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Radiographic sciences and technology: an overview

Radiographic Science and Technology have evolved through the years, ever since the discovery and use of x-rays in 1895. This evolution has resulted in the introduction of physical principles and technology with the major goal of improving the care and management of the patient. Furthermore, a significant benefit of these innovations is focused on reducing the radiation dose to the patient without compromising image quality. *Radiographic sciences* deal with the physics of various diagnostic imaging modalities (radiography, fluoroscopy, mammography, and computed tomography [CT]) and include x-ray generation, x-ray production, x-ray emission, and x-ray interaction with tissues. Furthermore, radiographic sciences also address radiation risks and radiation protection. *Radiographic technology,* on the other hand, addresses the equipment components and how they function to produce diagnostic images, image quality characteristics, and quality control (QC) aspects of these imaging modalities.

A Comprehensive Guide to Radiographic Sciences and Technology, First Edition. Euclid Seeram.

The workhorse of radiology has been *film-screen radiography* which is now obsolete and has been replaced globally with *digital imaging*. The scope of digital imaging is extremely wide and now involves a basic understanding of computer sciences, to explain how the new digital imaging modalities work. These modalities include computed radiography (CR), flat-panel digital radiography (FPDR), digital fluoroscopy (DF), digital mammography (DM), digital tomosynthesis, and CT. In addition, the digital imaging environment now demands that operators understand what has been referred to as “imaging informatics,” an area of study that involves picture archiving and communication systems (PACS), enterprise imaging, Big Data, machine learning (ML), deep learning (DL), and artificial intelligence (AI).

With the above in mind, various professional organizations such as the American Society of Radiologic Technologists (ASRT), the Canadian Association of Medical Radiation Technologists (CAMRT), and other professional medical imaging organizations throughout the world have prescribed curricula for diagnostic imaging programs which provide guiding, principles that assist academic program leaders in designing foundational learning outcomes that are intended to meet the professional standards, and more importantly meet the entry requirements for clinical practice. Institutions offering educational programs in diagnostic imaging should be then able to raise the level of these foundational learning outcomes and content to meet the requirements of degree programs, including graduate degree programs in diagnostic imaging.

A good example of the above is offered by the ASRT curriculum content which is organized around the following subject matter [1]: Introduction to Radiologic Science and Health Care; Ethics and Law in the Radiologic Sciences; Human Anatomy and Physiology; Pharmacology and Venipuncture; Imaging Equipment; Radiation Production and Characteristics; Principles of Exposure and Image Production; Digital Image Acquisition and Display; Image Analysis; Radiation Biology; Radiation Protection; Clinical Practice; Patient Care in Radiologic Sciences; Radiographic Procedures; Radiographic Pathology; Additional Modalities and Radiation Therapy; Basic Principles of Computed Tomography and Sectional Anatomy. Similar content is characteristic of other curricula offered by other medical imaging professional organizations around the world.

Keeping the above ideas in mind, this book will address content that are considered radiographic sciences and technology. Specifically, the chapters included present a summary of the critical knowledge base needed for effective and efficient imaging of the patient, and wise use of the technical factors that play a significant role in optimization of the dose to the patient without compromising the image quality necessary for diagnostic interpretation. Furthermore, the summaries of the technical elements of radiographic sciences and technology will assist the student in preparing to write certification examinations. As such, the major and significant principles and concepts will be reviewed in three sections as follows:

Section 1: Radiographic imaging systems: major modalities and components
Section 2: Radiographic physics and technology
Section 3: Radiation protection and dose optimization

RADIOGRAPHIC IMAGING SYSTEMS: MAJOR MODALITIES AND COMPONENTS

In this book, the following *radiographic imaging systems* will be reviewed. These include x-ray imaging modalities such as digital radiography (DR) which includes CR and FPDR, DF, DM, digital radiographic and breast tomosynthesis, and CT. Furthermore, these systems include imaging informatics which has become commonplace since radiology and more importantly hospitals are now all operating in the digital environment; that is, all data acquired from the patient are now in digital form and are stored and communicated using digital technologies. Informatics topics of importance include that nature and scope of PACS, enterprise imaging, cloud computing, Big Data, and the more recent of computer applications in medical imaging: AI. More details of these major technologies and how they work will be presented in Chapter 6 on Digital Imaging Modalities and Chapter 10 on Imaging Informatics.

RADIOGRAPHIC PHYSICS AND TECHNOLOGY

Radiographic physics and technology subject matter include basic physics concepts, and more specifically the physics of diagnostic imaging; technical aspects of the modalities; radiographic exposure technique; image quality, quality assurance (QA), and QC; CT physical principles; imaging informatics; radiobiology and radiation protection.

Essential physics of diagnostic imaging

The *physics of diagnostic imaging* is an important and vital topic that explains the nature of how these imaging modalities work to produce diagnostic images of the patient. Understanding the fundamental physics will provide the user with the tools not only needed to produce optimum image quality but more importantly to protect the patient from unnecessary radiation. As such, it is now a common characteristic of imaging departments to optimize radiation dose and work within the International Commission on Radiological Protection (ICRP) philosophy of as low as reasonably achievable (ALARA) to reduce the dose to the patient but not compromise the diagnostic quality of the images used to make a diagnosis of the patient's medical condition.

In this book, the topics in physics that will emphasize the imaging modalities are the nature of radiation, x-ray generation, x-ray production, x-ray emission, x-ray attenuation, and x-ray interaction with matter. Furthermore, other physics topics of significance are radiation quantities and their associated units and measurement concepts. These topics and more fall in the domain of *Health Physics*. Three radiation quantities that are important to radiation protection of the patient are exposure, absorbed dose, and effective dose (ED). The units associated with each of these include coulombs per kilogram (C/kg), Grays (Gy), and Sieverts (Sv), respectively. In order to measure radiation, it must first be detected.

Digital radiographic imaging modalities

As listed earlier in this chapter, these modalities include CR, FPDR or DR as it is sometimes referred to, DF, DM, digital radiographic tomosynthesis (DRT), digital breast tomosynthesis (DBT), and last but not least CT. Additionally, since all of the above-mentioned modalities include image processing using computers, the concepts of Digital Image Processing will be reviewed since it has become an essential tool for technologists, radiologists, and medical physicists working in a digital radiology department.

These imaging modalities include specific physics concepts that must be understood for optimum results. For example, CR is based on the use of photostimulable phosphors (PSP) which are based on the physical principle of photostimulable luminescence (PSL). An example of one such phosphor is barium fluoro halide (BaFX) where the halide (X) can be chlorine (Cl), bromine (Br), iodine (I), or a mixture of them. When the PSP imaging plate (IP) is exposed to x-rays, electrons are moved from the ground state (valence band) to a higher energy level (conducting band) and are trapped there until the PSP plate is exposed to a laser light and subsequently the electrons in the higher energy state return to their ground state, thus emitting a bluish-purple light referred to as PSL.

The detectors used in FPDR are based on semiconductor physics. Examples of two such common detectors used in DR are indirect digital detectors which use amorphous silicon photoconductor coupled to an x-ray scintillator (cesium iodide for example) and direct digital detectors which use amorphous selenium photoconductor. While the former detector converts x-rays to light which falls upon the silicon photoconductor to produce electrical signals, the latter detector converts x-rays directly into electrical signals. The other digital imaging modality detectors are based on photoconductor physics.

The imaging modalities listed above convert radiation attenuated by the patient and falling on the digital detector to digital data. This is necessary since computers are used to process these data through popular digital image processing operations. These operations have become commonplace and must be fully understood for effective use in clinical practice. One such tool is the concept of windowing, where the image brightness and contrast can be changed by the operator to suit the viewing needs of the human interpreter. Furthermore, other digital image processing tools that are vital in DBT and CT image reconstruction algorithms. These algorithms have evolved from the filtered back projection (FBP) algorithm to more complex algorithms such as iterative reconstruction (IR) algorithms. These algorithms play an important role in building up an image from data collected through 360° around the patient in CT, for example. Today, IR algorithms are now used by all CT vendors.

Radiographic exposure technique

Radiographic exposure technique refers to the use of exposure factors coupled with other elements on the x-ray control panel, selected by the technologist to produce diagnostic images. Exposure factors include the kilovoltage (kV), the milliamperes (mA), and exposure time (s) and the selection of the appropriate source-to-image receptor distance (SID). Furthermore, the proper positioning of the patient and image receptor, tube alignment with the image receptor, use of appropriate filtration and collimation, and patient instructions, are all the other elements that play an important role during the radiographic examination.

Image quality considerations

Image quality is a significant goal of radiographic imaging modalities. The attenuated radiation data from the patient are used to create images that are used for diagnostic interpretation by a human observer. There are at least five important descriptors of digital image quality and these include spatial resolution, contrast resolution, noise, detective quantum efficiency (DQE), and image artifacts. While spatial resolution addresses the sharpness of images, and is related to the size of the pixels (picture elements) in an image, contrast resolution or density resolution deals with the ability of the imaging system to demonstrate differences in tissue contra, and is linked to the bit depth, that is the range of gray levels per pixel. Noise, on the other hand, depends on the number of x-ray photons used to create the image. While fewer photons (low exposure technique factors) will result in more noise (grainy appearance), more photons (higher exposure technique factors) will create a better image (less noisy image), but at the expense of dose. Another digital image quality descriptor is the DQE, which is a measure of the efficiency and fidelity with which the detector can convert an input exposure into a useful output image. Finally, digital images are not free of artifacts. These are features seen on the image that are not present in the patient, and can pose challenges for the human observer in detecting fact from artifact.

Computed tomography – physics and instrumentation

This section will present a broad overview of the essential elements of the *Physics and Instrumentation of Computed Tomography*. One of the major advantages of CT is that it provides improved contrast resolution compared to radiography and for this reason, it has proven to be worthy of further developments in imaging soft tissues of the human body. It is important to note, however, that magnetic resonance imaging (MRI) has superior contrast resolution compared to all other imaging modalities, such as radiography, nuclear medicine, and diagnostic medical sonography.

CT is a sectional imaging technique that produces direct cross-sectional digital images referred to as transverse axial images which has been referred to as planar sections that are perpendicular to the long axis of the patient. The word "computed" implies that a computer is used to process and reconstruct x-ray transmission data collected from the patient. The CT scanner has evolved from single-slice CT scanners (SSCT) to multi-slice CT scanners (MSCT). State-of-the-art CT scanners are now MSCT scanners capable of a wide range of applications. The increasing use is that CT in clinical practice has led to increasing doses to the patient and a well-documented fact is that CT delivered the highest collective dose in the United States compared to other medical imaging modalities.

Two individuals shared the Nobel Prize in Medicine and Physiology in 1979 for their development of the CT scanner. These include Godfrey Newbold Hounsfield in the United Kingdom (UK) who invented the first clinically useful scanner, and Allan Cormack, a physicist at Tufts University in Massachusetts.

CT is a multidisciplinary technology and has its roots in physics, mathematics, engineering, and computer science. The CT process consists of at least three major system components that are used to produce the CT image; the data acquisition system; the computer system; and the image display, storage, and communication systems.

Data acquisition means that radiation attenuation data are collected from the patient during the scanning. In this respect, an x-ray tube coupled to special electronic detectors rotate around the patient to collect and measure attenuation readings as the x-ray beam passes through the patient.

The attenuation is according to Beer–Lambert's law:

$$I = I_o e^{-\mu \Delta x},$$

where I is the transmitted x-ray beam intensity, I_o is the original x-ray beam intensity, e represents Euler's constant, μ is the linear attenuation coefficient, and Δx is the finite thickness of the section. In CT, the system calculates all μs for all structures seen on the image. Special detectors and detector electronics are used to calculate the attenuation data and convert them into integers (0, a positive number, or a negative number) referred to as CT numbers using an image reconstruction algorithm to build up the image in numerical format. The CT numbers (numerical image format) are converted into a gray-scale image for display on a monitor for the observer to interpret.

The CT numbers are calculated using the following relationship:

$$\text{CT number} = \frac{\mu_{\text{tissue}} - \mu_{\text{water}}}{\mu_{\text{water}}} \cdot K,$$

where K represents a scaling factor. In general, K is equal to 1000. When Hounsfield invented the scanner, K was equal to 500.

The technology aspects of CT are complex and are responsible for using the attenuation values collected around the patient for 360° to build up an image of the internal anatomy of the patient, and displays such image for interpretation by radiologists. The technology addressing the collection of these values includes the x-ray tube which is coupled to special electronic detectors and detector electronics. Another major technology component in CT is the computer system which captures the raw data from the detectors and uses sophisticated image reconstruction algorithms for creating the image from the raw data.

Present-day CT scanners are MSCT scanners. One characteristic feature of MSCT is the two-dimensional detector array, compared to a one-dimensional detector array of SSCT. This means that there will be additional specific technical factors that affect the dose in CT. One such notable factor is the pitch (P), which is defined by the International Electrotechnical Commission (IEC) as the distance the table travels per rotation (D) divided by the total collimation (W). This can be expressed algebraically as:

$$P = D / W$$

The increasing use of CT has led to widespread concerns about high patient radiation doses from CT examinations relative to other radiography examinations. The distribution of the dose to the patient in CT is significantly different than the distribution of the dose in radiography. These differences require additional CT-specific dose metrics. There are essential four CT-specific dose metrics: the computed tomography dose index (CTDI), the dose length product (DLP), the size-specific dose estimate (SSDE), and the ED. These and other elements of CT physical principles will be described further in Chapter 7.

Quality control

QC is an essential activity of all medical imaging departments and it is part of a QA program. QA deals with people and includes the administrative aspects of patient care and quality outcomes. QC addresses the technical aspects of equipment performance used to image patients. QA and QC programs have evolved into what is now referred to as *Continuous Quality Improvement* (CQI) which includes *Total Quality Management* (TQM). CQI was introduced by the Joint Committee on Accreditation of Healthcare organizations (JCAHO) to stress the importance that all employees play an active role in ensuring a quality product. The purpose of the procedures and techniques of CQI, QA, and QC is threefold: to ensure optimum image quality for the purpose of enhancing diagnosis, to optimize the radiation dose to patients and reduce the dose to personnel, and to reduce costs to the healthcare facility.

An effective QC program consists of at least three major steps, namely acceptance testing, routine performance, and error correction. While acceptance testing is the first major step in a QC program and it ensures that the equipment meets the specifications set by the manufacturers, routine performance involves performing the actual QC test on the equipment with varying degrees of frequencies (annually, semi-annually, monthly, weekly, or daily). Error correction means that equipment not meeting the performance criteria or tolerance limit established for specific QC tests must be replaced or repaired to meet tolerance limits. These limits include both qualitative and quantitative criteria used to assess image quality. For example, the tolerance for collimation of the x-ray beam should be ±2% of the SID.

QC for DR has evolved from simple to more complex tests and test tools to assure that the DR equipment is working properly to meet optimum image quality standards and fall within the ALARA philosophy in radiation protection. The American Association of Physicists in Medicine (AAPM) has recommended that several testing procedures for CR QC, using specific tools developed for CR QC. A few examples of these test procedures include physical inspection of IP, dark noise and uniformity, exposure indicator (EI) calibration, laser beam function, spatial accuracy, erasure thoroughness, aliasing/grid response, positioning and collimation errors, to mention a few.

QC is now an essential requirement of CT imaging and requires that users have a clear understanding of the various tests that play a significant role in dose-image quality optimization.

Imaging informatics at a glance

Imaging Informatics is the current term used by the Society of Imaging Informatics in Medicine (SIIM) to replace the old term medical imaging informatics. SIIM notes that imaging informatics "is the study and application of processes of information and communications technology for the acquisition, manipulation, analysis, and distribution of image data."

Imaging informatics is based on core topics that range from information and communication technologies, PACS, radiology information systems (RIS), the electronic health record, to cloud computing, Big Data, AI, ML, and DL. In this section, these core elements that characterize these topics will only be highlighted as a basis for setting the stage for the more detailed coverage later in the book.

Information technology (IT) refers to the use of computers and computer communications technologies to not only to process, store, secure electronic data but to communicate these data using computer networking infrastructure. PACS is an excellent example of an informatics-rich medical device. PACS include the imaging image acquisition modalities such as digital radiographic and CT modalities, a computer network database server, storage and archival systems, and display workstations. PACS may be connected to information systems such as the RIS and the hospital information system (HIS). Furthermore, these systems must be fully integrated and secured for efficient and effective data interchange. One such approach within the PACS infrastructure is cloud computing, which simply provides a means of using the Internet for storage and retrieval (for example) of data using specific software packages. Additionally, emerging topics which will have an impact on the practice of medical imaging include Big Data, AI, ML, and DL.

Big Data is characterized by four Vs: Volume, Variety, Velocity, and Veracity. While Volume refers to the very large amount of data, Variety deals with a wide array of data from multiple sources. Furthermore, Velocity addresses the very high speeds at which the data are generated. Finally, Veracity describes the uncertainty of the data such as the authenticity and credibility. AI uses computers in an "effort to automate intellectual tasks normally performed by humans." A subset of AI is ML which includes "a set of methods that automatically detect patterns in data, and then utilize the uncovered patterns to predict future data or enable decision making under uncertain conditions." A subset of ML is DL which uses algorithms that are "characterized by the use of neural networks with many layers." These emerging technologies will evolve and more importantly become useful tools in medical imaging. Therefore, students and technologists alike should make every effort to grasp their meaning and applications so that they can communicate effectively with radiologists and medical physics in an effort to participate actively in the management of patient care.

RADIATION PROTECTION AND DOSE OPTIMIZATION

Current radiation protection standards and recommendations for the safe use of ionizing radiation to image humans are based on the fact that exposure to radiation can cause biological effects. These bioeffects fall in the subject matter domain of radiobiology.

Radiobiology

Radiobiology is the study of effects of radiation on biologic systems which occur at the molecular, cellular levels and subsequently leading to whole-body biological effects generally categorized as early and late effects.

The study of radiobiology is vital for technologists and radiologists working in radiology departments, and it involves an understanding of related physics and chemistry, types of biological effects, radiosensitivity, target theory, and direct and indirect effects. Furthermore, radiobiology involves discussing of deterministic effects (early effects) and stochastic effects (late effects). These topics and their associated subtopics (for example, subtopics for stochastic effects are radiation-induced malignancy, and hereditary effects) will be outlined in Chapter 9.

Topics in physics that are significant to radiobiology include atomic structure, the nature and properties of x-rays, ionization, excitation, linear energy transfer (LET), and relative biologic effectiveness (RBE). Additionally, the essential chemistry of the interactions of radiation and patient which occur with water (since the body contains 70–85% water) is the radiolysis of water. Such chemical interactions result in ionization of water, forming ion pairs and free radicals of which the latter can react further to form other molecules that are toxic to the cell.

Two significant and important topics in radiobiology are stochastic and deterministic effects. Stochastic effects are those for which the probability of the effect increases as the dose increases and for which there is no threshold dose. For stochastic effects, there is no risk-free dose. These effects can occur at the local tissue level and can cause life-span shortening, radiation-induced malignancy, and hereditary effects (late effects that occur in the offspring of the irradiated individual). Stochastic effects are classified as late effects, since they occur years after the exposure of the individual. Deterministic effects on the other hand are those effects for which the severity of the effect depends on the dose. These effects have a threshold dose and increase with increasing dose. These effects are called early effects since they can occur within minutes, hours, days, weeks, and months after the exposure.

Radiation protection in diagnostic radiography

The overall objectives of radiation protection are to prevent deterministic effects and minimize the probability of stochastic effects. The current standards for radiation protection of patients in medicine are established by authoritative radiation protection organizations responsible for providing guidelines and recommendations on radiation protection. While some of these address radiation risks, others are devoted to radiation protection based on the radiation risks data. Three such organizations are the International Commission on Radiologic Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the Food and Drug Administration (FDA), the latter two are in the United States.

Radiation protection criteria and standards are guided by two triads, namely radiation protection principles and radiation protection actions. While the former deals with the ICRP's principles of justification, optimization, and dose limitation, the latter addresses the triad of time, shielding, and distance. The principle of justification is intended for physicians ordering x-ray examinations; it addresses the notion that there should be a net benefit associated with each and every exposure a patient receives. Optimization implies that radiation workers should work within the ALARA philosophy; that is, to obtain the best possible image with the lowest radiation dose and not compromise the image quality. Finally, the dose limits principle deals with the legal limits on the radiation dose received per year or accumulated over a working lifetime for persons who are occupationally exposed and for others as well, such as students in training and members of the public.

The triad of radiation protection actions include time, shielding, and distance. To be effective, it is necessary to keep the time of exposure to radiation as short as possible, since the relationship between time and exposure is proportional; that is, if the time of exposure doubles, the exposure doubles. Shielding ensures protection of patients and workers and members of the public through the use of lead shields and aprons for patients and workers, respectively. Furthermore, the walls of x-ray rooms are also shielded using concrete or lead, for example, to prevent exposure of members of the public who are in a waiting room, waiting for patients having x-rays. Finally, exposure is inversely proportional to the distance; that is, the further away individuals are from the source of the radiation, the less exposure they will receive.

The notion of dose limits is vital to radiation protection of occupationally exposed individuals such as technologists, for example, and non-occupationally exposed individuals (members of the public). Essentially, these limits are established by organizations such as the ICRP, and national organizations, to minimize the risks of the stochastic effects of radiation. The ICRP recommended dose limit for occupational exposure, for example, is 20 mSv/year averaged over defined periods of five years.

The *diagnostic reference level* (DRL) is a concept used to address the limits of exposure for patients. DRLs are not equivalent to dose limit s for occupationally and non-occupationally exposed individuals. The DRL has been defined by various radiation protection organizations. One such definition is that of the American College of Radiology (ACR) as "an investigation level to identify unusually high radiation dose or exposure levels for common diagnostic medical x-ray procedures." DRLs are tools that radiology departments can use to measure and assess radiation doses to patients for a defined set of procedures. If the doses delivered are consistently greater than established DRLs for that facility's country or region, then the department should be concerned about its radiation protection procedures, investigate why exposures are beyond the established DRLs, and take corrective action.

Technical factors affecting dose in radiographic imaging

Radiographic imaging includes modalities such as DR, DF, and CT. There are several technical factors including operator-selectable (under the control of the technologist and/or radiologist) factors that affect the dose to the patient and operator. The major factors affecting dose to the patient in DR include beam energy and filtration, exposure technique factors, beam collimation, the size of the x-ray field, the size of the patient, SID, grids, image receptor sensitivity or speed, and DQE. Major technical factors affecting the dose to the patient in fluoroscopy include beam energy or filtration, x-ray tube current, beam-on time, automatic dose-rate control, collimation, source-to-skin distance, patient-to-image intensifier distance, patient size, anti-scatter grids, image magnification, last image hold, image recording method, and pulsed fluoroscopy.

In CT, there are numerous technical factors affecting the dose to patients. Major factors include exposure technique factors, pitch, effective mAs, collimation and slices, overbeaming and overranging, automatic tube current modulation, automatic voltage selection, and IR algorithms.

Radiation protection regulations

Radiation protection regulations and guidelines address equipment specifications, procedures for minimizing the dose to patients and personnel, and shielding, outlined in various reports, and are issued by major agencies in respective countries. In the United States (US), for example, while the NCRP deals with medical x-ray, electron beam, and gamma ray protection for energies up to 50 MeV in NCRP Report No. 102: Equipment Design and Use; the Code of Federal Regulations (CFR) Title 21 (US Department of Health and Human Services, Food and Drug Administration [FDA]) deals with the Performance Standards for Ionizing Radiation Emitting Products.

Equipment specifications for radiography, fluoroscopy, and CT are intended for manufacturers. Specifications for radiographic equipment relate to the x-ray control panel, leakage radiation from the x-ray tube, filtration, collimation, SID, source-to-skin distance, and the exposure switch for fixed and mobile radiographic systems. An example of one such recommendation for the exposure switch is that for fixed radiographic equipment, the exposure switch must be on the control panel to ensure that the operator remains in the control booth during the exposure. Furthermore, the switch must be a “dead man” switch; that is, pressure must be applied to the switch for the exposure to occur.

For fluoroscopy, these specifications include specifications for filtration, collimation, source-to-skin distance, exposure switch, cumulative timer, protective curtain, table and Bucky-slot shielding, and accessory protective clothing. The recommendation for protective aprons worn during fluoroscopy is that they shall have at least a 0.5 mm lead equivalent.

Guidelines and regulations also focus on practices and procedures for reducing the dose to patients and personnel and to keep exposures according to the ALARA philosophy. Technologists must refer to the safety codes of their respective countries for more detailed information. Two such examples of these guidelines on radiography and fluoroscopy state that selection and use of the best possible exposure technique factors should keep the dose ALARA without compromising image quality. Additionally, high-kVp techniques reduce the dose to the patient.

Procedural factors for minimizing dose to personnel are wide and varied and technologists must work within the ALARA philosophy to accomplish this task. Two such examples of recommendations to ensure personnel dose reduction are that (i) only essential personnel must be present in an x-ray room during the exposure and (ii) technologists must remain in the control booth during radiographic exposures and must wear protective aprons when the situation makes this impossible. Another significant recommendation relates to shielding, a radiation protection action and design criterion that is intended to protect patients, personnel, and members of the public. Shielding includes specific area shielding (protecting radiosensitive organs) and protective barriers (walls) positioned between the source of radiation and the individual. This type of shielding, for example, is specifically intended to protect personnel and members of the public from unnecessary radiation.

Optimization of radiation protection

The ICRP optimization framework refers to optimization as keeping the dose ALARA and not compromise the diagnostic quality of the image. Therefore, optimization includes image quality and radiation dose.

The journal *Radiation Protection Dosimetry* dedicated a special issue to optimization strategies in medical imaging for fluoroscopy, radiography, mammography, and CT. Several studies identified at least four important requirements for dose and image-quality optimization research. First, patient safety must be a priority in any study. Second, the level of image quality needed for a particular diagnostic task must be determined. The third requirement involves acquiring images at various exposure levels from high to low and in such a manner that accurate diagnosis can still be made, and finally, use reliable and valid methodologies for the dosimetry, image acquisition, and evaluation of image quality using human observers, keeping in mind the nature of the detection task.

An interesting study utilizing these elements of dose optimization is one by Seeram and colleagues published in *Radiologic Technology* in 2016. The purpose was to investigate a technique for optimizing radiation dose and image quality for a CR system. The researchers measure the entrance skin doses for phantom models of the pelvis and lumbar spine imaged using the vendor's recommended exposure settings (i.e. the reference doses) as well as doses above and below the vendor's recommended settings for both body parts. Images were assessed using visual grading analysis (VGA). The phantom dosimetry results revealed strong positive linear relationships between dose and milliampere seconds (mAs), mAs and inverse EI, and dose and inverse EI for both body parts. The VGA showed that optimized values of 16 mAs/EI = 136 for the anteroposterior (AP) pelvis and 32 mAs/EI = 139 for the AP lumbar spine did not compromise image quality. Selecting optimized mAs reduced dose by 36% compared with the vendor's recommended mAs (dose) values. The study concluded that optimizing the mAs and associated EIs can be an ED management strategy.

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