of the machines [1]. A pure design task is one that can only be solved with respect to a decision in the above-named aspects. As such, it necessitates the profession to join the commencement of designing a new machine, including the review of commercial devices and the proposal of a unique combination of existing machinery coupled with original designs. Usually, a design task produces a single design that is usually set for the machine and gradually completed by minor refinements. Such a design task does not generally require a continuing cooperative effort. This kind of task evolves with respect to a unique design and tends to freeze needs in a particular device. A programming task is intended to maximize the performance of an existing design with respect to some practical consideration of the operation of the machine. Usually, it does require the cooperation of a team in which physicians and medical physicists have, respectively, leading and supporting roles in continually re-specifying the programming task. Typically, it features the adjustment of anatomical models, pre-processed image samples, and certain cooking parameters, and most importantly, the adjustment of the prescribed sequence. This programming task has to be performed anew for every particular patient and does not in itself have a long-term effect on the machine or its usage policy. In summary, medical physicists possess the unique capability of understanding and affecting key areas of modern medicine. [37][38][39]

10.2. Collaboration with Engineers

The importance of the close collaboration between medical physicists and engineers when designing new imaging products is illustrated through two examples involving GE Healthcare and the collaboration between engineering and medical physics. The continued technological advances in diagnostic imaging equipment, such as X-ray imaging systems, magnetic resonance imaging devices, and ultrasound systems, require a team of engineering and medical physicists to develop and optimize such designs into commercially viable clinical products. As engineers have deep expertise in designing detailed concepts into functional devices, medical physicists also play a vital role in assuring that imaging devices satisfy their initial design goals and deliver patient benefits, i.e. optimized image quality, reduced image dose, increased image throughput, etc [11]. Another example showcases numerous collaboration opportunities between medical physicists and engineers by 1) defining the problem specifications while balancing competing specifications, such as the image quality, the patient dose, the refresh rate, and the price; 2) generating design concepts, including X-ray tube and trajectory optimization, sinogram optimization, and filter design; 3) performing prototype testing to verify and validate design goals, such as mass/spring characterization and noise measurements; and 4) product refinements to improve product manufacturability, reliability, and maintenance. For any new product designs, a large number of design goals and competing design specifications need to be defined and carefully considered while brainstorming design concepts. Imaging engineers normally take a lead on such product specifications. During the early brainstorming stages, multiple design concepts across different fields are typically pursued simultaneously, from system hardware to technology concept. A proper assessment and analysis of various design concepts to ensure a robust design will lead to more optimal and product manufacturability designs [1].

11. Challenges in Diagnostic Imaging

The design, optimization, and regulatory approval of a new saturated solution (SS) diagnostic imaging device, such as a low-cost portable device utilizing X-ray fluorescence (XRF) for the qualitative and quantitative determination of mercury in fish, provide unique challenges and opportunities for medical physicists. While devices that use ionizing radiation in medical imaging (including mammography, CT, fluoroscopy, and general radiography) are somewhat better established, new kinds of devices can be tailored uniquely to underserved health management needs [32].

Envisioned medical imaging devices and attendant protocols may be faulty, suboptimal, or unfit for general use, even if implemented. Specialized degrees, training, and processes for model development, such as for image acquisition, processing, and analysis, as well as pictorial and numerical reporting, can prevent the oversized introduction of a new device, but economic disincentives may delay but not prevent the optimal design and regulation of a faulty device. Such interfaces may even act as an insurance policy for mishaps, as new devices may only fail “on the job” rather than in the test lab. Low-cost point-imaging devices may be readily prototyped to inform feasibility studies of new protocols, but just as there is no fire alarm in the heart or brain of a body, the problem of exploits with “clean looking” results still persists and may be compounded by testing incapacity and low management priority.

In very under-served low-resource settings, the fanciest and most costly protocol may ill-fittedly be pursued to its crash at astronomical societal costs – consider the 747s of a superpower nation “dreaming big” whilst a third-world nation crumbles for the lack of no-brainer simple fire-alarm protocols. The passive, accommodating roles of naïve physicists are burdened with moral imperatives, such as "grow the sectors" of intractable ill-serve or ill-designed technologies in capital-averse nations. Here, safety cannot be traded for sensitivity, with uncertainty quantification forcing better, simpler, faster protocols at almost no capital cost, only man-hours on cheap laptops.

11.1. Technological Limitations

Diagnostic imaging in medicine significantly improved with the introduction of digital systems in the last decade. The two main categories of biomedical imaging are dynamic and static imaging. Dynamic imaging yields time-varying and two-dimensional (2D) images representing the distribution of scintillation light attributable to fluorescent photons emitted from the scintillator material. On the other hand, static imaging provides one or a number of two-dimensional images of a distribution projected onto a planar area. Three-dimensional imaging is a fundamental requirement for contemporary examination devices and 3D images can be reconstructed in any computer-based (non-real time) system utilizing multiple two-dimensional images. The time needed for the reconstruction operation can be divided into two groups, namely, a few seconds of operation for computed-tomography devices and several minutes to even hours for tomosynthesis equipment. Digital X-ray imaging devices need a digital image acquisition system composed of scanning and 3D-i.e., utilizing a number of static images for three-dimensional images reconstruction.

The prerequisites for the design/manufacture/optimization of the image acquisition systems depend on tube-detector distance, as well as the additional conditions such as a parallel beam, reconstruction algorithm, etc. The price of the overall digital X-ray imaging system is very substantial, about an order of magnitude higher than its analogues. As a result, only one or two diagnostic units per hospital are available. Therefore, health authorities try to improve the information gain and to reduce the costs i.e., the number of patients re-examinations. Well-designed equipment results in improved diagnostic value as well as reduced prices. The design process is very complicated and should last from several months to a few years. It requires very innovative relationships that can help a designer to create such a system in a very short time. The mathematical basis should be very rigorous and should take into consideration technological limitations [6]. These qualitative and quantitative requirements should be considered in the design process of the digital X-ray imaging systems.

11.2. Radiation Safety Concerns

The environmental ramifications of diagnostic imaging devices are critical and need strong legislative underpinning in terms of public exposure to radiation. The implementation stages of any device involving x-ray or radioactive emissions should thus include the safety impacts as a corollary to public radiation doses. Hence, initial design architecture at R&D and system optimization at manufacturing plants should include consideration of public safety as mandated as part of CE marking regulations. In addition, formal price-based and cost-based procedures should be devised for comparison of different devices for regulatory purposes. Additionally, the thermal imaging devices should be included in any regulatory requirements for both public safety and price optimization. Finally computerized method should be utilized both for pricing optimization of new devices as well as on bulk pricing scenarios for procuring systems/soil. First formal WEE regulations similar to the ones in place for other domestic electrical goods should be implemented for low/medium level WEE. For high level waste the long-term geological disposal solution for radio-waste is in place and should be operationalized leading to an accepting agency being established for the UKs six unused VVER reactor cores. [12]

There is a logarithmic increase in doses delivered to the population by medical imaging. As new devices are introduced, legislation on safe working practices will ensure the market share of devices selling smart technologies. Currently the UK does not have any regulations for the public safety of diagnostic imaging devices. However the conclusions drawn could be extrapolated to target countries like Singapore, Malaysia or low/middle income countries in general. Sophisticated modelling algorithms covering public risk settings undermined here could be used to inform for rapid approval for sales of newly designed devices. Though fixed legislative safety parameters may be too prescriptive, bounds modeling parameters could be set by governments allowing the RCA equivalent for new devices. Hence for both the safety and financial optimization of agency at regulators would bemuse a streamlined pricing method involving uptake of the recent literature on multi-criteria education IRRs and sensitivity analysis on modelling parameters could be implemented. Finally on bulk procurements, free open source soft hardware utility software is now available for conventional mono screening that should also replace the proprietary and closed systems currently used, hence streamlining procurement costs for all involved; an approach that could again be gradually expanded to invite open source competitive bids for newer data mining devices, the pricing advantages likely outweighing the disadvantage of monopolistic contract regulator fines.

12. Conclusion

Being one of the foremost twelve subfields under the umbrella term "Medical Physics", the role of Medical Physicists in the design and optimization of diagnostic imaging devices is brought to be a scientific regard of the highest impact. A Medical Physicist is generally responsible for the evaluation of diagnostic imaging devices with respect to governmental regulations and accreditation standards so that the final goal of the design is achieved. Such regulations and standards specify the basic physical designs, operational principles, and attainable detectivity levels of various diagnostic imaging XS-CT, MR, US, and NM modalities. Simulations based on physics long sufficiently developed are effective in estimating specific performance metrics of diagnostic imaging devices. The developed simulation tools are as brief as applicable to the estimation of performance metrics of various imaging modalities. Being an important part of system optimization, Medical Physicists performs the design and optimization of the individual functional blocks for a given medical imaging device along the requirements granted by the system. The detailed designs, experimental implementations, and evaluations of some of blocking components in experimental imaging pincodes have been presented. For a large variety of other functional blocks where experimental implementations are bounded outside of the abilities of organizations, virtual designs based on simulation tools are described. Despite a constant decrease in the share of manufacturer's involvement in the device design and optimization, active collaborations with manufacturers where possible are always preferred. For a design-against-regulation job, results are mutually published with manufacturers. In both cases, competitive technologies are openly presented and granted for a further evaluation by manufacturers, which is considered a grasp of the highest ethics. The developed simulation tools sufficiently solve the issues of device evaluation, and manufacturers need be urged to develop sophisticated simulation tools for the design and optimization of diagnostic imaging devices. These tools will positively inflect the next generations of medical devices and all-related advanced technologies.

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