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Advancing Diagnostic Medical Physics: AI, MR-Guided Radiotherapy, and 3D Printing in Modern Healthcare

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Abstract
Modern medical practice incorporates to implementation of new technologies such as artificial intelligence (AI), MR-guided radiotherapy, 3D printing, and diagnostic medical physics co-evolves. Specifically, this paper describes a pressing need for diagnostic medical physicists in the realistic augmented development of imaging modalities for accurate diagnosis with as little radiation exposition as possible. AI integration has resulted in great improvements in efficiency such as automated detection of anomalies, real-time tumor delineation, adaptive treatment planning, and many challenges including but not limited to algorithmic bias and data privacy. For instance, MR-guided radiotherapy offers an unparalleled level of precision in the treatment of dynamic

tumors through novel soft tissue imaging and adaptive radiation delivery combined. Further, 3D printing is a means of creating custom options for example, patient-specific anatomical models and prosthetics, personalized care, and optimized outcomes. However these advances do not come without ethical, regulatory, and interdisciplinary challenges, and, as diagnostic medical physicists, we have the responsibility for helping to ensure that safety and efficacy are maintained. These challenges need solutions from the medical physics community and more widely medical and research communities.

Keywords: Diagnostic Medical Physics, Artificial Intelligence (AI) in Imaging, MR-Guided Radiotherapy, 3D Printing in Healthcare, Advanced Imaging Modalities, Radiation Therapy, Personalized Medicine, Ethical AI Deployment, Radiation Dose Optimization, Tumor Delineation

Introduction

In the opinion of the author diagnostic medical physics appears as an interesting blend of physics, where from among medical applications those play a vital role in modern health care. The development and optimization for safe and effective use of imaging and therapeutic technologies is based on this. The main imaging modalities by which clinicians can accurately delineate structures and assess the function of the body comprise X-rays, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, and nuclear medicine. Being able to diagnose different medical conditions like cancer and cardiac problems with the least ionizing radiation exposure to patient cells (Jeraj et al., 2009; Hendee & Ritenour, 2020) is the key result of this analysis.

This expansion is factored in by incorporating new and often 'intelligent' technologies, especially artificial intelligence (AI) technologies for medical applications. Convolutional neural networks (CNN) are artificial systems that have revolutionized independent tomography, the detection of abnormalities, and the separation of tumors. Finally, computational tools like that developed by DeepMind's AlphaFold have reached unprecedented accuracy in predicting protein structure – a disruption with far-reaching implications for molecular imaging and personalized medicine (Jumper et al., 2021). Furthermore, AI speeds up clinics' work cycles by eliminating uninteresting tasks and reducing other diagnosis mistakes while hastening the disease detection process (Litjens et al., 2017; Liu et al., 2023).

This includes MR-guided radiotherapy systems such as Elekta Unity and ViewRay MRIdian systems. These systems combine the superb soft tissue imaging capabilities of MRI with real-time delivery of radiation and create adaptive radiotherapy. This is particularly useful for tumors in areas with high movement (e.g. pancreas, lungs), where it most matters to dose the radiation to something in real time to minimize collateral damage to adjacent healthy tissue (Raaymakers et al., 2017; Lagendijk et al., 2018).

3D printing in medical physics is also another innovation that altered patient care. 3D printing creates patient-specific anatomical models, used for surgical planning, custom prosthetics, and customized radiation therapy. Although the implementation of 3D-printed materials in the clinics has been mainly limited to peer-reviewed implementations of the use of patient-specific bolus material to

improve dose conformity for head and neck and breast cancer radiotherapy (Morrison et al., 2020; Ehler et al., 2018), there has been increasing use of various printing techniques for the development of patient-specific products in clinics.
The complexities involved with these advancements are the challenges. Like all other fields, the transition to greater reliance on AI can lead to problems of ethics such as data privacy, algorithmic transparency, and sensibilities in the training sets. However, these issues should not be ignored and the role of the diagnostic medical physicist is determining how to guide AI to be a trusted member of the clinical team. They are an essential tool in ensuring trust and reliability of medical technology applications within existing regulatory standards and promote trust and reliability in using AI systems for validating AI for its unbiased results (Gallo & Veronese, 2022; IAEA, 2023).
Medical physicists, in addition to radiation safety, have the task of applying to patients, as low as reasonably achievable (ALARA), that is, efficient treatment. Thus, it is appropriate that patient exposure levels be as low as possible while the diagnostic yield is as high as possible. Recent developments in low-dose CT imaging and iterative reconstruction algorithms which have equally affected the radiation risks of patients, without losing sight of image clarity have further reinforced this balance (Boedeker et al., 2017).
Diagnostic medical physics is more interdisciplinary than ever and now requires collaboration among radiologists, oncologists, and biomedical engineers. Diagnostic medical physics roles and responsibilities are being transformed by emerging technologies, such as AI, MRguided radiotherapy, and 3d printing. It touches on ethical and regulatory concerns associated with these innovations and points to the important role of the medical physicist in quality and safety in healthcare.

Literature Review

Diagnostic medical physics has changed slowly from simply performing basic radiation protection and imaging calibration to the direct application of advanced technologies including artificial intelligence (AI), magnetic resonance (MR) guided radiotherapy, and 3D printing. Medical physicists acted primarily to determine and confirm doses to limit radiation exposure risk to patients and other healthcare workers (Vetter et al., 2004). Sometime over the years, the medical imaging and therapy systems have matured increasingly to the extent that medical physicists are today required to assist in the implementation of AI algorithms in complicated aspects of the clinical diagnostics and therapy pipeline.
Diagnostic medical physics has continued as a radiation protection priority Then, early efforts concentrated on reducing radiation hazards through accurate dose calculations and implementation of strict quality assurance regimes (Cypel & Sunshine, 2004). Increasing complexities in the delivery of radiation treatment and the underlying requirements for better quality control and calibration practices have faced advancements in imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET) (Malicki, 2015). Medical physicists for MR-guided radiotherapy make the accurate delivery of treatment to basins of complex anatomy possible (Kurz et al., 2020), where radiation treatments are

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synchronized with real-time MRI to enable unparalleled treatment precision.
In the last few years, the impact of AI has been a game changer for diagnostic medical physics, especially radiation oncology (RO). With the rapid advancement of machine learning (ML) and deep learning algorithms, imaging, treatment planning, and dose optimization have become much more advanced. Recently, AI-based systems have been used to automate tasks e.g. tumor delineation and organ segmentation, which have been performed manually so far by clinicians. Per (2023), Liu et al. showed that CNN-based models provide greater accuracy in labeling and finding anatomical structures than human perception. Another major application of AI in treatment planning is in developing models for predicting how radiation doses are distributed within an organ so that healthcare professionals may tailor treatment plans (Zhao et al., 2019). Adaptation therapy opens the possibility of calculating the real-time motion of the tumor and adapting treatments according to it (Mardani et al., 2016), in regions such as the lungs, where motion is high.
3D printing in conjunction with the capabilities of AI revolutionizes medical physics by taking advantage of patient-specific models built on accurate anatomical structures. These models are used in anesthesia immersion planning and space in medical practice, implant production, and radiation therapy. For example, in gynecological oncology, 3D print boluses are very useful in optimizing the dose distribution with radiation therapy. Furthermore, 3D printing has allowed patient-specific molds and implants to improve the accuracy of the treatment in complex fields such as skin cancer, and head and neck tumors (Segedin et al., 2023). These devices have adhered to many clinical specifications, which include radiation shielding requirements and dose conformity, playing a key role in ensuring that medical physicists have had a role to play in making sure.
Nevertheless, the inclusion of AI in medical physics is increasingly also accompanied by important ethical issues. Data privacy and algorithmic transparency, and the possibility of biases in AI systems, are becoming more and more buzzworthy. According to Gallo and Veronese (2022), given the ethical dilemmas and challenges AI raises in clinical settings, they called to make algorithms' decision-making transparent and to reduce possible bias to justify fair practice of clinical work. Medical physicists are at the forefront of addressing these issues, as they work to ensure that AI applications are conducted ethically, operate with a patient's data privacy in mind, and adhere to regulations that support just patient care.
Therefore, the need for interdisciplinary collaboration has been accentuated with the integration of new technologies such as artificial intelligence (AI) for the acceleration of the treatment process, MR-guided radiotherapy, and 3D printing for patient-specific solutions in medical physics. Medical physicists help clinicians, engineers, and regulatory organizations to make sure these new technologies are deployed properly to benefit patients maximally. The simultaneous integration of these advanced technologies has allowed diagnostic medical physics to be able to provide more accurate, efficient, and individualized therapies, particularly in complicated oncology cases. The significance of pairing technological advancements with specific patient safety protocols is increasingly revealed by this growing body of research, as the best potential effects of each are turned. With ever-advancing diagnostic imaging, therapeutic techniques, and

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personalized medicine, medical physicists continue to be at the forefront of innovation as well as practical application of the new tools in clinical practice. But used wisely, these technologies could improve medical practice and improve diagnoses treatment, and outcomes in practice.

Table 1: Evolution of Diagnostic Medical Physics and Technological Integration

Period	Technological Advancements	Key Development Areas	Impact on Medical Physics	Sources
1940s-1950s	X-ray Imaging	Early diagnostic techniques	Initial diagnostic methods for disease detection	Kurz et al., 2020, IAEA, 2023
1970s	CT Scans	Introduction of computed tomography (CT) imaging	Revolutionized non-invasive diagnostic imaging	Kurz et al., 2020, Gallo & Veronese, 2022
1980s-1990s	MRI	Magnetic Resonance Imaging (MRI) technology	Enhanced tissue differentiation and imaging capabilities	Kurz et al., 2020, Caruana et al., 2008
2000s	Integration of AI in imaging (e.g., image segmentation, treatment planning)	AI-driven diagnostics	Improved accuracy in image analysis and treatment planning	Gallo & Veronese, 2022
2010s-2020s	MR-guided Radiotherapy, AI-enhanced imaging, Adaptive Treatment Planning, Robotic Surgery	Real-time imaging and adaptive treatment systems, AI in radiation therapy	Enhanced treatment precision, real-time adjustments in radiation therapy	IAEA, 2023, Kurz et al., 2020

Diagnostic Imaging Techniques

Diagnostic imaging is an essential aspect in the early diagnosis and treatment of many medical illnesses which permits clinicians to visualize the internal structures of the body and study its physiological functions. These techniques use these approaches to detect diseases such as cancers, cardiovascular diseases, and musculoskeletal diseases using noninvasive approaches. These imaging modalities are monitored for their safety, optimized to allow for the best quality imaging, and medically accepted by medical physicists. The most common diagnostic imaging modalities include X-rays, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, and nuclear medicine. Each

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modality has its advantages, and usually, a combination of differing modalities is used to obtain a complete image of a patient's affliction.

X-Rays and Computed Tomography (CT) Scans
One of the oldest and most widely used tools for diagnosis in modern practice is X-ray imaging. Using ionizing radiation, it produces images of internal body structures and is essential to the diagnosis of bone fractures, infections, and some tumors. It can also yield fast, effective imaging of a bone injury or a lung condition that must be evaluated in emergency settings. X-ray imaging is such an important part of modern medicine, but this comes with limitations, as excessive exposure to the ionizing radiation used has been linked with an increased risk of cancer (Brenner et al., 2007). Computed tomography, or CT, is a newer, more advanced form of X-ray imaging that greatly expands the range of diagnostic possibilities by taking multiple, different X-ray images from different angles and combining them to form cross-sectional slices of the body. Because of this capability, CT scans are a diagnostic that is now indispensable in the diagnosis of complex pathologies including injuries of the brain, cancers, and cardiovascular diseases (AAPM, 1993). However, radiation exposures from CT are considerably higher than from conventional X-ray studies and therefore involve some risk, especially for children and pregnant women. Over the past few years, artificial intelligence (AI) has dramatically increased the performance and safety of CT imaging. Achieving this has been possible with the availability of AI-driven IR techniques which not only provide substantial radiation dose reduction but also improve image quality by a factor of several hundred. Noise can be minimized and images can be displayed better through such techniques – to the maximal extent without having to make exposure from a higher degree of radiation (Shen et al., 2022). The imaging protocols are adapted and optimized, using smart AI algorithms based on the individual patient, to give the patient the lowest dose of radiation and diagnostic accuracy. While readers are assisted, AI has proven invaluable in predicting the risk associated with diseases in the first place using CT imaging, enhancing workflow efficiency and accuracy for diagnostic tests (Liu, et al. 2023). Thus, CT imaging systems are inextricably connected to medical physicists because of their important role in designing and maintaining these important nuclear safety devices. They calibrate the systems; they ensure safe radiation doses; they are the arbiters and enforcers of a severe quality control program. Medical physicists ensure high-quality diagnostic images occur without exposing patients to unnecessary radiation exposure related to the use of CT equipment. With that knowledge, the patient's protection of the diagnosis advocate, and their duties are protected along with the evidence of medicaments (the continued utility of their find) (Frenso, 2021).

Magnetic Resonance Imaging (MRI) and MR-Guided Radiotherapy
(MRI) is a medical imaging technique that uses strong magnetic fields and radio waves to produce detailed images of soft tissues, non invasively. Unlike X–rays and CT scans, MRIs are a safer imaging option using no ionizing radiation, which means imaging parts of the body like the brain, heart, and muscles. It can hopefully show a better contrast for soft tissue as opposed to X-ray, and be amazing for checking out many neurological disorders, cardiovascular illnesses, and musculoskeletal accidents. In addition, it is nonintrusive to facilitate imaging

sessions several times without the fear of radiation exposure (Haacke et al., 2019). MR-guided radiotherapy is one such revolutionary development in MRI technology that has incorporated features of MRI's high-resolution imaging with that of radiotherapy precision. Using their implementation approach, they were able to observe the treatment in real-time and potentially follow the movement of the tumor while adapting the delivery of radiation on the fly. Tumors situated in areas subject to motion can move to positions that make treatment challenging for example, in the lungs, where respiration can move the tumor so this kind of adaptability is particularly important. Because these variations can not be precisely planned, MR-guided radiotherapy delivers greater accuracy by constantly accounting for the variations that focus on the tumors, sparing the surrounding healthy tissues (Gallo & Veronese, 2022). Medical physicists are crucially involved in the deployment and optimization of MR-guided radiotherapy systems. They also make sure the imaging and radiation delivery components perfectly work together and deliver exactly as desired. Finally, medical physicists will validate algorithms to make sure an AI system, when used to track a tumor or assist in treatment planning, plays nicely within the clinical setting. They have a good ability to boost the precision of treatment and have important impacts on patient outcomes, so this vivid technology is the main issue (Liu et al., 2023).

Ultrasound and AI-Enhanced Imaging

Ultrasound imaging is one of the most common tools in the diagnosis of many diseases, using high-frequency sound waves to produce images of soft tissues in real time. This imaging technique has wide application for such sensitive procedures as assaying maternal fetal growth during pregnancy, etc, unique in utilizing sound waves rather than potentially harmful ionizing radiation. Additionally, ultrasonography is commonly performed in cardiology and vascular studies owing to its ability to deliver dynamic real-time imaging. What is so great is that it is portable and affordable, adding to the usefulness of the device which is a very necessary device to have in many different clinical situations from the emergency department to the outpatient clinic (Frenso, 2021). Ultrasound imaging is rapidly changing through recent developments recently on artificial intelligence (AI) applications that would help improve the current precise diagnostic tools promptly. Tissue characterization, anomaly detection, and image optimization have started to be automated with AI algorithms, providing smoothing operator dependence. These systems can look at ultrasound images and automatically identify and classify abnormalities so that doctors will no longer try to guess an unidentified spot in an ultrasound image thus doctors can procure quicker and more accurate diagnoses. For example, AI-enabled ultrasound has demonstrated that in some cases like when diagnosing liver and breast abnormalities, it can be more accurate than a human in making diagnoses by picking up on cues a human might completely miss (Duke University, 2024). Additionally, AI can automatically tune ultrasound settings on the fly based on the parameters of a specific patient, and clinical objectives, leading to a better signal-to-noise ratio with less manual input. The significance of the medical physicist's role in ensuring reliable and consistent performance of these systems increases as ultrasound systems, and especially systems using AI technologies, become more sophisticated. One of their tasks is to check whether the equipment

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is calibrated correctly and whether AI-enhanced algorithms behave as expected. These standards enable medical physicists to play an important part in uniform, high-quality images covering multiple clinical settings, thereby maintaining the consistency of diagnostics.

Nuclear Medicine and Positron Emission Tomography (PET) Imaging

Imaging with Nuclear medicine, and in particular with Positron Emission Tomography (PET) imaging, provides important information on tissue metabolic and molecular activity. For positron emission tomography (PET) imaging, the tracer is most commonly injected into the body, and positions released from the tracer annihilate electrons from the environment. Specialized scanners can detect the gamma rays the body is emitting, allowing clinicians to see, at the cellular level, what's happening in patients' bodies. Oncology, cardiology, and neurology are classic fields of application for PET to determine tumor viability, evaluate the response to treatment, and detect metastasis. Of all the imaging modalities like CT or MRI, PET excels at visualizing cellular activity (Chen et al., 2019). PET imaging, from diagnosis to operations, has been transformed by AI-based solutions. At the same time, machine learning-based image reconstruction algorithms have been able to significantly boost the quality of the corresponding PET image, but also enable dose reduction of the relevant radiation doses. Additionally, the evaluation of metabolic patterns with more sensitive tumor detection, characterization, and staging are being re-engineered by AI. This technology is particularly important in oncology where proper tumor staging is critical for the formulation of the correct treatment paradigms (Ouyang et al., 2019). Additionally, artificial intelligence is also used to develop hybrid imaging systems that combine PET with CT or MRI so that clinicians can merge function-specific information from PET with detailed anatomical images from CT or MRI. It allows understanding of what is happening with the patient from data across multiple channels to assist in accurate diagnosis and treatment planning (Zhao et al., 2021). The role of a medical physicist in the use of PET imaging in an effective manner. Typical responsibilities of medical physicists include PET calibration to detect tracer response and optimize radiation dosimetry for optimal efficacy versus off-target activity and safety. Also, medical physicists ensure these AI-based algorithms or models used in PET imaging quality provides, which go through a thorough, clinical need-compliant, and accurate diagnostic output validating process. The accuracy, safety, and effectiveness of PET imaging procedures depend upon expertise (Chen et al., 2019).

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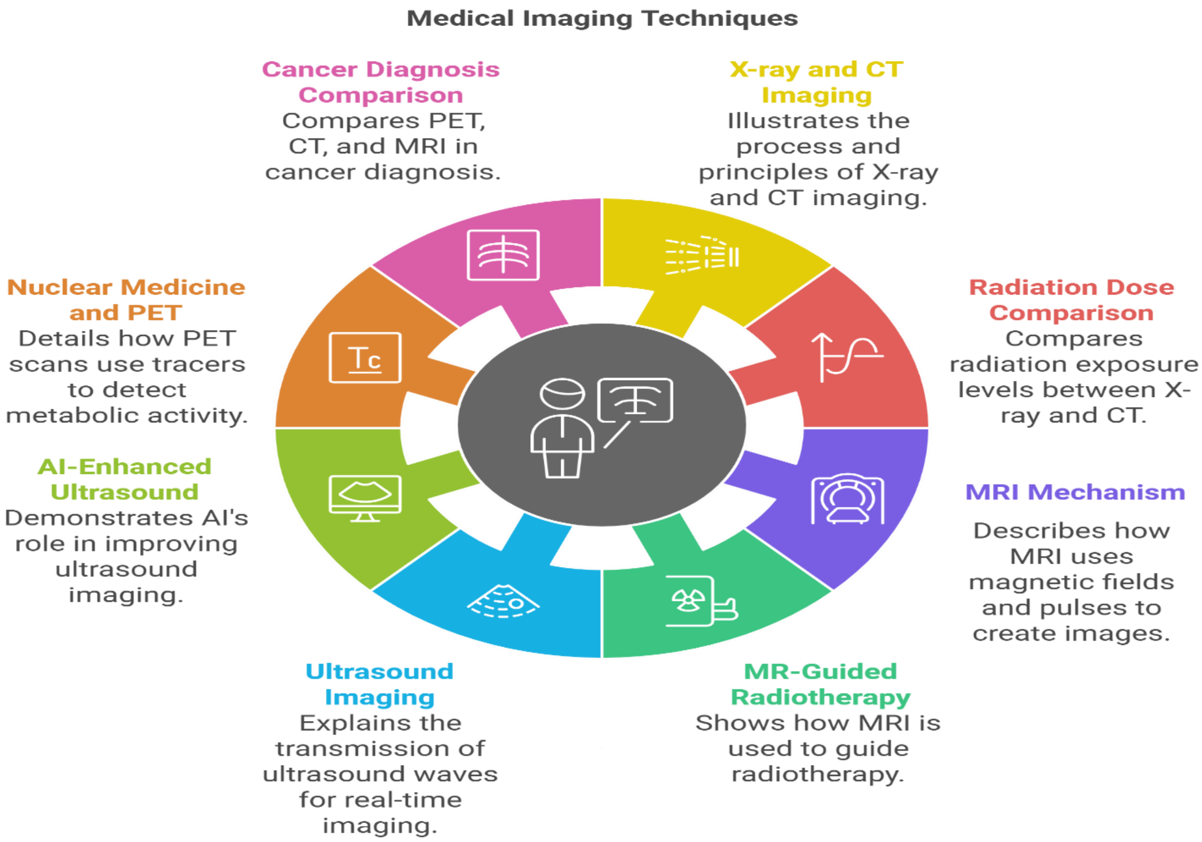

Figure 1: Medical Imaging Techniques

Table 2: Comparative Analysis of Diagnostic Imaging Modalities with AI Advancements

Imaging Modality	**Key Features**	**Major Applications**	**AI-Driven Advancements**
X-Rays	Quick imaging using ionizing radiation	Diagnosing fractures, lung infections, tumors	Noise reduction, radiation dose optimization, anomaly detection using AI
Computed Tomography (CT)	Detailed cross-sectional imaging via X-rays	Brain injuries, cancers, cardiovascular diseases	AI-based iterative reconstruction, patient-specific imaging protocols, condition prediction
Magnetic Resonance Imaging (MRI)	Non-ionizing imaging with superior soft tissue contrast	Neurological disorders, cardiac diseases, muscles	AI for tumor tracking, enhanced image segmentation, real-time adjustment in MR-guided radiotherapy
Ultrasound	Real-time imaging using sound waves	Obstetrics, cardiology, vascular imaging	Automated anomaly detection, tissue characterization,

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			dynamic setting optimization
Positron Emission Tomography (PET)	Molecular imaging with radioactive tracers	Oncology, cardiology, neurology	Hybrid imaging (PET-CT, PET-MRI), enhanced tumor staging and characterization using AI.

AI Applications in Diagnostic Medical Physics and Radiation Therapy
Artificial Intelligence (AI) has become an indispensable tool of diagnostic medical physics through the development of AI as an enhancement tool for imaging accuracy, automation of complex processes, and optimization of treatment planning, which has radically transformed radiation therapy. Different phases during the radiation therapy workflow (image segmentation, target volume delineation, dose prediction, and optimization, adaptive planning, and quality assurance) have used AI technologies. Improving therapeutic outcomes is the ongoing evolution of AI, which also creates new responsibilities for medical physicists. That is a responsibility that professionals in the field must ensure that AI-powered technologies are applied safely and ethically with patient safety and compliance with the relevant laws always upheld in mind.

AI in Image Segmentation and Tumor Delineation
With the introduction of Artificial Intelligence (AI), the field of image segmentation has undergone significant evolution regarding its use in medical imaging for tumor and organ at-risk delineation. After many cases were sorted manually by radiologists as well as medical physicists, this can be labor intensive and when cases did not match, they differed. Traditionally, these methods were tedious and needed a fair bit of manual work, but with the advent of AI (mainly convolutional neural networks/ CNNs), this pipeline has made it possible to automatically segment complex anatomical structures in a very accurate and efficient way. Semi-automatic tumor and organ delineation with the use of AI-based segmentation techniques have been proven to be faster, more accurate, and more reproducible. (Men et al., 2017) reported that AI is resulting in improved consistency and reliability of tumor delineation which is critical for treatment planning. In particular, these ideas are particularly useful for tumors that will move, such as as tumors that are in the lungs or abdomen, where motion due to breathing or other physiological activity would be a serious source of difficulty. For example, AI has real-time contouring potential which allows clinicians in MRgRT to create dynamic treatment plans as tumors shift inside the body during treatment. It allows the treatment of radiation to healthy tissues as much as possible while restraining the effect on tumors as little as possible, essential for effective radiotherapy. AI's role is still more important when systems are designed for real-time treatment modifications where anatomical changes throughout treatment must be continuously readapted quickly and accurately. In this process, AI validation for medical physicists is critical to ensure that these algorithms are living up to the most rigorous clinical accuracy standards. It includes making sure AI tools get built into clinical workflows and as part of technology, monitoring their performance so that there aren't errors, and always making sure that systems are delivering results that can be depended

upon, she says. Implementing standards of protocols for AI-based segmentation tool validation and surveillance and through the goodness of scientific principles will ensure the adoption and growth of AI in the clinical domain. But with this regulation, these AI technologies that will help enhance clinical efficiency will still maintain the highest standards of safety and accuracy (Liu et al., 2023).

AI for Dose Prediction and Optimization

Radiation therapy using accurate dose to the tumor is one of the most impactful areas where AI can significantly impact dose prediction and optimization. Existing dose planning tools depend on experience and manual calculations, while effective, they are limited by human mistakes and subjective interpretation. AI contrasts by utilizing large datasets to reveal patterns that can best maximize dose delivery for patients shortening treatment time and increasing accuracy. Both anatomical and clinical data can be processed by AI-based systems to supply personalized radiation treatment plans that target to destroy tumors as generously as possible while targeting to entail the least possible harm to healthy tissues. AI models in MR-guided radiotherapy have the advantage of providing the ability to change dose in real-time as the patient's anatomy changes. For instance, AI-based dose optimization tools dynamically change the radiation dose due to tumor motion (e.g. in the lung) (Zhu et al., 2018). Because this is a personalized strategy, it can serve towards better therapeutic responses, clinical outcomes, and minimization of toxicities of treatment. “Predicting and optimizing treatments with AI algorithms to estimate and optimize radiation doses require verification by medical physicists to ensure the safety and clinical suitability of the treatment algorithms. Additionally, they contribute by frequently recalibrating AI systems relative to the evolving standards of care as well as population heterogeneity of the patient population.

Real-Time Adaptive Treatment Planning with AI

Radiation therapy in real-time adaptive treatment planning has already been applied to AI, especially with MR-guided systems so far. In the case that the tumor position or shape changes during treatment, the conventional treatment planning is static and based on imaging done before treatment, which is a problem. However adaptive radiotherapy uses AI to dynamically change a treatment plan as shown in real-time imaging feedback. Tumors in organs that get mobilized within the breathing or peristaltic cycles (lung, liver, etc.) appear to need this more so. By leveraging AI algorithms, we can analyze dynamic imaging data to predict how your tissue is going to move and the structure of the organ underlying that tissue in real-time, and adjust treatment accordingly. For example, artificial intelligence can detect small variations (such as a change in size, shape, or placement) in tumor growth and then adjust, based on the growth, both the direction and intensity of the beam of radiation (Ouyang et al., 2019). Furthermore, by remaining accurate and targeting a moving tumor, this adaptability in real time is also beneficial to radiation therapy. Suppose AI adaptive planning is to become a reality. In that case, medical physicists will be integral to that reality, steering implementation in the clinic and ensuring, through their expertise, that new treatment plans are clinically appropriate and safe for patients. Here, the chief advantage of AI-driven adaptive treatment planning comes into play: The technology allows those treatments to be delivered

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with optimal precision. A big advantage of this technology is for patients who have complex anatomical structures or whose tumors are near to sensitive structures. In addition to preventing unnecessary harm, this leads to an enormous improvement in both patient outcomes and maximizing therapeutic efficacy with minimal healthy tissue irradiation.

Quality Control and Validation of AI-Enhanced Imaging Systems

The integration of AI in medical imaging and radiotherapy which already happens, will require dedicated quality control (QC) processes to achieve this with reliable and accurate outcomes with AI-enhanced systems. For example, all the requirements for the AI systems to serve all clinical aims, i.e., image reconstruction, dose planning, and segmentation, entail the validation that outputs from such systems meet clinical standards and checkbox regulatory compliance. Within this process medical physicists are important and, for instance, they for example conduct performance evaluations and routine checks to ensure that the AI model is providing consistent, in the sense of providing clinically meaningful results, in a variety of patient scenarios. As is the case for MRI-guided radiotherapy, where imaging and treatment delivery systems are combined. To do that, regular validation of AI algorithms (tumor segmentation, dose planning, treatment adaptation) must be established to determine that the accuracy is there. In this way, we can avoid discrepancies that may compromise the outcomes of the treatment or the patient's safety (Gallo & Veronese, 2022). In addition, they keep an eye on AI tools to be periodically recalibrated to avoid performance drift over time. For this reason, continuous checks are crucial to guarantee that AI algorithms do not become unfit for purpose as they are iteratively (maybe silently) updated or migrated to clinical practice. Rigorous QC practices by medical physicists maintain that bond so that AI-augmented imaging systems perform as they are designed to deliver the desired patient care that is safe, accurate, and high quality. That's particularly important given how embedded AI systems are becoming in diagnostic and therapeutic decision-making.

Ethical Implications of AI in Diagnostic Medical Physics

Introducing new technologies also comes with ethical concerns, and introducing AI into medical physics also brings its share of challenges: how do we ensure data privacy, avoid algorithmic bias, and agree on key performance indices? Large datasets on which AI models are trained are very often comprised of sensitive patient data. It is crucial to keep patients involved by making sure that this data is anonymized and treated according to strict privacy rules: The HIPAA and the GDPR. There is also a major ethical issue, in that there's the possibility of algorithmic bias. Performance metrics of individual AI model performance on nonrepresentative datasets may not represent well patient populations that had been under-represented in the training data. As a consequence, quality of care and treatment outcomes may vary from one population to another. To address this, medical physicists are necessary to validate that AI programs are discussed by diverse data sets to ensure equitable performance (Liu et al., 2023). Additionally, decisions are made in ways that are hard to understand or explain, and models can be opaque. Oftentimes this can be a black box, and for the medical domain that can be a problem because you have clinicians and patients

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that need to trust in the decisions that these AI systems are making for patients. Medical physicists are playing an increasing role in demanding transparency of AI models, and operate in an explainable and justifiable fashion.

AI in Quality Assurance and Safety

Ai broadens the scope and capability of quality assurance (QA) systems in medical physics. AI applications in the QA domain include delivery of radiation dose, equipment malfunction detection, following safety procedures, etc. AI-powered QA systems can observe the execution of radiation delivery systems based on real-time data, recognize variability and hazards concerning expected performance, and help medical physicists take necessary actions proactively to prevent any adverse events. For example, scientists could let AI alert medical physicists when the dose delivered strays from what was planned so scientists can intervene on the spot. AI-driven QA systems improve operational efficiency by offloading a variety of repetitive functions such as calibration verification, equipment performance analysis, and potential fault detection. It provides a way for medical physicists to focus on more challenging and high-stakes work, and improve patient safety and treatment quality (Malicki, 2015). Finally, AI-based QA systems help hospitals stay compliant with regulations by automatically cataloging all checks and validations in elaborate logs that support their argument of being compliant with quality and safety guidelines.

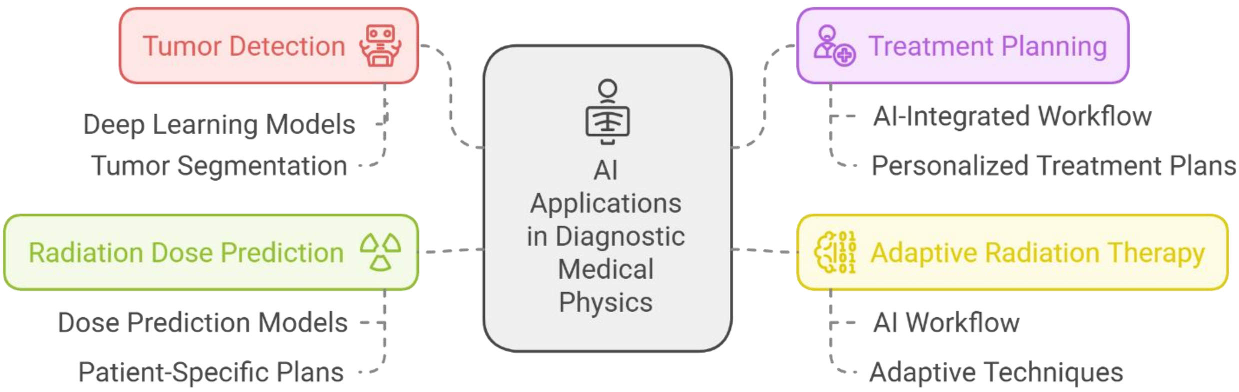

Figure 1: AI Applications in Diagnostic Medical Physics: Enhancing Precision in Tumor Detection, Treatment Planning, and Radiation Therapy

Quality Assurance and Safety Roles of Medical Physicists

The practice of medical physics in the setup of diagnostic imaging, radiotherapy, and radiation safety rests primarily on quality assurance (QA), safety, and its similarities. New medical technologies like AI in personalized medicine, MR-guided therapies, and 3D printing in medical devices will continue to grow in the area of safe, effective, reliable implementation of said technologies for human patient care and the contribution of medical physicists will continue to grow accordingly. This larger category of responsibility also includes calibration, equipment performance verification, radiation safety, quality control (QC), dose verification, and regulatory compliance.

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Equipment Calibration and Performance Verification

Medical devices must be calibrated to ensure patients get a correct diagnosis and the right treatment is delivered precisely. Radiological imaging device examples are CT, MRI, and linear accelerators, which require regular calibrations within specified limits to be in operation. Dosimetric methods used for this type of verification include various measurement methods used by medical physicists to ensure that such devices deliver the right amount (dose) of radiation or the right imaging resolution. For example, with radiotherapy, linear accelerators are required to deliver accurate doses to the tumors without (or with limited) deviations away from the prescribed dose to suboptimal tumor control and normal tissue damage (Schneider et al., 2015).

Since the magnetic field affects the radiation dose, the task of calibration becomes more difficult for new technologies like MR-guided radiotherapy. The combination of a radiotherapy system and MRI machines sensitive to magnetic fields are often paired. Effective treatment requires a synchronized performance of imaging and radiation components, making specialized calibration techniques essential to achieve a coherent performance. It is up to medical physicists to correct these discrepancies and account for the factors inherent to MRI-based guidance and radiation delivery (Macken et al., 2021).

Medical physicists also oversee and verify AI algorithms in AI-driven diagnostic imaging. While these algorithms can automate some of the diagnostic threads, such as image segmentation or lesion detection, they require rigorous testing and calibration before their performance reaches clinical performance. For example, they evaluated the performance of algorithms using specialized benchmarks and clinical data to validate precision (and therefore reliability) (He et al., 2020).

Radiation Safety Protocols and Shielding Design

Further, Medical Physics has one very concentrated area of practice and it was near the top of the heap in many points Radiation Safety was one. It covers such things as how much shielding is needed to protect patients and medical staff from harmful radiation. Medical physicists also assess the radiation output of diagnostic and therapeutic devices and recommend adequate shielding. This includes lead barriers for potential sources of lead in the environment, protective equipment designs, and patient/staff radiation dose limits. (Patterson et al., 2019).

The shielding design depends on the energy of radiation, the room treatment geometry, and the distance between personnel nearby and the source of radiation. For example, in radiotherapy, the patient treatment rooms are designed to have minimum leakage radiation. Finally, radiation safety extends to shielding but also safety protocols for patient management and it is particularly important when the patient is exposed to ionizing radiation (nuclear medicine and radiation therapy).

Another part of safety in MRI-guided radiotherapy is controlling for the strong magnetic fields generated by MRIs. MRI machines are safe for clinical use with devices that provide ionizing radiation but clinical radiographers must ensure that pacemakers or other implanted electronic devices are not actively operating simultaneously with an MRI machine as the magnetic field could interfere with these devices. Patient movement during MRI must also be considered in safety protocols because it can also affect treatment delivery (Parker et al., 2021).

Quality Control in AI-Enhanced Diagnostic Systems

Broadly, AI-informed diagnostics like image segmentation, tumor delineation, and radiotherapy predictive models are being widely adopted. To do this, these technologies and systems are incorporated to finely tune diagnosis, personalize treatment plans, and eliminate or minimize human error. With AI proliferating healthcare, medical physicists will be an integral part of the clinical quality control of these systems. Human comprehensible content requires that the performance of AI algorithms be validated and tested rigorously to clinically appropriate safety and efficacy standards.

In both radiology and radiation oncology, the adoption of AI will require continued safety evaluation. The validation studies needed to measure, in a medical context, if the AI is performing a task like tumor segmentation or predicting a dose of radiation, as well, are conducted by Medical Physicists. However, the variance in clinical data and differences in patient anatomy require continuous development of and adaptation systems for AI algorithms that are reliable and valid across multiple patients (Zhao et al., 2021). Moreover, these systems require continuing performance monitoring by medical physicists to detect any drift and bias and to ensure that the AI tools remain clinically reasonable and safe as stated by (Gavrielides et al., 2018).

Dosimetry and Dose Verification

The reliable delivery of radiation in diagnostic imaging and radiotherapy rests upon dosimetry. Medical physicists check the radiation dose patients receive against their prescribed (or prescribed) dose and treatment plan. In the domain of radiotherapy, a high dose of radiation is applied to treat a tumor; the critical point here is keeping the dose sufficiently delivered to the spot and releasing as much as possible from the healthy tissue (Jursinic, 2012).

However, because AI algorithms are frequently utilized to predict and optimize treatment plans for AI-based RT systems, the dosimetric verification of these systems is a complicated process. Validation of the algorithms should be done on actual dosimetric measurements to guarantee the delivery of correct radiation. For example, discrepancies in AI models that predict radiation dose distributions must be compared with dosimeter measurements. The validation of these processes is crucial to guarantee that, beyond the capacity of the AI system to suggest a treatment, it will not propose a treatment beyond suitable clinical parameters (Koutsouvelis et al., 2020).

There is also an effort for medical physicists to validate the dosimetric accuracy of treatment delivery systems for MR-guided radiotherapy. Patient motion and anatomy cannot be assumed static throughout a treatment session and must be verified in real-time that the planned radiation is being delivered (Nath et al., 2020).

Safety Standards and Regulatory Compliance

Because diagnostic and therapeutic technologies must be regulated by national and international authorizing authorities, medical physicists are involved in compliance with these regulations. Safe use of radiation in medicine is established by international regulators, such as the International Atomic Energy Agency (IAEA). IAEA (2018) recognizes these standards as ways in which medical physicists assist in the use of imaging and treatment technologies to

meet safety guidelines, dose limits, and other quality assurance principles.
The IAEA, for instance, publishes, for example, guidelines for the design of radiation therapy rooms, tests to be carried out on equipment, and training of staff in radiation protection. These guidelines are very important for medical physicists to play a critical role in making sure that these guidelines are to be followed and make an effort the develop institutional policies to promote device performance and patient safety criteria. This compliance is important because radiation technologies are inherently risky when misused or poorly calibrated (IAEA, 2018).
Although AI is applied to diagnostic and therapeutic environments, their regulations are beginning to suggest guidelines for AI in health care. Medical physicists now bear the responsibility of making sure that these AI systems play by the rules and safety protocols. In other words, this means that their illuminated NOTICE is confirmed in AI algorithms, that there is no hidden error or bias within them, and that they are certain in their clinical applications (Eckert et al., 2021).

Incident Response and Error Prevention

Root cause investigation of incidents due to equipment malfunction or unexpected deviation from the treatment plan is the responsibility of medical physicists. What they are most focused on, though, is making sure that the kind of mistakes they are making aren't putting patient safety at risk, and doing things about it. For instance, medical physicists may collaborate with other healthcare professionals during the delivery or imaging of radiation to detect problems that could lead to the design and implementation of corrective actions and continuous process improvement (Chmielewski et al., 2014).
Artificial intelligence (AI) systems incorporated into radiotherapy and diagnostic imaging add to the risk of error from embedded algorithmic bias or technical failure. Although physicists are not the operators, they check if the systems make any errors or if they malfunction or deviate from expected performance. Therefore, medical physicists must be involved in the pro-active identification of (and the mitigation of) these potential pitfalls even though the possible errors, such as AI-driven algorithms that mis-segment an image or incorrectly calculate a radiation dose, for instance, may not seem great at the time, but could be catastrophic (McKinney, et al., 2020).

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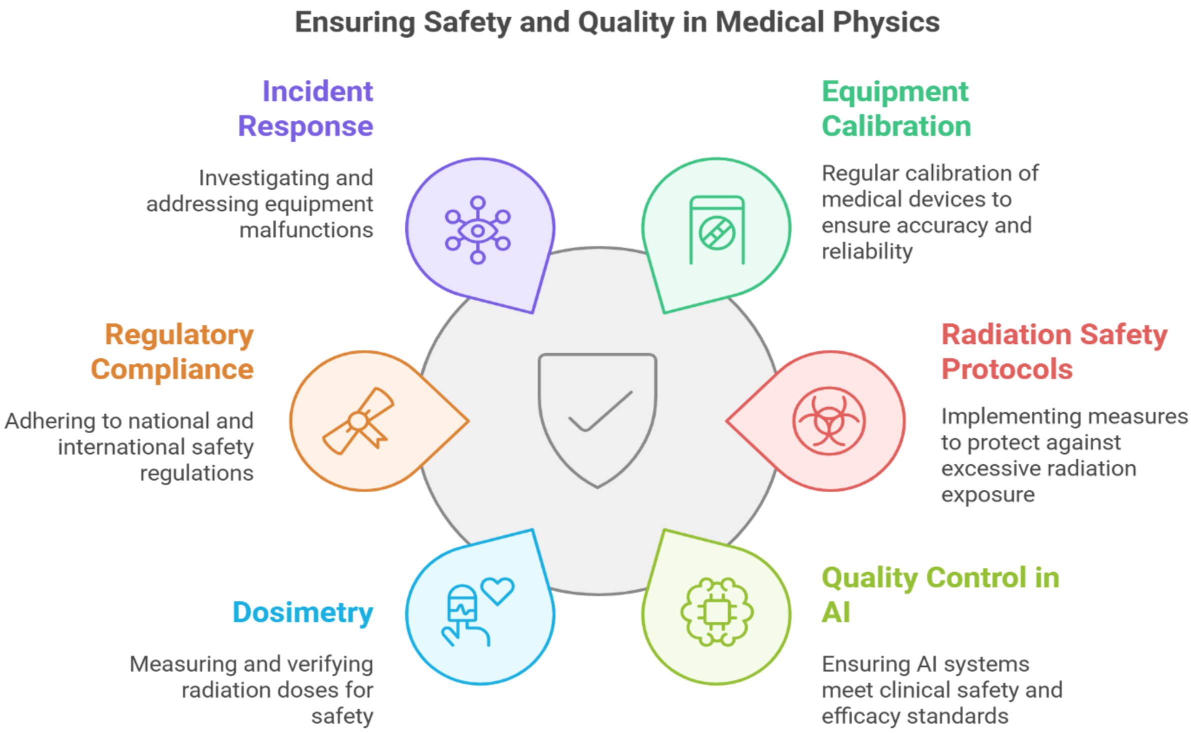

Figure 3: Framework for Safety and Quality in Medical Physics

Educational and Collaborative Roles of Medical Physicists

In technical/quality assurance roles, as educators, and as collaborators medical physicists are important components in the healthcare delivery system. However, for the increasingly more complex medical technologies used in diagnostic imaging and radiotherapy, medical physicists increasingly support healthcare professionals to complete training to use these systems safely and effectively. In recent years, emerging technologies including MR-guided radiotherapy and AI-enhanced imaging systems are attracting increasing interest, and medical physicists are well positioned to take on the role of translation expert, drawing together clinical knowledge with technical expertise. They also train clinicians and technicians as well as interdisciplinary teams to maximize patient outcomes and quality (Kurz et al., 2020).

Training Healthcare Professionals in MR-guided Radiotherapy

The introduction of MR-guided radiotherapy has presented challenges and opportunities for medical physicists. To navigate with this technology, clinicians need a complicated interplay between radiation and imaging systems. Among other responsibilities, they work with doctors, radiation oncologists, and technologists to ensure they're trained to operate the systems. MRI-based systems will be trained in aspects of their functioning, i.e., knowledge of composite imaging and background radiation safety with knowledge of moral use of this knowledge, and how to integrate both modalities in an optimal accuracy of treatment and safety of patients (Kurz et al., 2020).

Medical physicists have also been increasing their attention to educating clinicians not just in the technology as a fundamental operation but also integration of AI with MR-guided radiotherapy. However, the use of AI systems affords new capabilities (e.g., for image segmentation and adaptive treatment planning), which often necessitates particular knowledge to apply them correctly. Medical physicists teach us how to understand AI-generated data, read the AI-generated data, check the validity of AI algorithms, and understand the potential limitations and risks of using AI tools. To amplify the usage of AI, in clinical practice, its training programs provide knowledge tools for healthcare professionals to use, as well as keep a critical eye on the technology's limitations (Gallo & Veronese, 2022).

Collaborating with Interdisciplinary Teams

Implementation of AI in the routine clinical setting and MR-guided radiotherapy is complex and is best delivered by multi-disciplinary teams. Radiation oncologists, medical physicists, radiologists, engineers, and data scientists are all involved. The technical backbone of these teams is medical physicists possessing imaging, radiation physics, and how AI can be integrated into the clinical workflow expertise.

Another example is medical physicists working with radiation oncologists to create personalized treatment plans utilizing real-time imaging data in, for example, MR-guided radiotherapy. Adapting to tumor motion or anatomical variations demands imaging and therapeutic modalities to coordinate closely to change radiation dose adaptively (Kurz et al., 2020). Radiologists are working in tandem with them to build imaging techniques and protocols such that these radiophones produce high-quality images with low patient discomfort and exposure exposure.

As we start integrating AI into clinical systems, we need the same attention to interdisciplinary URM collaboration amongst engineers and data scientists. This is why we are the logical and preferred providers to vet and review AI algorithms concerning their clinical reliability and, crucially, safety standards. An approach such as this one that is multidisciplinary is critical to ensure that AI systems are practical and implemented on ethical and safe bases for patients (Caruana et al., 2008). Working together, however, medical physicists contribute to the seamless implementation of new technology MR-guided radiotherapy, and AI into clinical practice.

Developing and Sharing Best Practices

As new technologies such as AI and MR-guided radiotherapy are becoming available, medical physicists play an important role in helping define best practices in how they are brought into a clinical workflow. Medical Imaging Data Science Also, important contributions are made by medical physicists (and many other professionals) to have standardized and quality protocols for new systems coming into healthcare (e.g. equipment calibration, quality assurance, safety,...) and further, physicists are important to introducing new medical imaging techniques and ensuring quality in clinical use. It applies to all kinds of healthcare settings and the safe use of advanced technologies (IAEA, 2023).

Furthermore, medical physicist contributes to the greater scientific and medical groups using presenting their experiences and research results. Attending

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academic colloquiums, publishing papers, and working on clinical guidelines and protocols is a role to be played by them. But it's important to tell health professionals and keep them up to speed with progressions in innovation. Notably, MR-guided radiotherapy is an emerging field that continues to require training, and medical physicists are particularly important in the sharing of information advances (Gallo & Veronese, 2022).

Also, medical physicists help to establish laws and rules for employing new medical technologies. We would be lost without their expertise, and their ability to ensure the safe and ethical use of these AI systems, MR–guided radiotherapy and other advanced technologies is invaluable. For instance, how healthcare organizations participate in the formation of regulations and standards that control patient safety, and data privacy as well as other ethical use of AI in healthcare (Kurz et al., 2020).

The Role of Medical Physicists in Ethical Oversight

If AI and advanced radiotherapy technologies are to successfully integrate into the clinic and benefit patients directly, there are ethical complexities in terms of data privacy, fairness in algorithms, and transparency in decision-making of integration at the current lightning-fast pace. Medical physicists as custodians of patient safety and technology integration serve as critical players in facing these ethical problems. By helping in building AI algorithms to train on heterogenous, wide datasets that attempt to reduce bias and prevent impact to patient outcomes," Moreover, they demand enhanced transparency of AI systems, in that clinicians must be able to interpret and understand how AI algorithms come to their decisions (Gallo & Veronese, 2022). The ethical responsibilities of the use of AI tools in MR-guided radiotherapy lie with medical physicists to define the volume of the tumor and to optimize the radiation dose contribution. This all means that the reliability and accuracy of all these tools, and more importantly their alignment with clinical guidelines, are also ensured. Medical physicists also advocate for AI systems to be made transparent and fair, to deal with and try to eliminate biases and to ensure that patients themselves truly benefit from their treatments. Medical physicists have a critical role in a healthcare ecosystem that decisions to prioritize patient rights, promote autonomy in adopting those technologies, and foster a climate of trust in healthcare systems (Gallo & Veronese, 2022).

In addition, medical physicists take part in the broader ethical discussion about how AI should be implemented in the healthcare arena, urging for policies in place that protect data privacy, ensure informed consent, and address the responsible use of AI algorithms for making clinical decisions (IAEA, 2023). In addition, medical physicists perform a role in addressing ethical use in healthcare, providing medical physicists such as beneficence, autonomy, non-maleficence, and justice in AI technology usage in the healthcare industry.

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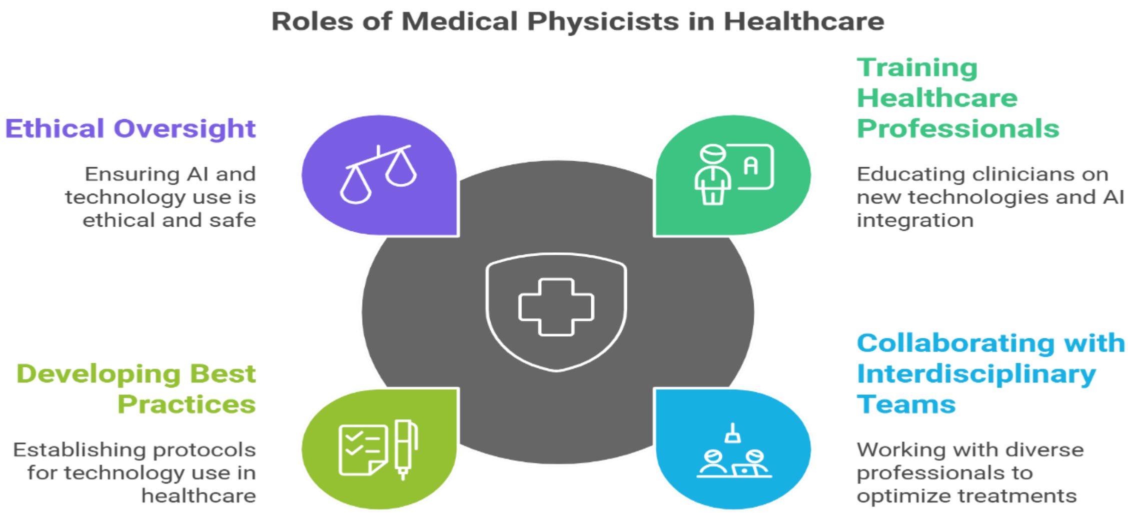

Figure 4: Medical Physicists' Contributions to Ethical and Technological Advancements in Healthcare

Future Trends in Diagnostic Medical Physics

While these challenges and technological advancements will all present themselves in future challenges for diagnostic medical physics, they will together shape the future of this field with rapid developments and advancements in technology in the realms of artificial intelligence (AI), the expansion of adaptive radiotherapy (ART) and ever-growing use of hybrid techniques of imaging. These trends can reduce the accuracy, efficiency, and personalization of medical diagnostics and treatment planning, whilst bringing new challenges that need to be adapted to.

Advancements in AI and Machine Learning

And in fact, AI & machine learning are going to be big in the future of diagnostic medical physics. Machine learning algorithms are trained on complex medical imaging data, treatment prediction data, and treatment optimization and dose delivery. Within this context artificial intelligence provides one of the most exciting applications for adaptive radiotherapy, where treatment plans are updated continuously on the fly, utilizing real-time imaging feedback to deliver an adaptive, customized treatment regimen. So, as these technologies emerge, medical physicists will need to guarantee that AI systems used in clinical workflows remain open, bias-free, and explainable, and maintain adherence to sound ethical principles (Kurz et al., 2020).

Furthermore, with a growing reliance on imaging for clinical decision-making, AI-driven models are likely to make radiotherapy planning more efficient by automating tasks like tumor segmentation and dose calculation so that medical physicists can focus more on those nuanced clinical decisions. As AI gains an increasing role in clinical practice, better training for medical physicists would need to be designed to ensure they are up to date with such innovation (Pan et al., 2020).

Expansion of MR-guided and Adaptive Radiotherapy

The advent of MR-guided radiotherapy and other adaptive treatment engineering heralds a paradigm shift in cancer treatment delivery. Clinicians can use these systems to adapt radiation treatment when the position, shape, or size of a tumor changes during therapy, and to decrease the radiation dose to healthy tissue near the tumor. Especially useful for tumors whose location changes during respiration or other physiological processes, personalizing treatment on the fly is made possible.

As these technologies continue to be integrated into the clinical arena, medical physicists will be critical to treatment protocol optimization, system calibration optimization, and system safety standard compliance. The application of AI in MR-guided radiotherapy will enable more accurate decision-making and a more personal treatment pathway. Hybrid technologies will call for the realignment of medical physicists with new technologies, as well as their continuing clinical implementation (IAEA, 2023).

Hybrid Imaging Modalities

Hybrid imaging techniques (e.g., PET/MRI and SPECT/CT)) are one of the main trends for diagnostic-oriented medical physics. These systems combine functional and anatomical imaging to provide a more complete, more accurate approach to diagnosis and treatment planning. For example, PET/MRI may offer the potential for oncological imaging because it allows the combination of detailed anatomical information with functional information such as glucose metabolism in tumors. Such mixed modalities add the information needed to optimize early-stage cancer detection and treatment monitoring, resulting in higher-quality treatment plans and a better outcome for patients.

Optimization of these hybrid imaging systems by medical physicists is still crucial to deliver high-quality imaging in a range of clinical applications. His job also involves calibration and maintenance, and as such these systems are complex requiring a thorough understanding of the physical underpinnings of both the imaging modalities involved. Moreover, hybrid imaging modalities can accommodate more than one acquisition, and new approaches enabling in vivo and in situ, real-time, monitoring of drug biodistribution and treatment effects will be a great leap forward in the field of personalized medicine (Caruana et al., 2008).

Emphasis on Radiation Dose Reduction and Safety

In contrast with this present role for radiation therapy and diagnostic imaging, and with the latest in clinical progress, the focus now will be on reducing patient exposure to radiation while preserving accuracy. Radiation doses will be adjusted to the needs of each patient with little unnecessary exposure and no loss in image quality or treatment effectiveness thanks to computers, AI, and machine learning. Depending on the patient's size, age, or type of examination, AI algorithms will dynamically adjust settings for the radiation on the spot in real-time.

Because medical physicists will continue to be at the cutting edge of radiation dose optimization, their existing methods in dosimetry and safety protocols are expected to be enhanced by these efforts. Radiation safety guidelines will form the basis of what they will attempt to develop and apply to reduce patient

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radiation exposure, along with regulatory agencies and other health professionals. Not only are these advancements going to increase patient safety, reducing healthcare costs associated with overexposure to radiation (Gallo & Veronese, 2022).

Focus on Ethical and Regulatory Standards

As AI and data-driven technology continue to be integrated into healthcare they will require more comprehensive ethical and regulatory frameworks. Issues about patient consent, data security, and accountability of AI-driven decisions will be discussed. Patients will only trust the use of AI-based technologies if they don't have biases and if they are transparent and explainable.

As this new ethical and regulatory landscape develops, medical physicists will be one of the central sequential decision-makers, around the use of patient data (full health records, and AI-based models) in practice. Also, they will help to determine protocols for making AI treatment planning systems robust but also accurate and safe over time. Advances in diagnostic medical physics also mean medical physicists must be ready to speak out on behalf of patients and work with oversight agencies to limit emerging technology usage to ethical and safe deployments (Bengio et al., 2017).

Continued Professional Development and Education

Medical physics is a rapidly evolving field, and Quality and Continuing Education of the medical physicist will be needed. As these technologies, along with hybrid imaging and MR-guided radiotherapy, become more integrated into the clinical arena the medical physicist must have familiarity with technologies, software, and regulatory policies that are in evolution. To carry out this work ongoing training and cross-disciplinary work with radiologists, oncologists, and other health providers will be required.

Because medical physicists must also become familiar with new and emerging fields e.g., computational modeling, data analysis, and artificial intelligence it becomes even more imperative that they pursue both interdisciplinary training and certification programs. Diagnostic medical physics will depend on professional roles and educational institutions to provide suitable education and wider resources to facilitate adaptation (Khan, 2020).

Conclusion

The future of diagnostic medical physics will be the integration of novel technology and multidisciplinary teamwork. As we integrate new AI technology, MR-guided radiotherapy, hybrid imaging, and radiation safety, the role of medical physicists will be more important than ever. But medical physicists will continue to lead the field, with diagnostic imaging and treatment plans that are increasingly personalized, accurate, and patient-centered as they adapt. In a quickly evolving framework, tomorrow's healthcare practices will rely on the work of medical physicists to achieve the uptake of innovation while maintaining remains of the most solid standards of patient safety, and the most influential ethics and professionalism.

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