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Radiation Physics and its Applications in Modern Radiotherapy Equipment

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Annotation: With the emergence of a highly sophisticated and complex health system, exquisite methods had to be developed for the diagnosing and treatment needs of patients. One of these advancements was the initiation of using radioactive materials for medical purposes, also called radiotherapy (RT). Initial transmission to adopt this vague method had a lot of human casualties and unintended exposures to high-dose regions. By the invention of new generation healthcare equipment and highly sophisticated computer systems, RT was refined and became a common and routinely used method for treating various tumor types. Currently a treatment plan derived for one patient for a given time will be used as a reference for all patients treated with a system. All parameters affecting the plan will be monitored and confirmed, to be similar to the reference format. There are two major systems for administering RT treatment: teletherapy with high-energy X-rays or gamma-rays and brachytherapy with different energy gamma-ray sources. Teletherapy has become a routine technique and the number of RT treatment facilities has increased rapidly since the establishment of this technique. A minimum necessary condition for reliable treatment was the production of high dose rate teletherapy equipment which was done in many

countries. With the establishment of computerized number crunching systems and three-devices, new and sophisticated techniques for treating with high-energy X-rays were developed and implemented. One of these advancements was a multi-leaf collimator (MLC) for conforming radiation doses to the shape of treatment volume (TV). Treatment technique, shielding and other requirements had to be calculated and drafted for each treatment plan (TP) which made this technique a very time-consuming process requiring long co-operation of a medical physicist (MP), oncologist and medical technical personnel (MTP). Thus, to facilitate using external RT treatment systems, a collection of codes was developed for implementing an easy, safe and done with a minimum time program for achieving fluency in treatment and including human resources and decreasing their time consumptions, costs and errors. The codes were written in the Pascal Delphi programming language and run on MS-DOS operating system. Different sets of applications were implemented, which concentrated on designing the fastest code with the most accuracy for a specific evaluation for an RT technique. With the first generation of MS-DOS operating systems, first applications were written in Basic computer programming language which became obsolete in a short time. This shortened life cycle caused great losses in both investments and time consumptions. To cover this weakness, and provide a compact system which is cheap, portable and still fluent, a new technique was developed in order to convert an application coded in Pascal Delphi programming language to that run on mobile phones. An application code, called RT Number Crunching, with a good technical performance, was developed for teletherapy systems of this type. It contained several applications for commonly run calculations, tables and notations with transparent operational steps for trained users. So far, there has been an installation version for central processing units (CPU) of the type of intel which can be used on MS window operating systems of computers, with a good success, usage and good comments from users. A mobile phone version, compatible with Android operating systems, was coded using Java-scripting language. This code provided users great advantages due to its own nature

of mobile phones such as being cheap, portable and easy usage.

The first fully code run program, compared to application “Didactic”, was “Specific” that was specially coded for a detailed calculation in non-standard procedures, external beam brachytherapy systems and seed-pulse gamma-ray brachytherapy teletherapy systems. Both of these phone and computer codes are applicable and run in treatment facilities for both brachytherapy systems. A computer version of “Integration” was developed and just entered fixed numerical data and coded all follow-up settings. It cuts all procedural steps and saves a minimum time for obtaining results. For use of portable and mobile computer facilities in hospitals, there would be some new versions to cover this request. All complied codes and applications of the software are available publicly for free or highly discounted because of their long time, great caution and high human costs for numerical evaluations in each treatment facility.

1. Introduction to Radiation Physics

Radiation is described as the process in which energy is emitted as particles or waves. Particles may be charged, such as electrons and protons, or uncharged, such as neutrons and gamma rays. These rays are usually produced in nuclear reactions but are also widely available in space. Radiation can be described as electromagnetic radiation or as particle radiation [1]. When charged particle radiation interacts with matter, they collide with the atoms of that matter and lose energy. This process is called energy deposition. Charged particles contribute to the dose deposition distribution in radiotherapy procedures but virtually all equipment provides x-ray or gamma-ray irradiation which depend on an indirect secondary particle emission. Dosimetry based on this kind of irradiation involves multiple interactions that can be quite complex. On the other hand, calibrations based on direct charged particle measurements are less complicated. Recommending ionization chamber calibrations based on charged particle beams, this paper intends to make a contribution to the international calibration effort necessary for the quality assurance of the new radiotherapy equipment [2].

Characterization of radiotherapy equipment requires measurements of beam quantities at pre-determined reference conditions and the determination of comparison beam qualities at user institutions. Given the flexibility of radiotherapy equipment, it is the user institution’s responsibility to conduct some simple performance tests and put the equipment to its best application. Radio-chemistry and physical property checks form an atlas of reference quality checks of equipment out of manufacturer warranty. Detailed apparatus specification or comparison measurements against reference standards are demanded more on a routine basis. In order to provide the basis of confidence checks, frequent checks of quality performance at standard conditions are desirable. These tests are less expensive than comprehensive tests and detrimental to patient treatment characteristic. According to strictly defined test philosophies, a sequence of measuring steps, methods and instruments is necessary to demonstrate the correctness of computation. There should also be a measure of completeness of comparison measurements. A Monte Carlo method for radiation transport simulation is generally required, detailed on patient doses.

2. Fundamental Concepts of Radiation

Radiation is a form of energy that travels through space at the speed of light in a vacuum. There are two basic types: electromagnetic (or wavelike) radiation and particulate radiation. Although they differ in their basic characteristics, both types can travel through space (albeit, in different ways) and can ionize matter. This means that energy can be removed from the radiation in sufficient amounts to cause chemical changes in matter [3]. Common naturally occurring sources of radiation include the sun, fire, natural gas flame, old style bulbs emitting a continuous visible light spectrum, and X-ray tubes among members of the electromagnetic radiation family. On the other hand, lightning, neon lamps, cathode ray tubes, TV sets, and cigarette lighters can produce high energy electrons in a vacuum or gaseous state mode of particulate radiation.

Radiation is described by its wavelength, frequency, and energy. A digital dial on the microwave oven operates at a frequency of 2.45 gigahertz corresponds to a wavelength of about 12.2 centimeters. All of the information-bearing radio waves that make up the sound and images heard on radios and TVs, pages on the Internet, and voices on cell phones is carried by the same type of radiation. The difference is in the frequency of oscillation modulations. The shorter the wave or the quicker the oscillation the higher the frequency (higher energy) and the smaller the wavelengths. Therein lies the difference between radio waves and the myriad of kinds of ionizing radiation such as ultraviolet light, X-rays, and gamma radiations. Each of these radiations is more energetic and shorter than visible light.

2.1. Types of Radiation

The type of radiation used for cancer treatment is called ionizing radiation. The absorbed energy forms electrically charged particles in the cells of the tissues the ionizing radiation contacts by removing electrons from the atoms and molecules in the tissues, forming ion pairs. These high energy charged or neutral particles are highly reactive and unstable and will react with nearby molecules to return to a stable state. The results of this ionization and dissociation process are chemical changes in the molecules of the tissue. These changes include oxidation and ionization of critical biomolecules like DNA, leading to single and double strand DNA breaks, cross linking between DNA, and DNA-protein cross linking [4]. These changes kill the cancer cells by damaging their DNA. If the radiation damage is severe enough, the cell cannot repair itself. The tumor mass can be reduced because the cancer cells are damaged and die, while healthy surrounding tissue is spared because the damage to the DNA is repairable. Radiation damage takes place on the order of picoseconds after the molecules have absorbed the energy, while the chemical changes take place on the order of nanoseconds to seconds after irradiation, and the biological effects take place on the order of seconds to hours after irradiation.

Approximately half of all cancer patients receive radiation therapy at some point during the course of their disease. Radiation therapy for use in the treatment of cancer can take the form of either photon therapy or charged particle therapy. Charged particle therapy can take the form of proton therapy and electron therapy. A certain type of radiation can be administered in situ by external-beam radiation therapy, that is delivered from a machine outside of the patient’s body, or by internal radiation therapy or brachytherapy [5]. Each type of radiation produces a distinct quality of radiation that interacts with tissue in a different way, which leads to different potential treatment efficacy and toxicity profiles. A broad range of other qualities of radiation exists, including heavier charged particles like carbon particles, and neighboring energy ranges of x-rays and therapeutic gamma-rays. This review discusses and briefly reviews the various forms of radiation therapy commonly used to treat medical conditions, many of which are used to treat cancer or tumors. The physics behind this basic form of treatment, as well as the issues of feasibilities and safety for usage in current medical environments, are discussed.

2.2. Radiation Interaction with Matter

Interactions of radiation with matter enclosed within shielding flasks, collimators, detectors, and various structures must be considered for mathematical model evaluation. Implausible behavior may indicate a lack of understanding or insufficient knowledge of the important physical processes involved. Knowledge of basic mechanisms of radiation-matter interactions is critical. The term "radiation" includes charged particles, ions, etc., unless specifically limited to electromagnetic or charged particles. For electron or photon shielding, classical EM theory must be employed, considering the atomic structure of matter. Energy transfers to matter, perturbation or collision processes arising from individual scattering events involve various types of electric fields. The behavior of all these processes can be well described using methods of statistical mechanics. The first part of this chapter discusses primarily theories of radiation-matter interactions [1]. The second part considers various mathematical theories used to characterize and implement such interactions. Some questions such as the potential numerical point of view and the great importance of understanding the physics in setting the numerical limits to avoid errors are also discussed. None of these discussions is complete and perfect, but if they can stimulate knowledge and encourage painstaking exploration and learning, they will have achieved their purpose and regard as their success. To avoid losing sight of the physics, a simple notation and mathematical style are employed. Thus, modern radiobiological-related topics such as track structure theory, biological modeling, cancer treatment planning, and computational methods now can be modeled more realistically and precisely [6].

3. Radiation Measurement and Dosimetry

Radiation measurement and dosimetry are necessary for evaluating the physics of any radiotherapy system. Items like on/off switches, displays, and control knobs are typically overlooked by the average user of most radiotherapy systems. On the other hand, some large, well-equipped hospitals have radiation physicists who thoroughly examine the physics of these systems, and their assessments are taken seriously. The basic approach uses a table loaded with detectors, and some reference beam quality criteria and values are suggested in the form of individual channels. This measurement and evaluation process yields a score for the unit under examination and the means for produced reports and correspondence with manufacturers to correct the defects in equipment performance [7].

Radiation measurement as a discipline has continued to grow in sophistication since the discovery of X-rays. Recent advances in high-volume computer technology have introduced the potential for improved measurement and computational techniques that can lead to new practical solutions to old dosimetric problems. However, these advances in radiation measurement have been slow to percolate down to the average radiotherapy clinic. Most clinics still rely on air-filled ionization chambers of various designs to characterize the dosimetry of megavoltage X-ray beams. The almost universal use of this term draws attention to the dominance of ionization chambers in clinical dosimetry and, to a lesser extent, their use in research applications.

Measurements of linear accelerator (linac) output and beam uniformity are typically made using ionization chambers. The most common clinical linac utilization is the treatment of cancer patients with high-energy visible Photon X-ray radiation. Modern clinical linacs generate well-collimated, dose-stable, high-energy beams of X-rays or electrons. Each generated beam requires quality checks and regular maintenance to verify safety and treatment delivery accuracy. Ionization chambers are commonly used to assure beam intensity, dose uniformity, and calibration accuracy. As the most widely used detectors, ionization chambers and their associated electronics are calibrated for traceability against a standard geometry. Large volume ionization chambers are used in reference beam rooms to validate the output of the linac and room shielding. The radiation physics of the determined parameters is summarised as follows: each ionization chamber cavity is characterised, its performance checked and recalibrated if necessary. Other issues are rapid transit of electronics, differences between measurement mediums, hardware upgrades, and non-linearity response. [8][9][10]

3.1. Dosimetry Techniques

In radiation therapy, in-vivo dosimetry is necessary to measure the dose actually delivered to the tumor. As radiotherapy technologies progress, patients receive higher doses over shorter times, thus radiation verification is crucial. Real time assessment of the delivered radiation requires the use of small detectors. Ideally, implantable nano detectors would be able to measure the dose to tissue through ionization of its atoms. The self-sufficient operation of essentially any transducer, numbering less than a few hundred micrometers, is impossible, so a larger read-out device would be necessary and the active detection volume would be limited by the signal to noise ratio (SNR) to several hundreds of micrometers [11]. For that reason, knowledge of nano dosimetry is mandatory.

Solid state nanodosimeters have been commonly studied. They are minituarized ionization chambers, fabricated in silica-on-silicon wafers due to their compatibility with micro-fabrication techniques. Charge collection takes place through diffusion, thus reading out in real time requires elaborate and expensive custom made electronics [12]. Multiple nanodosimeters need to be used simultaneously for a single measurement, increasing costs, size and packaging difficulties. To be feasible in-vivo, these devices would have to have a transplant friendly design and no toxicity for the tissue, in addition, no energy or angular dependence and low speed of sound are ideal. The reading out will require a locally implanted circuit to process the signals to digital output for wireless transmission.

3.2. Calibration of Radiation Detectors

The calibration of detectors, used in the measurement of ionizing radiation, involves a few methods. The assumptions and a few simple results are given, that agree with sensor manufacturers and some of their calibration methods. The differences are discussed. After discussing the statistical nature of radiation measurements a few experimental results are given, from which it seems proper for the end-user to check a large statistical effect as the measurements are lowered in number. Different systems employ different detector types of scintillation, silicon-based radiation pulses, gas-filled chambers, etc. They are mostly calibrated by manufacturers roughly to acceptable norms. There is some uncertainty in the calibration, before being put into use and for different applications. One may wonder how well the measurements of the manufacturer are conducted and how the count rates are compared to each other. Moreover, different application software has both its advantages and disadvantages. The count rates of a scintillator's peaks are all additive. Different estimates of the FWHM of the pulse height spectrum give different purities of the gates in the single-channel analyzers. The uniformity for different sources can be compared, and the energy of the detector may be determined with the ratio of peak to channel allocation frequencies to depths. After this delimit the integral area to estimate the net area and the purity of the spectral channel. A few differences seem important. For a Pb metal detector or a source, this operational cost is probably dwarfed by the trivial distance to the instrument and to the source effects and therefore calibration rather unlikely with bare, uncovered detectors. [13][14][15]

4. Radiotherapy: An Overview

The term “radiotherapy” refers to the medical specialty involving the use of ionizing radiation for treatment of disease. The particle types used in modern medicine and clinical studies include photons (x-rays and gamma rays), electrons, protons, neutrons and heavy ions with atomic numbers greater than 1. A more general term, “radiation therapy” includes non-ionizing radiation treatment modalities, such as infrared, visible or radio-frequency. Radiotherapy also denotes the application of ionizing radiation from sealed source applications, i.e. brachytherapy. This review concentrates on radiation sources and physics related to external-beam radiation therapy (EBRT), i.e. treatment and delivery equipment configured to direct beams of radiation toward tumor targets from substantial distance. Most of this review pertains to the use of megavoltage (MV) photons and electrons produced by linear accelerator (linacs) [4]. However, relevant concepts extend to the use of kilovolt (kV) tube- and linac-based photon devices and other machines that produce high energy electrons. Radiation therapy (also known as radiotherapy, x-ray therapy, irradiation therapy, or cobalt therapy) is a medical specialty that uses ionizing radiation to treat cancer. It is a key component of curative cancer treatment and treatment processes ensure the survival of healthy cells and normal functions. About half of all cancer patients are treated with ionizing radiation [16]. Radiation dosimetry is concerned with the determination of the quantity, spatial distribution, energy spectrum, and temporal histories of radiation in medical environments and with the quantification of radiation-induced biological effects. The latter is founded on estimations of dose, a rhythmic quantity that measures the energy imparted by radiation to matter and that depends on radiation interactions with matter. Various forms of coupling between radiation and matter convert the incoming energy into a detectable quantity. Such couplings produce a detector signal that, when interpreted, produces a deterministic retrospect of the incoming radiation.

4.1. History of Radiotherapy

The first therapy using ionizing radiation was performed in Paris, while the French capital was proclaimed the capital of the “City of Light.” After observing the beneficial effects of x-rays in France, Germany and the United Kingdom, the first clinical application was applied on January 12, 1896, at the hospital of Salpêtrière. Stuffed with unwell people the patient waited during 20 minutes to be electrocuted. This was the first bedside teletherapy machine. The hard x-rays, “made in France,” were used to treat these patients, who were usually suffering from “epithelioma.” They rarely had “indications for surgical removal,” but they were peaceably cured in due course. Radiotherapy was arrived in the United Kingdom by the West End hospital, taking possession of a magnificent x-ray apparatus.

The success of this first source of radiation assured the advent of light-advanced beam therapy in Europe. In 1901, Ernest Hall, a London physician, acquired a 900 mean tube for a limited exposure, which was used with reported success against transitory fibromas. However, orthovaluga “rosodontia” and half-destructive standard tube “perichimials” was then emitted on air in France. According to physicists’ prophecies diffusion of bethel rays and then of soft x-radiation was expected to prevail at that time. With the safety of the “skin sequentions,” activated tubes fell into disuse. Subsequently come forth tubes “nervous x-ray” or equally TPT plates “nervous attrition” for the curative use of invisible.

By enlarging these epitomizing patent tube at the expense of costs and profits, the high voltage generators of considerably powerful, soft, or ultra-soft x-ray were enabled by inventors or acquiring patents “from rus to tumtum,” which ensures a measure of worldly prominence to reflect upon for earlier unnamed benefactors now somehow of yesteryear. Therapies of deep-seated cancers with these 20-30 kV apparatuses began after the first or second world wars. These included objectives of aspects as that of ‘mislaying a pathology in a body,’ while they were already known drawbacks [17] [18].

4.2. Principles of Radiotherapy

Radiotherapy Physicists and Radiation Oncologists devise radiation treatment plans based on pretherapy imaging information and the laws of radiation interactions with matter. Equipment that generates the desired radiation and associated computer and mechanical systems deliver the treatment plan to the patient. All information and calculations required to deliver a treatment plan must be included in a treatment record or a treatment planning system transfer file. The treatment records and transfer files are rigorously checked and signed. The delivery process must be closely monitored with regularly maintained quality assurance protocols [16].

Radiation oncologists and radiation therapy physicists manage these complex workflows to ensure safety and accuracy. For example, exponential attenuation of x-rays in the head of a linear accelerator is used to devise a transmitted primary dose rate determination. Auditing of all treatment records is illustrated by a means of generating an instantaneous report of the number of fields delivered and whether any more complex field arrangements need auditing. Over time, these methods are developed and refined using inexpensive, available, existing software.

Orbital viewing locations and a head of institutional use-adjusted quick reference for those viewing locations. This practical example illustrates some of the ways team members professionally engage in advanced understanding and solving of problems in complex, involved systems of modern clinical radiotherapy. Pictorial exemplars are illustrated for both treatment planning and treatment delivery, and practical advice is offered on how to better work and operate within complicated systems. It is seen that institutions and healthcare organizations need a greater understanding both of what skills a team member possesses and how to best use them.

Cancer cells develop when a healthy functioning cell or group of cells acquires a mutation which, for various potential reasons, affords them a reproductive benefit. Cancerous cells continue to grow, or to travel, into and over other boundaries, both tumor edges and tissue boundaries, into healthy tissue. Tumors grow to clinically significant sizes over periods of years, decades, and in some cases longer. While they do so, they are constantly thinning out and characteristically dying back towards a lesser evaporating cell population. Most treatment options aim to intervene when this topic is popularly considered curative and the tumor burden is still small relative to the volume of healthy tissue. [19][20][21]

5. Modern Radiotherapy Equipment

Radiotherapy (RT) is one of the most effective cancer treatment methods, along with surgery, chemotherapy, and immunotherapy. RT is based on ionizing radiation and produced using radiation sources such as radioisotopes or x-ray machines. Although using radioisotopes for therapeutic purposes dates back to the 1930s, the evolution of x-ray machines and clinical linear accelerators (LINACs) drastically improved the potential applications of RT [22]. In the early 2000s, after introducing the multileaf collimator mechanism, the complex design of modern CNC-based RT machines became a reality. At the same time, improvements were made to dose calculation algorithms and safety and monitoring systems; hence, instead of using external radiation sources for patient treatment, it was possible to treat cancer patients with more precise doses and customized treatment plans using a LINAC-based modern RT machine.

The basic physics principles of these machines will be explained during the inherent CT simulation and treatment planning and delivery phases for the Radiotherapy-Physics thematic area of the International Conference for Computer Applications in Industry and Engineering. In this thematic area, anatomical delineation, contouring, treatment planning using advanced treatment techniques (including highly sophisticated knowledge-based planning), and the application of deformable and rigid image registration will be covered [23]. The principles of conventional, batch, and systematic quality assurance measurements during autonomous in-house testing and factory-accredited machine calibrations will then be presented for verifying mathematical, dosimetric, and kinematics models.

Throughout the treatment process, monitoring systems or real-time verification procedures are applied by molecular MXAs (multi-X-ray acquisition systems) or by modeling methods. In addition, the subsequent delivery of advanced treatments using small-spotness high-dose-rate flattening-filter-free beams (IMRT, such as VMAT and SBRT), high PtD placement frequency brachytherapy sources and stepper-in-and-out CAT-based applicators, and mono/dual-isotope, multi-camera-based SPECT imaging-guided procedures, which are successfully carried out in CC/NCC institutes, will be described.

5.1. Linear Accelerators

Linear accelerators (linacs) are widely used in the creation of synchrotron facilities because they produce fleet particle beams from an ion source and accelerate the beams to the energy and intensity required to be injected into a synchrotron. As a result, there is a wide range of applications based on linac technology, including free electron lasers, neutron generation, X-ray generation, and medical therapy. The most prominent application is in the field of medicine, where electron linacs are an alternative modality of choice not only for the production of high energy X-rays for use in the treatment of deep-seated tumors but also in electron therapy. Like most medical linacs, the left linac is based on a traveling wave modulator design with a peak power of 24 MW and is designed to produce X-ray photon beams with an energy range of 6 - 18 MV for radiotherapy treatments, while the right linac is a compact design based on the single stage dual-frequency 1.3 GHz / 2.6 GHz engineering development and experimental linac and is intended for the treatment of skin cancers using a 230 MeV electron beam [24].

Linacs for medicine and research applications create energetic electron beams that are largely collated into a narrow pencil beam that propagates through a vacuum at the speed of light and eventually strikes a target to produce either X-rays or neutrons. In order to understand how these modern linacs function, it is important to understand the fundamentals of linac design. Medical linacs use the energy of colliding electron beams to bombard a tungsten target and produce photons before allowing the most collimated beams to reach the patient. Electron beams are well suited for the treatment of tumors just beneath the skin because they produce no radiation beyond a particular depth into tissue and can use high dose rates that allow shorter patient treatment times [25]. The most widespread medical linacs are designed to produce X-rays with energies in the range of 6 MeV to 18 MeV. These high energy accelerators improve treatment efficiency, as the radiation diverges faster when it exits the treatment head, producing beams with larger profiles and allowing field sizes in excess of 40 cm × 40 cm.

5.2. Brachytherapy Systems

Several types of brachytherapy systems are available today based on the different implementations of the above concepts. Most of these systems use a combination of an applicator, a high dose rate (HDR) source, and a treatment planning computer. Cobalt-60-based systems are mostly used for skin brachytherapy with a categorical demand for low-priced treatment systems. Iridium-192 based machines are broadly deployed for specific treatment such as gynaecological, prostate, and breast cancer brachytherapy. Such machines with advanced features are essential such as 3D treatment planning for better dosimetry and machine safety [26]. With the use of newer treatment protocols such as high fraction doses, multi-catheter implants with larger number of sources, and larger treatment volumes globally, there is a need for more advanced delivery devices incorporating larger number of channels and improved safety features.

HDR brachytherapy has drawn much more attention in the field of radiation oncology recently, partly because the increased compatibility of HDR treatment and a linear accelerator based external beam treatment machine, greater safety afforded to patients and staff, improved coordination between external beam treatment and brachytherapy, and the advent of digital imaging and memory-based treatment planning systems [27]. It is widely adopted worldwide nowadays for post-operative treatment of breast, cervix, and prostate cancers. Computed tomography (CT) based treatment planning systems contain translation, rotation, gantry angle, and collimator angle to specify the geometry of the brachytherapy under the assumptions of isotropic photon emission and uniform dose distribution from brachytherapy grains.

5.3. Image-Guided Radiotherapy (IGRT)

Image-guided radiotherapy (IGRT) is a technique that aids in tumor localization and translation matching, aiming to tumor and/or normal structure motion before the treatment delivery [28]. During the treatment delivery, IGRT recording enables the verification of treatment setup uncertainties. In IGRT, patients' anatomical imaging data acquired by imaging devices immediately before treatment delivery which are consistent with the planning computed tomography (CT) data are used to localize the exact tumor position. An adjustment of treatment setup prior to the patient treatment is done to achieve the precision/accuracy multilayer information of the tumor volume.

Target localization accuracy is indirectly assessed, which is done by an analysis of radiation treatment errors based on analysis and matching of pre-delivery CT images with simulation CT images of patients who are treated using the treatment delivery devices. Alternatively, the quality/accuracy of the treatment is more directly verified through the recording of the radiation beam verification images immediately after the treatment delivery and matching these images with the simulation beam verification images of the treatment plan.

The entire IGRT process can be regarded as a function of matching of the anatomical images or the verification images, including major processes of patient centering, changeable image parameter and matching functionality [29]. Thus, IGRT involves also key relevant techniques for management of the anatomical images or the verification images. Current state-of-the-art technical implementation of the entire IGRT process is described with examples. Over-55 research and developments are summarized as diverse aspects and categorized into areas/treatments of image acquisition/quality, image management/representation or review, image matching/refinement, verifying/option/feedback results and registration performance evaluation.

As an aid of localization technique in radiotherapy, IGRT does not replace other immobilization and patient setup techniques. There also exist complementary techniques whose accuracies should be regarded to maximize the effectiveness of radiotherapy. For example, diagnostic imaging techniques, x-ray CT (or MRI) scanners, and scanning protocols are likely different and/or incompatible from those of imaging in IGRT equipment. Nevertheless, if only the imaging properties of IGRT imaging devices meet the minimum standard and requirements, the IGRT process can be reasonably guaranteed.

6. Treatment Planning Systems

A treatment planning system (TPS) uses a computer program to calculate a treatment plan for the complex and often manual processes performed by radiation oncology physician, medical physicist, and radiation therapy technologist [16]. At the highest level, treatment planning for radiation therapy begins with a computer-based graphical user interface that invokes a series of programs, calculates results, and presents those results to the end user (analyst). In the middle is a complex computational back-end that retrieves physics-based data from disk, potentially transforms them, performs calculations, manipulates results, and writes output files for subsequent input. Transfer of data among separate components often requires serialization of data into ASCII or binary files which can impact performance. A TPS may also have custom rendering code to allow graphical presentation of results. In both the graphical front-end and the back-end calculation code, there are significant modeling assumptions that have important implications for the adoption of TPSs for IORT.

Computations performed by the TPS consist of significant modeling assumptions regarding beam models, dose calculation approaches, and treatment dose/volume calculations [30]. For example, a vendor-provided TPS might include Linux servers for Monte Carlo-based calculations that are not examined when the TPS is installed. Typical beam models include look-up tables based on various beam characteristics. The TPS might include beam data components at data collection (output versus depth, percentage depth dose, beam profiles, etc.) and at use (beam shielding, isodose cone generation). These and other models could be subject to accuracy limitations, difficult verification, and discovery of errors. Computing the dose delivered by a treatment could consume anywhere from milliseconds to hours of CPU time, depending on the size and complexity of the calculation (treatment) and type of algorithm utilized. Commercial code systems implement a range of dose calculation algorithms, all of which will require testing and validation when implementing a new TPS for IORT. Implementing a new calculation engine to existing TPS could also require large development resources.

6.1. Role of Treatment Planning

Treatment planning involves estimating the dose distribution of a treatment plan. It involves both computerized optimization of the beam set and treatment plan quality assurance. The two further aspects of treatment planning are: (1) specification of the treatment plan parameters such as dmax, dmin, and normal tissue dose volume constraints, and (2) an evaluation of the treatment plan [31].

Advanced five-dimensional CNC treatment machines create paradoxical challenges on a number of fronts, including higher complexity of the treatment plans and rapid delivery. One response has been an increased importance of information technology and software development in this field. Modern treatment planning systems have continuing roles in making beams and computing plans. Important clinical considerations beyond just dose-volume considerations must also be taken into account. Quality assurance techniques incorporating the measurement of 3-D dose distributions are evolving rapidly. Notably, a measure of planning quality assurance which quantifies the closeness to the best theoretical plan is an interesting topic to follow in the field of treatment planning [16].

Computerized optimization of treatment plans for radiotherapy generally operates in three steps. In the first step, the treatment plan start parameters are defined, including the beam set and angles, the axial dose distribution of each beam treatment and the beam treatment modalities. In the second step, a treatment dose map is simultaneously generated from the start parameters. In the third step, using this dose map, a measured dose distribution is simulated with correspondingly to the computed dose map.

6.2. Dose Calculation Algorithms

About two decades past, linear accelerators with multi-leaf collimators heralded the introduction of three-dimensional conformal radiotherapy systems. Despite this progress in radiotherapy technologies, after a new generation of more sophisticated medical imaging diagnosis devices along with the implementation of imaging reconstruction for positron emission tomography and magnetic resonance imaging have come up, treatment planning systems have only been improved slightly so that it is still based on a computerized implementation of mathematical models on the basis of 2D or 3D target area. These pre-RT process systems have certainly impeded the implementation of target conformal radiotherapy. To cope with such a stalled development in this area, an investigation into the advent of revolutionary treatment planning systems based on a completely different paradigm is undertaken. A statistical physics–based Fractal KMC treatment planning system consisting of photon, electron, and heavy ion dose estimation engines is developed. This treatment planning system has demonstrated its capabilities of performing new generation planning methods.

Dose calculation algorithms are a crucial part of treatment planning systems (TPS) in external beam radiotherapy. Of many dose calculation algorithms available for clinical use, it is important to understand differences in physical modeling of radiation transport and limitations of dose calculations in the context of their impact on target coverage and critical organ sparing. The choice of a dose calculation algorithm can also affect the magnitude of the observed difference, be it large or small, therefore it is important to evaluate thoroughly the practical relevance of these differences for the specific clinical situation before a decision is made regarding the switch of dose calculation algorithm in clinical practice [32].

7. Quality Assurance in Radiotherapy

The practice of radiation oncology has undergone rapid advancement over the last three decades, undoubtedly changing the face of the discipline. The type of external beam treatment of cancer has shifted from two-dimensional analogue treatments to three-dimensional (3D) image-based conformal radiation therapy using linear accelerators with sophisticated treatment delivery systems, such as multi-leaf collimation and robotic and tomograph treatment head. With the embedded 3D treatment planning computer systems, complex brachytherapy procedures can now be undertaken. In addition to treatment planning and delivery quality assurance (QA) systems, computerized information systems are widely used to manage patient treatment records and verify plan deliveries. The rapid development of complex systems and treatment modalities in a relatively short time has raised real concerns over the safe implementation of the new technology in practice. Regular review and benchmarking of both existing QA processes and computerized systems by competing groups in an institution, or between those from different institutions, have brought added transparency and credibility to the QA process. In some institutions, efforts are underway to make the measurement QA results publicly accessible to fellow group or state-wide peer review. The process of QA in clinical practice does not take place in a vacuum. Quality assurance (QA) programs are products of the medical, scientific, and technological developments of institutions and radiotherapy communities, driven by externalities, feedback, and shaping interactions between various stakeholders. The QA process and its procedures are determined by the professional environment, delivery technology, resource, and many other institutional factors. Consequently, QA programs are not developed and implemented uniformly across institutions. For example, not all institutions implement a rigorous assessment of the commission process as recommended by various organizations. The QA programs need to be customized and tailored to effectively meet the safety and reliability requirements of the individual institution.

7.1. Importance of Quality Assurance

In the last decade there has been an increase in the application of 3D-conformal high-energy ILR to treat early single brain tumors and metastases with greater accuracy and precision. These developments have led to the incorporation of another aspect of more complex treatment planning systems that can perform virtual treatment planning and leaf sequencing to instruct the dose delivery system, which is termed sophisticated treatment techniques. Complex treatment planning systems accept the anatomical data in various formats for delineating targets and critical structures. The nature of planning techniques for delivering 3D-conformal plans is inherently complicated because of the difficulties in determining optimal beam positions, shapes, and weights and greater delivery complexity when it comes to volumetric-modulated arc therapy (VMAT), intensity-modulated arc therapy (IMAT), and single isocenter multi-pencil beam systems. These advances in treatment planning, planning imaging modalities, and dose delivery systems are the need for a suite of machine-independent software.

A dose delivery system is an integral part of a modern radiation therapy department for the reliable delivery of the prescribed dose to a specific volume. The dosimetry protocols developed by various organizations are useful in the characterization and performance evaluation of the treatment verification systems. In addition, to achieve the goal of “mistakes should not happen” in treatment delivery, compliance with internationally agreed standard tests for modern teletherapy systems is important. These tests imply the use of a calibrated regular verification and certification procedure at the data acquisition or planning dose delivery system to mitigate treatment delivery discrepancies. The actual work is centered on a careful understanding of the role of various QA measures on planning and delivery machine-dependent and -independent dosimetry phantoms [33].

Most complex treatment techniques in a modern cancer therapy facility employ safety interlocks within a computerized dose delivery system to prevent inadvertent patient treatment deliveries on the machine. This is done by checking whether the treatment is in “ready” mode, during which the QA checks are not done or are incomplete. This closed control loop scheme is called machine-independent dosimetric QA [34]. A retrospective study on once-a-year barrel and diaphragm integrity checks was performed and histograms of the values were scrutinized. These analyses should also be a part of a sophisticated treatment verification machine in a modern radiotherapy service. The present studies cover critical QA checks for various treatment verification systems to be performed 1 day before treatment delivery.

7.2. Quality Control Procedures

Quality control procedures for a narrow range of modern radiotherapy equipment now defined under a Canadian Association of Radiation Oncology/Canadian Cancer Society funded initiative. In 2005, the Interprovincial Partnership for Cancer Control (IPCC)-funded report on the Careful Management of Radiation Therapy Equipment pointed to significant variations across the country in radiation therapy equipment quality control standards. Significant gaps were also identified in the national literature concerning quality control procedures. To address these issues, the recently completed Canadian report on quality control for modern radiotherapy equipment outlines standard quality control procedures designed to be national in scope. The equipment covered are the linear accelerator, multi-leaf collimator, image guidance systems for linear accelerators, diagnostic quality kV X-ray systems, radioisotope sources for brachytherapy, treatment planning systems, and modern electrometers. Additional quality control guidelines that might be of interest to institutions performing radiotherapy are: a protocol for patient dosimetry using high-energy electron beams, a review of procedures to reduce risks associated with radiation therapy, and a report on quality control for blood irradiators and related equipment. All reports were developed by Canadian practitioners, updated with a 2019 Canadian radiation therapy equipment database, and anticipated three-year revision cycles. Adaptable national standards for modern radiotherapy equipment quality control provide the motivation and framework to tackle more complex equipment types not yet included and for which it might be more challenging to develop general procedures.

Many innovations in radiation therapy, particularly in the last ten years, are due to enhanced imaging systems as they allow direct assessment of patient anatomy, thereby improving the accuracy of treatment. These technology advancements have not only increased the complexity of radiation therapy machines but also the need for quality assurance to guarantee that treatment is delivered correctly. Most people are familiar with the fundamental pyramid structure used to ensure safe and reliable operation of radiation therapy facilities. This begins with using established designs, followed by correct installation and commissioning prior to routine clinical use, and finally providing daily quality control and regular performance checks. Most quality control tests are simple to implement and do not require extensive training. However, two major radiotherapy systems were recently introduced, and new quality control tests are required: the electronic portal imaging device (EPID) system and the cone beam computed tomography (CBCT) system [35]. As electronic systems have been widely used in diagnostic imaging, the quality control tests for the EPID system were adapted from the American College of Radiology guidelines. Quality control tests for the CBCT system were developed based on the published testing methods and the results of the feasibility study conducted initially at the Cancer Centre [36].

For any quality control tests, the first step is normally to conduct feasibility studies to examine whether the tests can be performed practically in the clinic. There are many factors to consider, all of which need to be balanced. Performance tests that are more complicated but are better able to identify malfunction and may be clinically more important are of little value if it takes extra resources to implement or are more subjective, rendering the results open to interpretation and debate. Ideally, for each test, assessments of the degree to which they can be implemented in the clinic and standardization of the procedures to guarantee that different users would obtain similar results are needed. In this regard, automation should be considered to eliminate user bias performance tests such as collimator and electronic gantry angle accuracy tests. Automated tests also make it possible to save historical data for future analysis of performance trends. In this early period of implementation, however, the focus was on simpler tests such as qualitative assessments.

8. Clinical Applications of Radiation Physics

When an atomic nucleus is bombarded with a photon of energy exceeding the binding energy of one of its nucleons, then an electron is ejected from the nucleus and the nucleus becomes an isotone of the target [6]. This interaction is called photo-disintegration. Since X-ray photons emitted from a medical linear accelerator are relatively high energy photons (7-18 MeV) they can produce radio activity in both target and surrounding area. As a result, it is very important to estimate the radioactivity produced near the accelerator. Since certain optimization and safety considerations arise while working with radioactive sources, interest in estimating the activity distribution around a medical linear accelerator has grown. Various nuclear reactions produce activation products as a result of photon interaction with ordinary water.

There are many interaction mechanisms responsible for the activation produced by photons which are Compton scattering, pair production and photo-disintegration process. Monte-Carlo codes calculation allows to mention all the pre and post interaction phenomena in calculation time. But the calculated data must be verified with experimental results in order to be of practical use for physics and engineering applications. The experimental data for a target place close to one of the collimators has been given. The photo-activity of many nuclides produced in a water target by 18 MeV photon interacting with a medical linear accelerator is determined using GPUMCD code with standardized evaluated cross-section data [23]. It has been seen that for a target closer with the source, extra care must be considered.

8.1. Radiation Therapy Techniques

About half of all cancer patients undergo radiation therapy in the fight against cancer. The use of high energy radiation in cancer treatment derives from the interaction of charged particles (electrons and protons) or uncharged particles (photons and neutrons) with matter, primarily tissue, for the initiation, absorption of energy deposition and cell kill mechanisms. The absorbed energy per tissue mass, the radiation dose, is measured in Gray (Gy). Modes of tissue irradiation can include: • External-beam radiation therapy (EBRT) • Internal radiation therapy / brachytherapy • Systemic radiation therapy There are two major types of radiation: Photon radiation (x-rays and gamma-rays) used in most conventional cancer treatments today, and particle radiation including high energy electron beams used to treat tumours close to a body surface and heavy nuclei such as protons and neurotrons used to effectively irradiate deep-seated tumours [37]. Like all other forms of electromagnetic radiation, a photon propagates in a straight line at the speed of light in a vacuum. Part of the radiation crossing a medium is absorbed by it and the rest changes direction, loses energy, and is said to be attenuated. This attenuation is quantified by the mass attenuation coefficient and is essential for dose computation. The relative biological effectiveness (RBE) of radiation is its efficiency in cell killing and is used for the clinical system of dose estimation called total dose. Radiations with low LET including x-rays, gamma-rays, and fast electrons have energies of about 10-10 eV and result in relatively small amounts of energy deposition by ionisation. Low LET radiation is thought to kill cells largely by causing sublethal (repairable) damage to DNA [4]. Radiations with high LET such as thermal neutrons, protons, and alpha particles lose energy more rapidly than low LET radiations and lead to higher energy deposits by direct ionisation. High LET particle radiation results in large damage clusters consisting of multiple, closely spaced ionisations on one or more strands of DNA. Since radiation interacts with human tissue entirely within the ionisation chamber, the rate of ionisation due to energy deposited in the tissue by the radiation is measured in gray and referred to as the dose. All clinical radiation therapy systems are designed to deliver a well-defined dose distribution in space and time to a target volume containing the malignant cells and deliver a relatively smaller dose, referred to as the optimal 'safe' dose, to surrounding organs at risk (OAR) comprising normal cells. A typical 6MV linear electron accelerator (linac) has a gantry that can make arcs of 360° and its collimators can be turned on and off automatically to shape the radiation beam. Adjusting the aperture shapes, gantry angles, beam energy and collimators allow the linac to treat various tumour size, shapes, locations, and depths across different patients.

8.2. Combination Therapies

The vast majority of cancers are treatable using the available treatment modalities; however, many conventional treatments will inevitably end with recurrence and metastasis. Increasing treatment specificity while reducing collateral damage remains an active area of research and development in these areas. Combination therapies which traditionally are drugs plus radiation are some of the most easily translated treatments, as applications already exist, are often economical, and will require minimal additional effort in obtaining regulatory approval or new training. The movement of additional, contemporary technology into radiosensitization is explored here on the basis of evidence and availability of equipment [37]. Monoclonal antibodies and drugs that specifically target oncogenes and effects are discussed predominantly, although many of them have additional effects which differ from the traditional assumptions of the same effects/class/collection of effects based theories. Other possibilities offer complementary screening, application on similar timescales to treatment, and ease of target selection. Recent reviews on these aspects of combination therapies target discussion at areas likely to yield immediate advancement in patient care. Additional technologies which, so far, have been utilized in small animal research but which, given the prospect of an outbreak of this capability in a few years, warrant consideration for immediate purchase in advance of future protocols are also discussed. This includes developing methods of non-invasively and nondestructively observing the measurements and metrics of cellular biological outcomes of radiation treatment and their coverage by drugs or drugs action. Another major area of recent interest, development, and discovery in radioresistance has been on the means of interrogating the reliability of previously learned assumptions concerning the molecular origin of cyto-radiobiological response to projected outcomes by traditional means. Additional methods of treatment screening are discussed amongst these; technology which can assess hundreds of thousands of treatments in the time it takes to deliver one, ready for advanced metrics which can find and test novel treatments in the plethora of available conditions. [38][39][40]

9. Emerging Technologies in Radiotherapy

Technology has always driven advances in radiotherapy treatment. We describe the main technological advances in radiotherapy over the past decades for the treatment of nasopharyngeal cancer (NPC) and highlight some of the pressing issues and challenges that remain. With a goal of controlling NPC, improvements in radiotherapy treatment delivery that maximize tumor dose and minimize normal structures' dose disparities have had an important role in improving tumor clearance and toxicity outcomes. To achieve these goals, advances in treatment machine technology from 2D to high-energy 3D machines, and then to the implementation of various techniques such as intensity modulated radiotherapy, volumetric modulated arc radiotherapy, and advanced image-guided radiotherapy for accurate treatment delivery and macroscopic tumor control have become standard in clinical practice. With the prognosis of NPC dramatically improving, side effect management, surveillance, detection of recurrence, and salvage treatment of recurred NPC have gained more prominence and are of increasing interest [41].

Nevertheless, the ill effects of radiotherapy on intentional organs that are in close proximity to the radiation treatment fields are emerging areas of research. Cancer is a major public health challenge globally; nearly one out of every six deaths is caused by this disease. Early-stage cancer is managed with surgery, which is the best local therapy, followed by adjuvant treatment with chemotherapy and/or radiation therapy. Late-stage cancers where surgery is not possible are largely treated with chemotherapy and/or radiation. as hormone therapy, targeted therapy, and/or immunotherapy. Among these, radiation therapy (RT) uses high-energy radiation to kill cancer cells by damaging their DNA [37]. This results in the killing of cancer cells with minimized damage to normal cells. The importance of radiation treatment lies in the fact that around half of all cancer patients need radiotherapy during one or the other stage of their treatment. The main types of radiation used to treat cancer are photon radiation, which have been in use since the 1920s, and electron beams, which were introduced later. Particle radiation, such as proton and neutron beams, has gained popularity in recent years and has been shown to be very effective in treating deep-seated tumors, such as those in the brain which are difficult to reach with conventional therapy.

9.1. Proton Therapy

Among the studied hadron beam options, proton therapy has gained the most large-scale clinical acceptance and applications. This is because high energy protons can be relatively easy to generate, penetrate deeply into the tissues, transport well, and selectively stop close to the tumors [42]. With the understanding of the technical characteristics and applications of proton beams in health care, the design, manufacture, commissioning and operation of proton therapy teams and systems is aimed to provide a reliable and safe proton therapy modality which can directly compete with other modalities.

The specific ionization of charged particles in matter is not a constant value but a function of various parameters including charge and mass of particles, energy and type of matter, and also depends on the degree of excitation it transfers to matter. Protons with the same specific energy loss are more efficient than photons in treating tumors where low dose is desired outside of tumors. They have better lateral and range distributions than heavy ions. Compared with protons, heavy ions have better resiliency to small angle scattering but are much more complicated and expensive.

Proton therapy systems mainly consist of proton sources, accelerators, beam transport systems, treatment planning systems, patient position and immobilization equipment, control systems and machine rooms. There are more static treatment heads and shoulder complexes than linacs to prevent scattering in proton passive scattering systems. Proton therapy systems require more complex structure and larger space compared to linacs or rotating gantries. Multiple-layered degraders are used to modulate a primary proton beam with much higher energy to produce a clinically usable secondary proton beam in PPSs. They can also make use of a secondary proton beam with flat or Gaussian spot distribution produced by collimation. Compared to photon treatment systems, the target rooms housing proton therapy systems are built at much thicker shielding walls and are more complicated with more control and safety systems. Despite the high cost of equipment and facilities, safety and reliability of proton therapy systems are still king. Because proton therapy systems are, by nature, software-based systems composed of high-precision, high-performance and high-reliability equipment, the safety of their design and operation is mainly determined by their assurance of software quality.

9.2. Adaptive Radiotherapy

Radiotherapy, one of the major treatments for cancer, has undergone immense evolution since its discovery. From the first treatment of cancer using X-rays to the rapid advancement of medical imaging technologies, like MRI and CT images, radiotherapy has seen many revolutionary changes. In the early stage, classical telecobalt sources and high-energy linear accelerators were introduced as external beam radiotherapy devices. The traditional radiotherapy workflow included the following steps: 1) Initially, patients underwent a CT scan to produce a CT plan. The treatment plan was designed and optimized based on this CT scan. 2) While the treatment plan was based on the initial CT, the patient was treated with this treatment plan throughout the treatment course, which lasted for weeks. However, as the treatment progressed, patients might undergo some changes in their body, including tumor shrinkage and loss of muscle mass due to radiative response [43]. The treatment determined based on initial CT would no longer be optimal for the later treatment sessions. This might cause suboptimal clinical outcomes and not the best patient compliance. Adaptive radiotherapy (ART) has been proposed to resolve this issue. With ART, new images are acquired before each treatment session. The 3D image registration and image-to-dosimetry transformation technologies are developed to compare deformable image registration images of various types. Treatment plans can be replanned based on the newest images, and the plan is adapted to the changes in the patient effectively.

ART can be conducted in two ways: online and offline ART. With online ART, the initial plan is adapted to the newest images before every treatment session. The temptation of online ART is that treatment plans can match exactly to the anatomy of patients. However, due to high workloads and complexity of the plans, online ART is still only feasible for some special anatomical areas, such as the eye. With offline ART, ART treatment plans are generated for the patient after a certain period of radiation treatment. Time-consuming anatomical and dosimetry image comparisons are implemented to select photon and proton treatment plans. The replan accuracy for ARIEL planning methods can be achieved at a level comparable with that for DBTRR. The biggest advantage of offline ART lies in its wide applicability. For most of the patients, the bolus for the plan remains the same across treatment. And the prior plans created by other methods can still serve as a better basis for ART. With the convenience of energy compensators, offline plans from B-ITEA can be used for adaptive dose delivery. [44][45][46]

10. Regulatory and Safety Aspects

The use of medical radiation and its implications for patient, medical personnel and the public has attracted a lot of scientific attention. The first serious health hazard arising from the use of X-rays occurred in 1896 when a radiologist from Saint Louis developed the first case of radiation dermatitis [47]. Other examples are the A-bomb survivors in Hiroshima and Nagasaki presenting with hematologic disorders following the acute exposure and subsequent cancer development [48]. With the advent of computer tomography (CT), it is now well-documented that whole body CT's might expose patients to >10 mSv exposing them to a significant risk of radiation-induced cancer. Besides the documented serious health hazards arising from the use of X-,γ- and β-radiation, stochastic and deterministic radiation effects on health have been enhanced by the amalgamation of regional and new international atomic requirements. The worldwide adoption of alternative energy sources such as nuclear power promotes the current dialogue on security, and the civil applications of the non-military uses of radiation sources and the impact on their safe use and security following accidental, intentional or negligent exposure. Medical applications of radiation, primarily in radiotherapy, nuclear medicine and diagnostic radiology, but also in dermatologic and other procedures, contribute to the worldwide and population radiation doses similar proportionately as building the containment dams and toilets for waste disposal or deposited in repositories. Medical radiation doses in the USA are reported at about 3 mSv/y of public exposures from diagnostic radiology or 0.5-1.0 mSv/y in France from the use of high energy medical X-ray machine units. Efficiencies of convenience examinations have been propensity to growth in the quest for productive healthcare. Consequent the increasing incidence of thyroid cancer, occipital meningioma and brain tumours associated with the exposure from medical radiation, mainly from CTA's, have lead authorities and different stakeholder parties to reevaluate the medical exposure framework, both nationally and internationally.

10.1. Radiation Safety Guidelines

Radiation therapy is one of the fastest growing treatment methods for cancer patients. Precise dosimetry across the entire clinical dosimetry chain is required in delivering radiotherapy. Today many countries and regions without an existing QAT have the opportunity to implement a modern QAT based on the ARPANSA system. However, considerable financial and human resource support will be required to implement and sustain the QAT. Some developing countries may take years to establish, implement and sustain a national QAT [7]. Nevertheless, the globally accepted principle of developing a QAT suited to fit the needs, resources and constraints of the nation is endorsed for these countries. Other challenges facing the world's QATs and under-invested countries, and some recommendations to address them are highlighted.

Although much has been accomplished in improving standards of dosimetry in radiotherapy, several ongoing challenges continue to threaten treatment dosimetry. An ongoing challenge for

QA in teletherapy has been the limited technical capabilities, resources, and systems for tracing radiation dosimetry to high-energy units [49]. In the developing world the national metrology institutes that provide national QATs for radiotherapy are poorly resourced and may lack high energy standards. Among the world's QATs there is considerable disparity in resources, governance, skills, and capabilities. Some QATs are poorly resourced, are narrow in focus, or poorly govern the use of resources and draft more effectively executed plans for deploying the resources. This may lead to ineffective use of resources and poor sustainability for the QAT.

A participative approach involving users and a diverse range of stakeholders in developing the concept and design of the QAT is recommended. The free input from the expertise in the user community plus the participative approach to implementation is likely to lead to a less cumbersome and more effective QAT. Ensuring that there is sufficient backing and empowerment of the QAT, plus transparent governance on the use of resources is also emphasized. A recommended approach for expanding the reach of the national users is to convene free forums to discuss dosimetry amongst the remoter users. Added effort to seek external sponsorship, and to foster and seize mutually beneficial synergies with different units is also needed. The latter could include agencies, institutions, hospitals or departments engaging in supplier and researcher roles.

10.2. Regulatory Frameworks

National and international regulatory bodies have developed and refined standards and recommendations in response to technological advancements in high-energy radiation sources in medicine. These include dosimetry-related recommendations for planning and quality assurance of external photon and electron beam radiotherapy, as well as on photon and electron beams for its therapeutic use in medicine. Similar recommendations for brachytherapy widely adopted were proposed on control of optical radiation, laser device use, and enhancement of patient safety. Recently, there are ongoing discussions on developing guidelines on the epidemiology of clinical consequences of medical exposures to high-energy ionizing radiation and electromagnetic waves including ultrasound and MRI.

Even the more widely accepted recommendations or standards often have been considered to be advisory recommendations and have not yet been mandated by any national regulatory body in many countries. Without any national regulatory approval, medical physicists, manufacturers of radiotherapy equipment, and standards organizations in independent or volunteer organizations have been actively participating in the interactive and on-going process of developing guidelines and recommendations. Eventually, the process has led to maturation and implementation of good cooperation in the medical physics community among various organizations sharing a good common understanding. The newly developed standards and guidelines have been actively utilized in daily practice by various national and local organizations for quality assurance and risk assessment of equipment failing to comply with the standards.

There have been numerous and widespread implementations of the recommendations and standards on radiotherapy equipment. Modern medical linear accelerators have implemented all recommendations and standards. Eventual upgrading of older machines as well has been discussed for better understanding of safety design principles, features, and operational functions and for developing data flow in automated software environments. Strategies on licensing and routine inspection of protective shielding, procedural design for new machine installation, training of operators on safety issues and principles, and relevant regulations and codes of practices on safety standards modeling misuse or failure modes of machines to pro-actively find out or resolve any non-compliance issues have been well documented and reviewed.

15. Conclusion

Radiation Physics and Its Applications in Modern Radiotherapy Equipment has provided useful information for understanding radiation physics and its applications in radiotherapy, as well as a brief introduction to the basic mechanisms behind the functioning of radiotherapy equipment, such as linear accelerators and brachytherapy equipment. Due to the important role of physical principles in new radiotherapy equipment and especially the inevitable relationship of findings with physics, it is necessary for a radiation oncologist to be sufficiently informed about these issues. Produced from exciting and complicated physical phenomena, new radiotherapy equipment is much on the move in providing more modern and more effective methods of tumor treatment in the radiotherapy department. In addition, knowledge of radiation physics is necessary for properly using radiotherapy equipment and for improving this equipment in producing better product output. The equipment engineer, who generally is well-aware of physical principles, can only deliver a well-functioning, easy to use, understandable and reliable equipment if a good communication with the radiation oncologist is attained. The more knowledge a radiation oncologist has of radiation physics the better will be such a communication. The idea of writing a present article was born many years ago by Archimedes' finding, "Give me a place to stand on, and I shall move the earth." When discussing a piece of information, a better achievement can be accomplished for better understanding if the proper background is given. Moreover, a more uniform viewpoint toward a matter can be obtained. Similarly, a better communication can be flagged among a group with a more common background knowledge. Thus, a better treatment for cancer patients with more modern means is hoped to be afforded by this article. The authors are grateful to the people who had a role in article production. It is hoped that this article will offer a good reference for understanding radiation physics and finding a better understanding of the state of the treatment as well as a better means of treatment of the tumor. Aside from the importance of health standards, any opinion and information given in this article should not be relied on in legal decision or be transmitted in documents of institution or organization without the permission of the author.

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