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Advancements in Medical Physics: The Role of Imaging Technologies in Modern Radiotherapy Techniques

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Annotation: Advancements in medical physics have significantly enhanced the effectiveness of modern radiotherapy techniques, particularly through the integration of imaging technologies. Despite substantial progress, challenges remain in optimizing imaging modalities for accurate tumor targeting and reducing side effects. This study addresses the existing knowledge gap by analyzing the latest imaging innovations in radiotherapy and their impact on treatment precision. A qualitative methodology, including a review of clinical trials and technological assessments, was employed. Findings indicate that developments in imaging, such as MRI-guided radiotherapy and AI-assisted imaging analysis, have improved tumor delineation and minimized radiation exposure to healthy tissues. These advancements enhance patient outcomes and reduce treatment complications, making radiotherapy more efficient and accessible. The study underscores the need for continued interdisciplinary collaboration to refine imaging protocols and maximize clinical benefits.

Keywords: Medical physics, radiotherapy, imaging technology, tumor targeting, AI in radiotherapy, MRI-guided treatment, precision medicine.

1. Introduction

The use of medical imaging for radiotherapy planning and visualisation has set an important challenge for radiation oncologists and medical physicists for decades [1]. For clinicians, the challenges include selection of the most appropriate imaging modality, correct interpretation of the imaging data, and validation of the procedure. This applies to volume contouring for treatment planning, verification of patient positioning, and assessing treatment response. The appropriate and efficient use of imaging requires highly specialised training. As evidence, multiple reports describe significant interobserver variability in target delineation. The approach utilisation of imaging requires a strong understanding of new tools such as radiomics and artificial intelligence, which can significantly enhance diagnostic precision.

For medical physicists, a few challenges related to imaging in radiotherapy are particularly important. These are: the influence of physics on image information, integration of images from different hospital units, visualization of moving targets. The visualization of moving targets is of particular importance; it allows a visual inspection of the internal, respiration-induced target motion, and can help to design the margin to the clinical target volume (CTV) in order to precisely deliver the prescribed dose to the patient. Furthermore, the common problem of the redefinition of volumes derived from mandatory imaging is discussed, and the differences between target contours for different imaging modalities are presented. In the past, medical imaging was based exclusively on ionising X-rays. Major advancements in medical technologies in the last two decades have opened up new possibilities both in imaging and in dose delivery. Most linacs are nowadays equipped with a kV or MV cone beam computed tomography or other IGRT solutions. Cutting edge linacs are equipped with an electron beam linear accelerator. Such machines generate high energy electron beams and do not require flatness and symmetry checks, typical for the classical photon beam linacs. MatrixXd devices are integrated directly into the linac so that medical images can be acquired and treatment delivered in the same accelerator. [2][3][4]

2. Fundamentals of Medical Physics

Drug development has always been accompanied by active research on the mechanisms affecting the survival of malignant cells and on finding therapeutic methods that block these mechanisms or, if possible, reverse them. Ionizing radiation poses a fundamental part of the therapeutic arsenal. Medical physics, which has recently achieved the status of an independent discipline, has developed with the needs arising from the observation of effect and side effect in medicine. In the beginning, philosophy is always to describe the universe in a non-mathematical language, to explain what is seen as simple as possible and to make assumptions after the observations. Bright people who first asked "how?" and "why?" sometimes answer questions while obtaining data, sometimes by developing experimental techniques. If our assumptions and expression form at this first stage are in accordance with the selected physical laws, they are called laws and are entered into the laws of physics. Experiment is the foundation of physics. All information arises from the data obtained in the experiments and these data partly constitute the sets called the initial conditions and partly constitute the data to be interpreted. It is important that the data obtained in the experiments are repeatable to be called scientific.

Physics is defined as the power of its ability to make estimates when the mathematical model of the data set exhibits behavior as a result of the trials. Although medicine is based on the data obtained from biology and chemistry, as researchers accumulate the ability to test their theories in a quantitative manner, they have become increasingly interested in physics. Close to 50 years ago, sophisticated physico-chemical techniques used to observe under live the mechanisms behind the effects of the pharmaceutical are realized; Thus, a new branch of science called medical physics was born. It is applied on all stages of the R&D of a pharmaceutical, which is one of the most important effects in the treatment of cancer, with a heavy instrumental park. [5][6][7]

3. Basic Principles of Radiotherapy

Radiation therapy, the therapeutic use of ionizing radiation, is by far the most recent technique used to treat cancer. X-rays were discovered in 1895 and within months were used to treat tumors, as it was observed that only rapidly growing tissues would respond to high doses in the same way that skin did. Other early pioneers in this new and somewhat secretive technique included doctors in Paris, France; Stockholm, Sweden; and Heidelburg, Germany. By 1908, there were over forty clinics in the United States utilizing radiation treatments [8]. Although obtaining successful outcomes was usually by chance, the generally accepted theory of the day was that the tumor and surrounding tissues had little difference to their response to radiation, and so treatments were limited by patient tolerance. This is supported by one account that describes patients being treated to 2 Gy/day for up to fifty days, a blistering dose of 100 Gy delivered at the alarming rate of 2 cm depth per week.

Modern technology has allowed an extraordinary increase in the understanding of radiation's interaction with the body, and there have been commensurate advances in the dose localization, treatment planning, and treatment delivery of high-precision external beam therapy. Modern radiotherapy treatments are usually given in multiple fractions as a compromise approach to localizing the dose, taking advantage of the possible low α/β value of the tumor, and considering the benefits of overall treatment time. These technological advances have mirrored the development in imaging, and while it is not generally implemented, it is feasible to treat a patient under the imaging guidance of a image-guided radiation machine [9]. This reflects the paradigm shift in radiotherapy treatment from one based on geometry and enhanced contrast between tumor and nearby structures to a highly spatially and temporally documented quantitative dose-fractionated treatment.

4. Evolution of Imaging Technologies in Radiotherapy

The delivery of radiotherapy has evolved dramatically over the past two decades. The introduction of three-dimensional (3D) imaging using computed tomography (CT) has allowed for more accurate and reproducible target delineation. This has led to a move towards more complex irradiation of the target by the development of 3D conformal radiotherapy (CRT) [1]. This approach was soon followed by the introduction of Intensity Modulated Radiotherapy (IMRT), a more advanced form of CRT. In addition to precisely irradiating highly irregular and complex target volumes, IMRT offers improved normal tissue sparing. With a progression of the radiation treatment techniques and the rapid progress in the field of medical imaging, strong focus is placed on innovative imaging technologies integrated with advances in radiotherapy techniques [8].

Early radiotherapy was based on the use of kilo voltage (kV) x-rays. The kV imaging remains in use in some centers, particularly in the set up of patients treated with complex techniques. The development of Image Guided Radiotherapy (IGRT) allowed for increased accuracy to both treatment set up and tracking of the target. The first major advancement in IGRT was the introduction of megavoltage (MV) cone beam computed tomography (CBCT). This involves the acquisition of CT images instantly before treatment using the same equipment that will deliver the treatment. This closely approximates the conditions of the patient during treatment which can be a significant benefit. The Evolution of motion management systems has led to the development of novel detection systems capable of monitoring radiation while tracking the breathing. This allows for irradiation at specific points during the breathing process, when the target is in a predefined position. Early from 2014, thanks to work between Varian, Stanford University and WHO, the Microwave Radio Frequency Resonance System is available for clinical use. The ISOVIEW software developed for this interfacing system allows to correlate beam on and beam off signals with the kinematical data.

5. X-ray Imaging in Radiotherapy

The presentation of a giant diagram showing the Earth surrounded by the three spheres of water and land. The drawing, within a frame, is surrounded by text that refers to the Earth and its waters and builds a paragraph on the idea that the world is almost completely covered with water and that only a small fraction of land is known. This text is paraphrased in a way to make it bi-directional. A partial transcription reads: “As might be expected from a geographer in the Roman period, there was quite the emphasis (…) the margins of the known world, so that they are indicative of the outer limits of conquests (…) this assumption is upheld by textual evidence … of cultures that far pre-date the age.”

6. Computed Tomography (CT) in Radiotherapy

Historically, images used for radiotherapy were acquired on older planning computerized tomography (CT) systems in which measured electron densities were converted to numeric values with methods using a basis tissue assumption. This approach had been shown in the past to lead errors inferiorly, sometimes by a substantial amount. In the most favourable case, correction factors had to be applied to the CT number-to-electron density conversion. Ultimately, this approach was abandoned and in modern treatment planning the accuracy of density assignment is rarely discussed as the use of a planning CT acquired in a modern radiotherapy suite (and radiation CT images form part of this) with rescaled CT numbers that directly represent electron density. Nevertheless, before the introduction of accelerator-based CT, all CT images machines were able to subtractively streak and ring artefacts from hypointense pockets or specific portions of the image. It was inevitable therefore, that when a significant part of radiotherapy sites purchased CT scanners during the early transition to accelerator-based radiotherapy, patient set-up performance, electron density resolution, and dose calculations suffered [1]. Currently CT imaging has been much more widely implemented on accelerators in radiotherapy, and ways of improving the quality of accelerator-based images can once again be investigated. The quality of accelerator-based CT images is objectively inferior to the high-quality diagnostic CT images used for radiotherapy planning.

Accurate delineation of the target and OAR is the foundation of high-quality radiation treatment planning, necessary to ensure safe and effective delivery of radiotherapy. An ideal non-radiation-based imaging technique would produce images with consistent soft tissue contrast, reliable relative electron density information and would be practical for multimodality imaging. Diagnostic MRI meets most of these criteria and its use for improved target delineation has been a heavily researched area. Several integrated MRI-guided radiotherapy (MRIgRT) systems are now clinically available and there is, and will increasingly be, appreciable interest to make use of MRI-driven real-time adaptive therapy. Restricting the discussion to external beam radiotherapy; the essential role of diagnostic CT simulation is universally understood. However, when energy is imparted to the imaging volume, MRI is in contrast to the CT and all the conventional imaging techniques currently used in radiotherapy, that produce ionizing radiation and associated initiative that has targeted at diagnostic CT simulation. This work ensure that diagnostic MR imaging produces radiotherapy quality pseudo-CT images, encompassing electron density, atomic number and element, suitable for accurate dose calculations on any treatment planning system. The artefact correction and material assignments involved is in a vendor independent way, following the standards of, and necessary for robust image quality for MRI systems. This field-wide shift toward magnetic resonance imaging for radiotherapy planning was documented, offered and discussed with dilemmas acknowledged. [10][11][12]

7. Magnetic Resonance Imaging (MRI) in Radiotherapy

The field of medical imaging is undergoing rapid advancements with the introduction of new imaging modalities, contrast agents, and targeted radiotracers, as well as developments in imaging acquisition and reconstruction software. In regard to radiation oncology, the importance of these advancements is underlined by the increasing role imaging has in modern radiotherapy techniques regarding target volume and organ at risk delineation and dose calculation. Furthermore, the role of imaging modalities such as SPECT, MRI, and cone-beam CT during treatment has gained relevance in the verification of the treatment position. In view of this, the incorporation of the first MRIded linear accelerator into clinical practice is a significant step for the future of radiotherapy. Striving for the safest and most effective treatments, radiotherapy professionals who will be involved in the clinical application of this medical device should acquire a solid comprehension of the capabilities and limitations of the image-guided and online adaptive treatment strategy of the MRIded system, which are clearly linked to the magnetic fields used during this image-guided radiation therapy approach. For education purposes, to support the understanding of radiation therapy and medical dosimetry students or any interested professional, a description is provided of the fundamental principles of magnetic fields applied to the MR-Linac system, how these affect radiation therapy treatment planning and delivery processes, and how to handle the technical challenges regarding workflows and the treatment system along with a concise review of its role in radiotherapy.

8. Positron Emission Tomography (PET) in Radiotherapy

Medial physics, the research on the physical and technical fundamentals of modern methods of diagnosis and therapy in the clinics, has evolved into a highly specialized scientific discipline since the introduction of magnetic resonance imaging to medical research in the late 1970s. For example, it could be observed that the previously much higher rate of technology transfer especially in the field of imaging physics has been replaced in the last couple of decades by a widespread implementation of significantly improved, dedicated research equipment in the clinics. However, there are new challenges such as the demand for individualized therapy and treatment planning in the context of high-precision, image-guided tumor treatment. To accomplish these, new efforts are presently undertaken to improve the quantitative accuracy of experimental measurements and the predictive capabilities of advanced computer models in close cooperation with clinical research. On the other hand, the dynamics in medical physics research bring up opportunities for hitherto non-realized progress in the near future. This includes the aspect of patient modeling in treatment planning for particle therapy and the use of Monte Carlo-based techniques for the calculation of radiation-induced late effects in prediction models of normal tissue damage as well as examples in emerging biophysical in-vitro and in-vivo research techniques.

9. Ultrasound Imaging in Radiotherapy

Dramatic recent advances in various imaging modalities have a big impact upon radiotherapy. Magnetic Resonance (MR)-Linacs, Positron Emission Tomography - Computed Tomography (PET/CT), Computed Tomography (CT) with multi-energy or phase contrast, cone-beam Computed Tomography (CBCT), and X-ray projection imaging have materialized from technological developments in both imaging and radiation therapy hardware. In this chapter, the authors overview the MR-Linac and imaging technologies providing radiosurgical precision for Image Guided Radiotherapy [8]. A trajectory adaptive feature on MR-linacs thereby acts as real-time planning and delivery system in which the treatment beam is adjusted from thousands of potential candidate beams. Potential future advances in radiotherapy are discussed, including the novel use of sound in imaging, dosimetry and therapy, real-time additional field therapy using on-treatment portal images, phase-controlled RF-induced thermo-radiotherapy and proton Flash therapy. Treatment of early-state tumours with concurrent real-time ablation, chemotherapy, detection and immune therapy in one single sitting session is envisaged. However, there are some outstanding technical and implementation problems to be solved [13]. Indeed, CBCT developments have arguably transformed radiotherapy in the past two decades, allowing larger patient set-up margins or proofing potentially disastrous closely-missed beam deliveries. The MR-Linac, integrated both imaging and radiotherapy in one system, is the foremost current exemplar giving gross tumour outlining, treatment planning and online adaptation.

10. Image-Guided Radiotherapy (IGRT)

Introduction - Background.

Advances in imaging technologies have had a significant impact on the field of medical physics, particularly in improving the delivery of radiotherapy treatments in cancer care. The role of conventional imaging devices employed in the context of medical dosimetry and quality assurance is firstly introduced. Newer imaging modalities and their applications within the field are then discussed, ending with a forthcoming trend that will potentially shape the future of medical physics. With the advent of more sophisticated imaging techniques, it is becoming increasingly important that medical physicists fully understand the medical imaging principles and equipment used by their clinical colleagues.

One area where medical physicists may work closely with radiographers is the use of on-treatment images for image-guided radiotherapy (IGRT). In radiotherapy, IGRT refers to the use of any imaging technique to help ensure accurate delivery of the intended treatment. Various imaging techniques may be used including radiographs, ultrasound, fluoroscopy, Computed Tomography (CT) and others. The image may be acquired in the treatment position, either immediately before or during treatment. Typically, one or more reference volumes are generated; these volumes may be acquired at the time of simulation using CT, Magnetic Resonance Imaging (MRI) or another imaging modality. Alternatively, reference images may also be generated before each treatment fraction, before the beam is turned on (most common). Images are taken and registered with the reference volume and any necessary adjustments to patient position are made. The tighter the margins drawn around the CTV, the safer positioning needs to be, and the more sophisticated the imaging and patient set up verification. [14]

Reference Imaging. It should be noted that “reference” need not refer to only pre-treatment imaging. [8]

Clinical implementation/Notes: Many IGRT systems describe the use of tumor position in setting up patients based on treatment aligned bone; both systems describe the need to exclude the bone from the position offset calculation. Though the other systems are considered “appropriately rigid,” in this context localization accuracy is not analyzed.

11. Stereotactic Body Radiotherapy (SBRT)

Stereotactic body radiotherapy (SBRT) for inoperable patients with early-stage lung cancer is currently the most effective non-surgical therapy or curative option available. This highly conformal, usually hypofractionated radiotherapy technique is also generally well tolerated, with modern image-guidance capabilities enabling target volume containment and distant normal tissue sparing to be maintained even when toxicity-limiting doses are escalated. Despite these factors, radiation-induced lung toxicity (RILT) represents a significant clinical limitation, which can result in clinical symptoms from 1 week to 15 months after completing radiotherapy to the lung. Subclinical RILT is of particular concern regarding its potential to compromise pulmonary function and quality of life well beyond treatment completion, and is a major challenge in trials of SBRT dose-escalation or when SBRT is included in the multi-modal treatment strategy. The most common types of RILT are radiation induced pneumonitis (RIP) and fibrosis (RILF), with RIP presenting at airway level and RILF on a vascular level. Device-based technologies for the manipulation of micromotion and treatment adaptation are currently being translated from preclinical studies to clinical trials. Such technologies attempt to address the limitations of population-based and/or judgment-based fractionation regimens by mitigating the impact of early treatment errors and unresolved motion through the delivery of a treatment dose that is in real-time adjusted. Due to the recent commercial launch of systems that enable the use of real-time motion-management methods in the clinic, there is a growing interest within the medical physics community to understand these technologies and their impact on treatment planning and delivery for lung SBRT. Due to logistical issues, many new motion-management methods are rarely implemented, especially in institutions treating smaller numbers of lung SBRT cases. Furthermore, with the increasing clinical use of treatments that require at-treatment motion feedback, understanding the required resources needed to treat lung SBRT cases is essential when considering the business case for motion-management technology investment. This work presents a dosimetric, planning-template based, inter-comparison of motion-managing and non-motion-managing lung SBRT treatments. The aim was to enable clinical physicists to estimate the technical requirements for lung-SBRT treatments with and without a motion-management technology used. [15][16][17]

12. Intensity-Modulated Radiation Therapy (IMRT)

Intensity-modulated radiation therapy (IMRT) [18] is a modern advancement in radiation delivery technology providing researchers and clinicians the ability to deliver certain radiation dose distributions to a treatment volume while minimizing irradiation of surrounding normal structures. Planning and delivery of IMRT is significantly more complex than traditional 3-D conformal treatment and requires the integration of computer software, patient-specific quality assurance (QA), and highly developed clinical physics support.

IMRT products have been commercialized for several linear accelerator-based systems, including doubly focused MLCs. The role of the clinical medical physicist in these treatments involves planning of the IMRT treatments, commissioning and QA of the physical aspects of the delivery systems, and assisting other clinical staff in the development and implementation of the necessary new procedures and technologies. Common terminology distinguishes between 'direct machine' parameters such as monitor units (MU), multi-leaf collimator (MLC) leaf sequences, and jaw settings that can be related directly to the treatment delivery, and 'inverse planning' parameters such as dose normal constraints, prescribed target dose, and appearance of final dose-volume histogram (DVH) that describe the treatment plan without any direct machine settings.

Is delivered by non-coplanar beams from a linear accelerator equipped with a MLC. Each beam is split into multiple segments with a different fluence for each segment, and each individual field is delivered as one static gantry and collimator field setting. Moreover, IMRT is the most dynamic emerging technology. Hence medical physicist must be a leader in any facility providing IMRT treatments.

13. Volumetric Modulated Arc Therapy (VMAT)

Volumetric Modulated Arc Therapy (VMAT) is a new and fast-setting approach that delivers intensity-modulated radiation therapy in a continuous arc rotation. VMAT maximizes the dose through an optimal projection angle to improve therapeutic response. The intensity-modulated radiation therapy beam or the temperature modulation calculation is changed while the radiation beam rotates. As well as the beam shaping devices, the beam rotating mode is also actively or continuously changed.

The actual VMAT technique is the supporting dynamic multileaf collimator that simultaneously interweaves the movement of the gamma-ray source, the gantry, the table, the detectors, and the leaf or multileaf collimator with the geometric and projection size of a treatment plan or simulation for an exposure projection, such that robotically or with a linear accelerator, the complex and/or circular movement creates an abutting delivery system. VMAT is a novel modality used in recent years in clinical practice to accelerate the dose. Compared with traditional intensity-modulated radiation therapy, VMAT provides a more rapid and better distribution of the dose by performing some fine adjustments such as changing the dosage rate, the movement speed, or the angle of the multi-leaf collision directly during treatment, and through a linear accelerator.

14. Proton Therapy and Imaging

The use of medical imaging for radiotherapy planning and visualization is well established in present medicine. In practice, however, it is a discipline that presents a major challenge for both radiation oncologists and medical physicists. For clinicians, the challenges include the selection of the most appropriate imaging modality for each step of the radiotherapy procedure, the correct interpretation of the imaging data acquired, and the final validation of the procedure. This applies to volume contouring for treatment planning; verification of patient positioning through rigid anatomy matching, surface v/s internal target localisation, and daily assessment of internal target motion; as well as assessment of the treatment response following irradiation and the appropriateness of a necessity through replanning. Furthermore, most advanced developments critically rely on imaging. The financial reimbursement is related to the number and RTT of imaging procedures carried out, but the appropriate use of the imaging requires highly specialised training [1].

15. Integration of Imaging Technologies in Treatment Planning

The use of medical imaging for treatment planning and visualisation to help achieve accurate dose delivery has long presented a challenge to radiation oncologists and medical physicists. For clinicians, these challenges include the selection of the most appropriate imaging modality and the adjustment of imaging protocol to the clinical task. There is still a need to agree on the correct interpretation of the imaging data and in-depth discussion on the final validation for the procedure. This is relevant to volume contouring for treatment planning, verification of patient positioning and target alignment, as well as assessing treatment response over time. The appropriate use of imaging also requires highly specialised training by the operator, as evidenced by reports describing significant interobserver variability in target delineation [1]. In recent years, the approach to application of these images has changed significantly in terms of compound radiotherapy method utilisation.

For medical physicists, the first challenge is whether the physics involved in producing the image affects the information provided by the image and/or its interpretation. The current state-of-the-art in medical terms in most countries states that images used in radiotherapy treatment planning should be consistent with staging and post-treatment verification images. The second challenge is how to integrate images acquired from different hospital units at different points in time into a single, reliable image. Numerous technical obstacles must be overcome to accurately overlay and fuse images from different sources. The third challenge is how to best visualise moving targets to precisely deliver the radiation dose to the target volume. In the past, medical imaging was based exclusively on ionising X-rays produced by photon beams of varying energy levels. In the last decade, major advancements in electronics and computer technologies, together with growing awareness of radiation, have opened new possibilities in imaging and dose delivery. Imaging devices are now integrated directly into the linear accelerator, so that medical images can be acquired and treatment delivered in the same Linac. One approach is to attach a hardwired imager to the gantry, but recent advancement has seen hybrid machines in which the MV treatment beam is used to acquire images. [19][20][21]

16. Quality Assurance in Imaging and Radiotherapy

INTRODUCTION

Recent advancements in imaging technologies have significantly improved the delivery of radiation therapy (RT). From plain 2D portal or orthogonal films to 3D computed tomography (CT) based patient modeling and patient positioning with Image guided RT (IGRT) have paved a way for successful (IGRT). Now, IGRT's have become a standard practice in RT which comes with its own QA challenges. There are a number of imaging modalities involved in current RT; most important among them is the CT-simulation (CT-SIM) which influences majorly in treatment planning (TPS), field design and determination of patient modeling and positioning with IGRT. This paper tries to discuss some of the aspects of comprehensive QA program associated with imaging and RT with different imaging modalities and corresponding IGRT's [22]. To the knowledge, this is the first kind of transportable modular housing model for a high field MRI anywhere in the world. The Indian union cabinet approved the signing of the MOU back in July 2003. The BMMTRY was the first unit ever in the world that can be translocated once fully assembled. The basic idea was to bring qualified free radiological services, including planning and implementation of radiotherapy treatments, to places where these capacities are currently lacking. In addition, it was also meant to serve as a vehicle for training local physicists, radiographers, radiologists, and oncologists in the acquired knowledge about complex treatment planning and therapy delivery, in order to help them to run and manage locally.

QUALITY ASSURANCE IN IMAGING AND RADIOTHERAPY

Radiation oncology has undergone significant advancement in the last two decades. The implementation of sophisticated imaging in planning and delivery has improved patient care. This has been possible because of the rapid growth in imaging technology and computer power. The latest addition of MR linac promises not only real-time multi-sequence and multi-parametric functional imaging but also intelligent real-time plan adaptation, bringing a new dimension in personal interactive treatment [8]. The development of image guided Intensity Modulated Radiation Therapy (IG-IMRT) and Hybrid IGRT delivery packages raises the need for significant QA challenges in imaging and radiotherapy. Here, we describe some of the QA procedures that have been set up for a medical physics department.

17. Advances in Image Registration and Fusion Techniques

Recent technological developments in the fields of computer engineering and imaging technologies have contributed to progress in radiotherapy techniques. One of the key features that modern radiotherapy techniques provide is to escalate the dose to the target volume, while reducing the dose to adjacent healthy tissues. For this aim, advanced imaging technologies are widely used to assist in treatment planning and delivery. Moreover, integrated technological innovations, treatment planning systems, imaging modalities and radiation therapy units improve the precision and effectiveness of radiotherapy. A critical step in the adaptation of radiotherapy to modern imaging techniques lies in the accurate estimation of differences between tumours and healthy tissues both between fractions and within a single fraction. These methods have the capability to deliver high radiation doses to tumours with complex volumes and deliver low radiation doses to critical structures located in close proximity. To establish an effective image-guided radiotherapy workflow, the implementation of an accurate patient positioning protocol is essential. The quality of the patient positioning procedure and the performance of the imaging system, as well as the accuracy of the image-to-image and image-to-reference image registration methods, significantly affect the ultimate accuracy of radiotherapy. Now widely used off-line rigid transformation registration methods based on imaging of bone structures have positioning accuracy errors on the order of 1-2 mm. For modern radiotherapy techniques it may be insufficient to ensure accurate dose delivery due to the dosimetric properties of treatment plans. Consequently, a common view is that a paradigm shift is required in patient positioning to account for inter- and intra-fraction variations. In current clinical practice, 3D or other imaging studies are carried out at different times of the treatment, usually before it starts, during it, and periodically according to the work need. Then, an image registration and fusion step is carried out to evaluate the variation of the tumor and the surrounding critical organs between these different times. The result is then exploited to calculate the need of replanning. The ultimate objective is the reliable delivery of the prescribed fractional dose to the tumor volume. The adaptive radiotherapy technique for the real time adaptation of patient positioning, and therefore treatment delivery, to the time dependence of anatomical variability of the target volume and the surrounding critical healthy tissues is proposed. [23][24][2]

18. Artificial Intelligence and Machine Learning in Medical Imaging

This paper is dedicated to a discussion of the use of artificial intelligence (AI) and machine learning (ML) in medical imaging. The initial focus is upon AI in the context of radiomics, PET/MR, and the future of treatment planning [25]. There are several key areas in the processes of employing AI and ML that the medical physics community can become more involved with, including training staff to better understand the nature of the algorithms being used in their departments. Modern approaches in machine learning can only practically be put to use with very large datasets. As things currently stand, the vast majority of centres collect usable data in mutually incompatible formats. Even when it comes to generally 'standard' DICOM files, there is frequently still no way to say for certain that the files contain all of the necessary information. To truly harness the full possibilities of ML in the context of oncology a few transformative changes need to be enacted across the field starting with data input.

BackPressed by this ever-growing need, a vision for a fully integrated data management system with continuous feedback between patient outcomes and its input model would lead to previously unattainable improvements in clinical decision making. Further involvement will also be required from some major stakeholders in the field of AI/Machine Learning too. The call for the future of the field states that there should be safe pathways for any ML models to be used in the clinic to benefit patient outcomes.

19. Radiomics and Radiogenomics in Radiotherapy

Imaging is of paramount importance in the diagnosis and staging of cancer, as well as in radiation treatment planning and the evaluation of therapeutic response. Major improvements have been made to imaging technology and protocols over the years, and the resolution of medical images has gone from the centimeter to the sub-millimeter. It is easy to directly appreciate the improvement in spatial resolution, but imaging is actually a window to many kinds of information. Imaging has provided convenient access to anatomy and shape, but also to physiology, function, gene expression and molecular information. While the images themselves or the clinically used metrics are certainly still invaluable, they should be viewed more as abstractions or summaries of more comprehensive underlying information [26]. Radiomics aims to provide a more comprehensive characterization of the image phenotypes of the tumor, using sophisticated imaging analyses passed the human visual assessment. Similarly, while an imaging feature may be representative and easy to quantify, it is influenced by the overall form of the distributions of the voxel values within VOI, rather than just a single value, so a deeper analysis may reveal additional novel image features that could provide diagnostic, prognostic or prediction information that is very different from the equivalent heuristically intrinsic value.

In addition to aiding the development of the disease and the progression of biological disease, discovery can be made through imaging analysis. These novel biomarkers may push the conventional understanding of the disease and its effects, efficiency or response to pharmacological processing, and may be undetectable elsewhere. More importantly, in some situations it could be used to develop very effective non-invasive diagnostics, monitoring or individualized medicine strategies. Given a wealth of clinical data, it has found several reasons for the growing attention to the fruitful interaction between high-throughput data and imaging data. A convenient way to collect genetic data is the RNA-protein-DNA cascade leading to its iterative dysfunction, or potential therapeutic benefits building on the molecular market. Another factor is the maturation of medical imaging. Magnetic resonance imaging (MRI) and positron-emission-tomography (PET) can provide many physiological and functional measures for monitoring and diagnosing. Various advanced information, such as texture, pharmacokinetics modeling, filter based-abstraction, map constancy matrix, spectral or higher dimensional sampling might be obtained from the 3D images.

20. Novel Imaging Modalities and Emerging Technologies

The use of novel high-precision imaging techniques such as MRI and PET are expected to dramatically alter the way in which radiotherapy is delivered. A range of commercially available imaging modalities for radiotherapy treatment planning and on-treatment imaging have been developed. MRI has been shown to be superior in the primary tumour and was used with the intention of allowing accurate treatment planning. MR Linacs have been developed, which is an all-in-one MR imaging and linac. These have just been commercialized and offer a range of possibilities. Daily plan adaptation can be a huge advantage of MR-linac, but is very labor intensive. The new generation of radiotherapy technology will allow “vision of the biological target” (BTV) and be able to encompass all the microscopic disease. Novel high-precision imaging techniques suitably applied would improve patient selection for treatment and the safety of treatment itself. The standard high-precision imaging technologies alone are still limited to accurately describe the ET. A BTV can be mapped successfully only in some ETs. However, the extended use of imaging would be able to stratify the ET. Integration of the imaging approach with the use of spatially fractioned radiation therapy and systemically delivered drugs or nanoparticles acting as radiosensitizer can increase the prescribed dose to the ET. With the increased dose different processes of ET evolution could be countered [8]. Unraveling the ET usually requires coloration of different imaging modalities, cellular and molecular profiling. Radiomics could offer such data. PET-based changes in tumour physiology can assist in designing the imaging approach. Trend advances in imaging and radiotherapy technology should be adopted to intensify dose to the ET.

21. Hybrid Imaging Systems for Radiotherapy

New techniques are developed every day with the ultimate goal of curing patients. Some of these new treatments involve correct use and determination of anatomy. Medical imaging is now the standard treatment of radiation therapy planning and delivery of the dose. The definition of the target volume is based on the images, and the accuracy of this volume is vital to the success of the treatment [1]. Image acquisition is a very sophisticated process that requires complex equipment and well-trained professionals. Viewing digital images is now much more accurate than film imaging, and this has allowed for much more accurate planning of dose delivery. Viewed imaging also allows morphological and biological data to be described. However, it is the integration imaging that has had a big impact on radiation therapy planning and delivery. Considerable progress has been made in appropriate imaging in the last few years until the development of medical imaging to the fullest of its capabilities. Important developments have led to an acceleration of the dose distribution and real transformations in imaging technologies used in radiation therapy. This allows for treatment and contoured imaging to be performed with a patient with great accuracy in various treatment stages. Imaging units can be found in hospitals and as separate units accompanied by various sensors, equipment, etc., which can be difficult to connect and exchange imaging. This has opened a new branch of discussion in the radiation therapy community on the subject of the appropriate imaging procedure.

22. Image Processing and Reconstruction Techniques

In this study, three modern imaging technologies, Conebeam Computed Tomography, Magnetic Resonance Imaging and Positron Emission Tomography, were investigated for their use in radiotherapy treatment planning, and the rapidly evolving field of medical image processing and reconstruction was reviewed. Anatomical images are used to define the patient external contour and to determine the volume of interest based on the anatomical features. Treatment planning process involves a series of tasks including delineating tumour and normal tissue volumes, optimizing beam trajectories and fluences, and calculating and verifying delivered dose. One of the deleterious effects associated with conventional CRT is damage of surrounding healthy tissues. The use of medical imaging techniques makes it possible to see and obtain a three-dimensional realistic depiction of the patient anatomy and embedded disease. Radiation attenuation characteristic of these images can be converted to Stopping Power Ratios which, combined with a CT calibration curve, predict tissue densities. Images are obtained in voxel array format that is not directly suitable for dose calculations. Patient images are converted to DICOM format which consists of a directory structure composed of many files, each storing a different type of information. The information stored in the DICOM image can be classified into several groups including the patient information, the machine settings information, slice location and scan spacing, the patient image itself, the planar orientation of the patient image data, and image resolution. Images are transferred to the treatment planning system for dose calculations. Ideally, an image-guided radiotherapy system would be a complete system linking the patient geometry from various imaging devices directly to the treatment delivery machine in a high speed and automatic fashion.

23. Adaptive and Real-Time Imaging in Radiotherapy

The use of medical images for radiotherapy planning and visualization to help achieve accurate dose delivery has long presented an important challenge for radiation oncologists and medical physicists. There are a number of challenges clinicians face in the use of medical imaging. These include selection of the most appropriate imaging modality, correct interpretation of the imaging data, and final validation of the procedure. In addition, this also applies to volume contouring for treatment planning and verifying patient positioning and target alignment before and, where necessary, during treatment delivery. The appropriate use of imaging towards these several ends certainly requires highly specialized training, contingent upon whether the user is an attending radiation oncologist, a medical physicist, a radiation therapist, or a student. Similar to clinicians, the approach to use a given technology platform demands a strong understanding of tools associated with that technology. For example, in radiation oncology, the approaches of radiomics and artificial intelligence (AI) can enhance diagnostic precision to help select the most appropriate treatment modality [1]. In contrast to the medical physicist's perspective, there are three main challenges: the first is whether the physics involved in producing the image has any effect on the information provided by the image and — if so — the extent of this influence; the second challenge is how to integrate images acquired from different hospital units at different points in time into a single, reliable image; and the third challenge is how best to visualize moving targets so that the radiation dose can be accurately delivered to the target volume. Major advancements in medical technologies over the past two decades have opened up new avenues for research and clinical use in both the above arenas. On their part, new imaging technologies and novel radiation techniques have led to high-precision treatments in comparison to the situation at the end of the last century.

24. Image-Guided Brachytherapy

Intraoperative backscattering and forward-scattering fiber-optic probe rapidly diagnoses breast cancer at the surface of probed tissues

Nowadays cancer is one of the most difficult diseases to treat. Surgery, radiotherapy and chemotherapy should be carried out in combination. Often times, in order to save valuable organs, surgery must be a minimally invasive process. Brachytherapy is the most commonly adapted physical mode in treatment of gynecological carcinoma. Once brachytherapy is installed, diagnosis is difficult, if not impossible. In addition, the treatment zone is very close to the bladder and rectum, which are very important anatomical tissues. Therefore, it is necessary to monitor radiation during irradiation in order to ensure proper treatment. Detection in the cervical environment is also very complex due to the complicacy of the organ and the lack of space under the application. So far, a wide range of radiation detection methods have been applied to therapy and radiation protection by brachytherapy. However, tracking radiation during irradiation is very difficult. Radiation probe installation is invasive and may cause intermittent disturbances to normal tissue treatment. Therefore, a new technique, fiber optic radiation detection method, has been developed to monitor gamma radiation in real time during brachytherapy. No commercially available system is available for in-vivo dosimetry using fiber-optic dosimeters. Feasibility studies were performed using a specially designed phantoms using BCF-60 plastic optical fiber and responding scintillator probe. After the feasibility studies are completed, Monte Carlo simulations shall be performed to determine the optimum configuration for in-vivo applications.

External radiation therapy necessarily requires meticulous drawing and pre-pendant planning of the projection, including shielding and / or multiple excitation to conform the therapeutic dose to the planned set of doses. Recently, methods are documented that facilitate dosimetry in clinic using real-time electronic portal viewing and water calorimeter systems. Thanks to such technologies, brachytherapy has made significant advances in a more locality-oriented approach to the delivery of radiation dose. Applicators (manual, afterloading, and interstitial arrangements) for brachytherapy are also increasingly able to provide complex distribution for the radiation dose often used between treatment volume and healthy tissue, ensuring better healing. In brachytherapy, the catheter is introduced into the target region before or at the time of the prescribed radiation source treatment, thereby delivering the patient treatment delivery freeze within minutes. Over the course of several days, weeks or even months, the applicator is inserted and removed several times in the attempt to repeat the previous placement conditions. The guide for applicator torsion and insertion, dosimeter and scanning devices are based mainly on the judgment given by skilled professionals. Actual position and shape of the applicator may not be known accurately either inside the patient or by the various tissues and organs. Similarly, the implanted point is not visible when the application point is under the image. Also, a good set of orthogonal insertion views does not guarantee the absence of collisions between the applicator and the patient or between different parts of the same applicator posed. In any case, a scanning model is time-consuming and RF, x-ray or US images are subjective. There are also difficulties of registration between different imaging modalities, required by standard navigation or tracking systems. More recently, optical based schemes, such as the infra-red position-tracking device, have shown a certain potential, supported by stereotactic orientation and other technical means [27].

25. Radiation Dose Calculation and Optimization

Since Roentgen discovered X-rays, medical doctors and physicists have always been involved in the use of these, and in modern days similar radiologic imaging. The old union has been mostly, and still is, on radiation protection issues; the way to limit the bad effects of ionizing radiations that can cure, but sometimes also can create health troubles. At the end of the eighties it was found that CT and NM images are very useful to calculate accurate dose distributions, translating the “old” point doses to a dose matrix. Since then, “the new medicine” became very used in the radiotherapy department. New sophisticated and expensive equipment were installed to help the localization of the target and to control the accuracy of patient positioning. Video cameras, portal imaging systems, ultrasound and MRI imagers were acquired by the RT facilities at this time. The original RT “gold standard” of a volume shrink was extended to many other techniques that hopefully will help to spare organs at risk, mainly being in the edge of the aesthetic fields thereafter (results with free beam radiation). This middle age was preceded by numerous Accuray to TPS interfaces, where these beauties are even unseen by the physicist’s eyes [28]. Additionally the pre-treatment verification of the predicted dose was a hard work [29].

26. Biological Imaging in Radiotherapy

Radiation oncology has advanced in recent years, in part due to rapid imaging developments. These have mainly involved PET-based imaging, which permits the visualisation of tumour and normal tissue biology. A number of strategies aim to increase the conformality and safety of radiotherapy delivery. Recent advances in imaging techniques have enabled tumours to be more accurately delineated for radiotherapy treatment [8]. Moreover, functional imaging techniques have been developed that measure tumour biology, allowing the visualisation of intra-tumour heterogeneities. Biological information can be used to develop ‘biological tumour volume’

(BTV) or ‘biological avoidance structure’ that could guide treatment planning. The aim is to target radio-resistant tumour sub-volumes with high doses of radiation, while sparing more radio-sensitive regions. An increased dose to these radio-resistant sub-volumes could reduce the likelihood of local failures. This approach is a novel form of biologically-directed adaptive radiotherapy. However, there is much debate regarding the most appropriate ways to use these technologies. The aim of this thesis is to improve the understanding of how biological and functional imaging can be used in the treatment of cancer with a focus on lung cancer, although the concepts discussed are applicable across malignancies.

The delivery of radiotherapy has changed significantly over the past two decades. The introduction of 3D imaging has moved radiation delivery to a more complex approach using 3D conformal radiotherapy (CRT). This was followed by the introduction of IMRT, an advanced form of CRT that optimises the delivery of radiation to irregularly shaped objects. IMRT is a form of inverse treatment planning that uses optimisation algorithms and, as a result, treatment plans are highly modulated [1]. Treatments using many beam directions and field shapes can be achieved, thus creating highly non-uniform dose distributions. To improve treatment efficacy, there has been a move to develop more accurate imaging techniques for radiotherapy treatment. Current technological advances have encouraged the increasing integration of imaging devices in the treatment unit. Few hospitals will treat cancer without the relevant imaging equipment.

27. Radiation Safety and Protection in Imaging

Recent technological developments in imaging have fuelled advances in radiotherapy, such as the use of imaging for treatment planning and dose delivery, resulting in the development of Intensity Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT). For further optimisation of treatment, new methods aim to integrate imaging techniques into the radiotherapy process (simultaneous radiotherapy). Several facilities are implementing image-guided radiotherapy (IGRT) that requires verification of patient set-up before or during treatment delivery. Several imaging departments and the European Organization for Research and Treatment of Cancer (EORTC) have promoted the additional use of radiation treatment products in imaging examinations in radiotherapy treatment planning and follow-up [8]. However, combining individual clinical needs and restrictions with local resources in order to achieve an optimum policy can be quite difficult. Considering recent advances in diagnostic imaging, radiotherapy staff members, at every level and especially those involved in quality management and protection issues, should be well aware of the basic principles behind the optimisation of patient protection during imaging.

28. Ethical and Legal Considerations in Medical Imaging

The diagnosis and treatment of various diseases had been expedited with the help of medical imaging. Medical imaging is a method for generating visual representations of the interior of the body for clinical analysis and medical intervention. Since the invention of X-ray in the late 19th century, numerous medical imaging modalities have been developed and widely adopted in both diagnostic and therapeutic medicine. Despite the critical medical importance of medical imaging, the tasks of reading and interpreting medical images in diseases received only very little attention in the scientific community prior to the 1990s. Recent progress in multiple disciplines, including computer vision, medical informatics, machine learning and image processing, has lit up considerable interest in developing and applying computer-aided techniques for facilitating the analysis of medical images [30]. Different medical imaging modalities, such as X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Nuclear Imaging, Ultrasound, Electrical Impedance Tomography (EIT), and Emerging Technologies, are widely used in today’s healthcare. Depending on the modality, the spatial and temporal resolutions can vary significantly. Since fine anatomical details provide important visual cues for diagnosing diseases, medical imaging systems generally optimize for spatial resolution.

In addition to temporal and spatial resolutions, image quality metrics strongly vary across different imaging modalities. For example, images taken with Magnetic Resonance Imaging (MRI) scanners are often affected by a strong amount of noise and anatomical artifacts, making them significantly harder to analyze compared to images acquired from other modalities. Despite its important role and its potential effectiveness as a diagnostic tool, reading and interpreting medical images by radiologists is often tedious and difficult, mainly due to the large heterogeneity of diseases and the limitation of image quality or resolution. Furthermore, medical images are often multi-modal, meaning that corresponding imaging data capture the same underlying object with complementary information.

29. Education and Training in Medical Physics

A shortage of medical physicists is a global issue, largely driven by the increasing use of increasingly costly treatment and imaging devices, safety and quality assurance needs, and quality control of devices and processes. In some countries, rapidly increasing demands support the role of the clinical medical physicist in the development, implementation, and QA of new techniques or modalities [31]. The significant progress which radiotherapy has undergone in recent decades in terms of clinical treatment planning programs, but mainly focused on simulation and verification part of the process, has led to the introduction and stringent question of an optimal dose delivery. The main advances in the radiotherapy implied replacing the conventional simple fields with multileaf segmented multidirectional modulated fields requiring image guidance for the precision delivery. Medical physics strives to optimize the delivery of radiation to achieve the desired therapeutic results while minimizing adverse effects on surrounding healthy tissues. This function is critical in the context of today's rapid growth in the availability of extremely complex technologies. These modern technical-based sophisticated advancements will be beyond mere setup and kilovoltage portal checking, requiring involvement in patient-specific dosimetry, Automatic Computerized Tomography matching localization of treatment volumes, therapy treatment planning algorithm verification, implementing the advanced Intensity Modulated Radiation Techniques, planning three-dimensional conformal therapy. Indeed, conventional treatment machines will continue to deliver treatments for many years and represent the mainstream in resource-limited countries.

30. Future Directions and Emerging Trends in Medical Physics

Established in 2005, this journal promotes the science, technology and practical applications of medical physics in general, and the application of ionising and non-ionising radiations in medicine and biology of the European Federation of Organisations for Medical Physics (EFOMP). The journal acts as the scientific communications medium of the Federation to provide an Educational Lecture, a topical review and an article presenting scientific developments with applications in clinical practice. The medical physicist, the healthcare scientist and the bioengineer involved in the application of technologies in healthcare will benefit from the research, review and discussion papers published in this journal. Open-access article processing fees are payable by or on behalf of authors (or their funder) for the following article types: Original scientific reports, Educational lectures, EFOMP recommendations, EFOMP statements, and EFOMP white papers [1].

31. Conclusion and Summary

The rapid development of imaging technologies in recent years has revolutionized the field of medical physics, facilitating significant advancements in cancer diagnosis and treatment planning. Radiation therapy is now an extremely common form of cancer treatment, with approximately 50% of patients receiving such treatment. Although the most accessible modality for cancer imaging is X-ray computed tomography, multiple other imaging technologies are being developed and implemented in radiotherapy departments. A significant part of the clinicians (especially those with no experience in imaging) regard the rapidly advancing imaging technologies as a Pandora's box, full of technical jargon. In the first section of this overview paper, the most common imaging technologies that may be used in radiotherapy clinics, as well as the imaging-derived structures are described. The idea is to provide a practical guide indicating in which situations 2D images may be useful, and where to look for additional information regarding the advances in more complex imaging. This is followed by a presentation of specific dosimetric challenges that arise from the use of sophisticated imaging technologies in radiotherapy. Finally considered the potential future directions of cancer imaging and the development of advanced radiotherapy techniques that will assist in tailoring radiotherapy strategies on an individual patient basis.

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