РАДІАЦІЙНИЙ ЗАХИСТ
RADIATION PROTECTION

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Sören MATTSSON, PhD, Prof.
ORCID ID: 0000-0002-6443-1913
e-mail: soren.mattsson@med.lu.se
Lund University, Skåne University Hospital Malmö, Sweden

CURRENT DEVELOPMENTS IN MEDICAL RADIATION PHYSICS AND RADIATION PROTECTION

The paper reviews current trends and future directions for diagnostics and therapy with ionizing radiation. Recent advances in medical physics applied to radiation therapy, diagnostic radiology, nuclear medicine, MRI, and radiation safety are summarized. Today, much of the development is concentrated on providing conditions for individualized diagnostics and therapy for the patient, which requires increased precision and accuracy in both radiological diagnostics and radiotherapy. Areas of active development are the use of artificial intelligence (AI) for improved and more efficient diagnostics and therapy, theranostics, radiomics and dosiomics. All these approaches are parts of the so-called precision or personalized medicine. The ongoing revision of the ICRP's radiation protection recommendations is also commented on. For dose and risk estimates in diagnostic applications (X-ray imaging, CT, interventional radiology, diagnostic nuclear medicine) a change from population-based average phantoms, calculation methods and risk figures to patient-specific calculation methods, phantoms and risk figures (as is done in radiotherapy) is proposed.

K e y w o r d s : ***radiotherapy, diagnostics, dosimetry, safety, CT, PET, MR-Linac, AI.***

Introduction

Radiation diagnostics using X-rays and nuclear medicine methods are of crucial importance for the correct diagnosis of various disease states and for follow-up of treatments. The development of the technologies is going very fast. The use of CT is increasing dramatically in many countries. At the same time, the diagnostic methods based on non-ionizing radiation, such as MRI and ultrasound, are also developing rapidly. The improved diagnostics provide conditions for an improved and more individually tailored treatment of various diseases, including cancer, for which radiation therapy retains its place as an important treatment method alone or most often together with surgery, chemotherapy and now also immunotherapy. While it is important to fully exploit the potential of ionizing radiation for improved medical diagnostics and therapy, the side effects of the radiation must be under control. This applies to deterministic tissue effects as well as stochastic (mainly cancer) effects. This review article intends to highlight the ongoing development in medical radiation diagnostics and therapy. It is an update of earlier reviews in the field, e.g. (Mattsson, & Adlienė, 2013; Mattsson, Adlienė, & Laurikaitienė, 2023). At the same time, the ongoing revision of society's radiation protection standards will be highlighted.

Materials and methods

Diagnostic methods. Since 2010, there has been a new imaging technology using ionizing radiation on the market every five years (IAEA, 2024; compare Fig. 1). After introduction, it has shown to take in average 10–15 years for a more widespread implementation in clinical practice (IAEA, 2024).

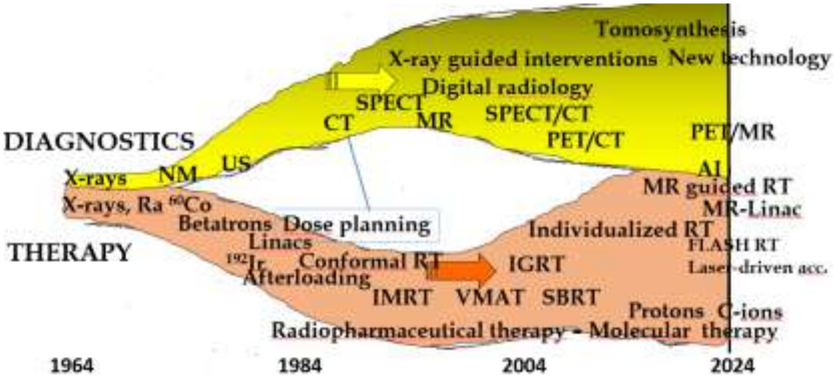

Fig. 1. Schematic description of developments in medical physics for diagnostics as well as radiation therapy since the 1960's.

IMRT=intensity modulated radiation therapy, VMAT=volumetric modulated arc therapy, IGRT=image guided radiation therapy, SBRT=stereotactic body radiation therapy, NM=nuclear medicine, US=ultrasound, CT=computed tomography, SPECT=single photon computed tomograpy, PET=positron emission tomography, MR(I)=magnetic resonanse (imaging), AI=artificial intelligense

The most common types of new imaging techniques implemented in diagnostic and interventional radiology are photon-counting CT, dual-energy CT and cone beam CT (CBCT) scanners, and breast tomosynthesis systems. The use of CT has been instrumental in the improvements of radiation therapy dose planning. Using CBCT for image-guided radiation therapy ensures a more precise delivery of the absorbed dose than was previously possible, but it will also cause an increase in the patient dose outside the treated volume.

Whole body PET/CT scanners have become more and more common in clinical practice. Recently, a new image reconstruction method that enables simultaneous imaging of two PET substances at the same time (Pratt et al., 2023) has been developed. One can be labelled with a pure β^+-emitter (e.g. ^{18}F) and the other with a positron emitter which also simultaneously emits a gamma-photon (e.g. ^{124}I). With the help of this "multiplexed PET", the amount of information is increased during a single scan. Also the use of SPECT/CT has increased in the managing of chronic diseases. The use of other so called hybrid imaging technologies combining *anatomic* (ultrasound, CT, and/or magnetic resonance (MR) imaging (MRI) *and molecular imaging modalities* (SPECT and PET) is also increasing.

Therapeutic methods. The use of multi-modality imaging in radiation therapy is increasing significantly. It is an important task to optimise these images – for improved target volume definition, treatment planning, for image-guided radiotherapy, for monitoring the motion during treatment and for response evaluation.

External radiation therapy. Computed tomography (CT) has, as mentioned above, revolutionized external beam radiation therapy by making it possible to visualize and segment tumors and organs at risk in a three-dimensional manner. However, CT has some limitations in terms of tissue characterization and delineation. Over the last decade there has been an increased clinical use of both MRI and PET to enable accurate delineation of the target volume (Decazes et al., 2021). The radiotherapy workflow does however still depend on CT information as the treatment planning softwares require attenuation data to be able to perform accurate dose calculation and to generate reference images for positioning. It has been shown that it is possible to generate CT equivalent information based on MR data, and with this technology it will be possible to abandon the CT for those diagnoses where MR is the modality of choice for target delineation (Nyholm, & Jonsson, 2015).

Three-dimensional conformal radiotherapy, intensity-modulated radiotherapy (IMRT), stereotactic body radiotherapy (SBRT), and image-guided radiotherapy (IGT) have facilitated tumour delineations and dose delivery. Today modulated radiation treatment techniques are used for both photon and particle beam irradiations. The most common technique today is volumetric modulated arc therapy (VMAT) delivered with high energy photon beams (Koka et al., 2022). The introduction of modulated treatment techniques has for some patient groups been revolutionising, e.g. for those with head and neck cancer and cancer in the pelvic region (Bäck et al., 2017). The modulated techniques are however associated with an increased treatment complexity and a larger uncertainty in the delivered dose distribution to the patient compared to the conventional treatment technique (Bäck et al., 2017). An important task is therefore to evaluate and reduce the absorbed dose uncertainty for modulated radiation therapy. A reduced dose uncertainty makes it possible to improve the quality of the treatments to enable a higher degree of individual adaption and optimisation and to increase the quality of clinical trials (Götstedt, Karlsson, & Bäck, 2023). There is still a need to improve target volume definition and also to explore the possibilities of artificial intelligence (AI) and automation (Fromherz, & Makary, 2022). The recent combination of MR scanners with treatment machines (MR-Linacs) has pushed the integration of treatment and imaging further, enabling simultaneous visualization and treatment of the target (Liu, Li, & Yin, 2023). Recently an on-line ionising radiation acoustic imaging system has been developed, which directly images the absorbed dose distribution inside the patient without interfering with the treatment delivery (Zhang et al., 2023).

Proton therapy is a promising treatment technique especially for patients whose tumors are close to sensitive organs in the head, chest, or abdominal cavity. A proton beam can be controlled more precisely than traditional photon radiation, which can reduce the risk of side effects. The energy in a proton beam can be varied so that the radiation dose almost entirely ends up at a certain predetermined depth. Therefore, radiation with proton therapy can be almost completely concentrated on the tumor itself, thus the absorbed dose can be increased, while maintaining a low dose to the surrounding normal tissues. Proton therapy is particularly suitable for children and adolescents since fewer long-term side effects are expected than from conventional therapy. In a few places in the world, therapy is also done with heavier ions, usually carbon ions. Compared to protons, the carbon ion beams add to the geographical precision also a higher biological effectiveness for treatment of some specific types of cancer.

FLASH radiotherapy is defined as an ultra-fast delivery of radiation at absorbed dose rates several orders of magnitude greater than those used in conventional radiotherapy (40 Gy/s versus 0.5–5 Gy/min). Recent animal studies have shown that FLASH radiotherapy can reduce radiation-induced damage in healthy tissues (Giuliano et al., 2023). Before FLASH can be used routinely in the clinic, the biomedical mechanisms behind the FLASH effect must be understood, demonstrating that it indeed reduces normal tissue toxicity, and its impact on medical personnel and instrumentation characterized.

For proton therapy, FLASH treatments may also prove beneficial by significantly increasing patient throughput, while improving treatment outcomes and reducing side effects.

Laser-driven accelerators. In the future, laser-driven accelerators may be an alternative to providing compact and cost-effective particle and photon sources. The accelerating field is a plasma, driven by intense laser pulses, and is typically several orders of magnitude larger than that of radiofrequency (RF) accelerators, while control of plasma media and intense laser pulses is very demanding. Therefore, many efforts have been directed towards developing compact, high-quality particle beams and radiation sources based on intense laser-plasma interactions, with the goal of paving the way for these new sources to be used in a variety of applications (Kojima, & Hata, 2023). Using a laser-driven ion source could mark a radical new approach, reducing the transport and delivery costs of the particle beam.

Artificial intelligence in the medical use of radiation. Artificial intelligence tools that can help with patient dose optimization and image-recognition and interpretation, automatic merging of images and digital mobile radiography, treatment planning, and response assessment, leading to more precise and individualized imaging and treatments are being introduced at high speed. However, the instantaneous image interpretation is the ultimate ambition of AI. Although AI technology has not yet achieved this ability in a broad sense, some examples of applications involve image segmentation, reconstruction, and disease registration. AI segmentation has the ability to automatically delineate structures and provide measurements such as organ volume or the surface area of a tumour. Taken a step further, these AI algorithms can hopefully be specialized to stage tumours and provide pre-interpreted read-outs such as scores for cancer staging. Automated segmentation and pre-interpreted read-outs may be maximally utilized in areas that have the most amount of data, such as screening imaging studies.

Theranostics. The concept or expression theranostics (alt. theragnostics) is defined as a combination of molecularly targeted imaging and therapy in which imaging provides information that enables new or more effective therapies, with the purpose of delivering treatment to each health condition, focusing on tailoring the approach for each patient (Pini, Gelardi, & Sollini, 2022). In nuclear medicine, the same radiopharmaceutical is used both for finding cancer cells and delivering targeted radiation to kill those cells.

Radiomics. Radiomics refers to the extraction of quantitative features from medical images, thus converting the digital images into extractable data, which offer unique biological information that can enhance our understanding of disease processes and provide clinical decision support. (McCague et al., 2023). ("Omics" is a new term that has emerged to describe the field of large-scale data-rich biology). These features have the potential to uncover tumour patterns and characteristics that fail to be seen by the naked eye and converts them into useful data. The driving hypothesis is that these features reflect the underlying biology.

Dosiomics. Dosiomic means trying to extract a dose distribution in 3D using data characterization algorithms to be able to predict radiation therapy response, both in terms of tumor and side effects in the form of e.g. radiation pneumonitis (McCague et al., 2023).

RADIATION PROTECTION FOR PATIENTS. There have been concerns about the increase of dose to patients from some newer imaging technologies that go against the prevailing impression that the newer technologies provide less patient dose, e.g. (Rehani, & Nacouzi, 2020; IAEA, 2024).

The findings (IAEA, 2024) indicate that there are remaining challenges, such as: missing policies, lack of guidelines, appropriateness criteria and audit programmes in the new aspects of radiological imaging practices. The lack of human resources in the medical imaging fields, inadequate training, and obsolete educational curricula are also pointed out as problems for the implementation of the radiation protection requirements.

NEED FOR INDIVIDUAL OPTIMISATION IN DIAGNOSTICS. Individual patient dosimetry is well established in radiotherapy treatment planning where organ and tumour doses are patient specific. Recent developments that involve the application of imaging data, anthropomorphic phantoms and Monte Carlo calculations have led to real time treatment planning capability where tumour and organ doses are accurately assessed prior to an exposure. Such techniques are equally applicable to diagnostic image planning, whereby organ doses as well as accurate virtual images of normal anatomy can be produced for every patient examination.

Reporting of images by means of AI algorithms will mean that diagnostic accuracy as well as organ dose risk factors would be available for every patient, thus providing the basis for true optimisation (Moores, & Mattsson, 2023; Rehani, & Xu, 2024).

RADIATION SAFETY FOR PERSONNELL. The annual effective dose limit at occupational exposures is 20 mSv averaged over 5 years, with no single year exceeding 50 mSv (ICRP, 2007). The same limits apply to the equivalent dose to the lens of the eye (ICRP, 2012) while the equivalent dose limits for skin hands and feet is 500 mSv per year (ICRP, 2007). For members of the public the annual effective dose limit is 1 mSv per year on average.

ONGOING REVISION OF THE ICRP RECOMMENDATIONS. The current recommendations from the International Commission on Radiological Protection (ICRP) are from 2007 and ICRP has now finished the first phase of its work towards a review and revision of the recommendations. In the initial work, ICRP has identified some areas of research to support the System of radiological protection (Laurier et al., 2021). Views from inside ICRP (Clement et al., 2021) as well as from people outside ICRP (Rühm et al., 2022) have been asked for and the results have been reported and discussed.

When it comes to radiation risk assessments, the reviews point to the need for: 1) Better characterization of tissue reactions; 2) Stochastic effects and radiation detriment; 3) Individual response of humans to radiation; 4) Radiation effects on non-human biota. Other requirements are: 1) Dosimetry in emergency situations; 2) Identification of dosimetric targets in organs and tissues, as well as 3) Dosimetric targets and methodology for the protection of the environment; 4) Biokinetic models for human tissues; 5) Development and use of radiation technologies (medical use implications, veterinary practice implications, NORM, natural sources); 6) Ecosystem protection; 7) Research needs for the application of the system of radiological protection (AI, social science, stakeholder involvement, communication); 8) Ethics, and 9) Behavioral science.

EDUCATION, TRAINING AND RESEARCH. The development in medical imaging and radiation oncology as well as in medical physics and technology is fast and impressive. In order to take advantage of all the opportunities that are now opening up, increased efforts from medical physics are needed. This means that there is a need for sufficient staffing, an in-depth collaboration between personnel from different areas and good training of new employees in the form of basic education and training as well as active research. At its symposium in Vancouver in 2022 (Rühm et al., 2023), ICRP called for action to strengthen expertise in radiological protection worldwide through:

• National governments and funding agencies strengthening resources for radiological protection research allocated by governments and international organisations,

• National research laboratories and other institutions launching and sustaining long-term research programmes,

• Universities developing undergraduate and graduate job opportunities in radiation-related fields,

• Using plain language when interacting with the public and decision makers about radiological protection, and,

• Fostering general awareness of radiation and radiological protection through education and training of information multipliers.

Discussion and conclusions

The field of medical radiation physics is developing rapidly. The boundaries between medical physics specialties disappear in step with the increased use of imaging to guide the radiation therapy to obtain personalized and adaptive treatments. The use of AI will be an essential part of the future. The increasing use of software and AI will change the role of medical physicists but the need for the skills of medical physicists will increase. They are also needed for the development of new technology and to ensure that the technology is understood and used correctly. It can be expected that the developments towards more and more individualised diagnostics and therapy will continue, which will require increased precision and accuracy in both radiotherapy and radiological diagnostics.

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Сьорен МАТТССОН, д-р філософії, проф.
ORCID ID: 0000-0002-6443-1913
e-mail: soren.mattsson@med.lu.se
Лундський університет, Університетська лікарня Сконе, Мальме, Швеція

СУЧАСНИЙ РОЗВИТОК МЕДИЧНОЇ РАДІАЦІЙНОЇ ФІЗИКИ ТА РАДІАЦІЙНОГО ЗАХИСТУ

Розглянуто сучасні тенденції та перспективні напрями розвитку діагностики і терапії з використанням іонізуючого випромінювання. Узагальнено останні досягнення медичної фізики, які впроваджені у променевій терапії, діагностичній радіології, ядерній медицині, МРТ та радіаційній безпеці. Сьогодні велику увагу спрямовано на розвиток створення умов для індивідуальної діагностики та терапії пацієнта, що вимагає підвищеної коректності як у радіологічній діагностиці, так і в променевій терапії. До сфери активного розвитку належить використання штучного інтелекту (ШІ) для покращення діагностики і терапії, тераностики, радіоміки та дозіоміки. Усі ці підходи є частиною так званої прецизійної або

персоналізованої медицини. Також коментується поточний перегляд рекомендацій МКРЗ щодо радіаційного захисту. Для оцінювання дози та ризику в діагностичних додатках (рентгенівська томографія, КТ, інтервенційна радіологія, діагностична ядерна медицина) пропонується перехід від середніх фантомів, методів розрахунку та показників ризику на основі популяції до методів розрахунку, фантомів та показників ризику для кожного пацієнта (як це робиться в променевій терапії).

К л ю ч о в і с л о в а : ***променева терапія, діагностика, дозиметрія, безпека, КТ, ПЕТ, MR-Linac, ШІ.***

Член програмного комітету С. Маттссон заявляє про відсутність конфлікту інтересів та невтручання в процес оцінювання цієї статті відповідно до міжнародних стандартів публікаційної етики. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

The member of the Program committee S. Mattsson declares no conflict of interest and has not interfered in the evaluation process of this article, in accordance with international publication ethics standards. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results.