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Research Article

Radiation Physics: The Future of Medicine

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Abstract

The future of radiation physics and medicine promises groundbreaking advancements that are transforming diagnostics, treatments, and patient outcomes. In recent years, these fields have become increasingly essential in healthcare, with radiation being widely applied in cancer therapies, imaging techniques, and sterilization processes. The continuous advancements in this field have paved the way for more accurate diagnoses, targeted therapies, and improved overall patient care. As technology continues to evolve, the future of radiation physics and medicine is expected to bring forth groundbreaking innovations that will significantly enhance diagnostics and treatments, and ultimately lead to better patient outcomes. One area of promising advancement in radiation physics and medicine is the development of more precise and targeted radiation therapies. Traditional radiation therapy often involves treating the entire affected area, which can lead to damage to healthy tissues surrounding the tumor. Recent technological advancements, such as intensity-modulated radiation therapy (IMRT) and proton therapy, have enabled more precise targeting of tumors while minimizing harm to surrounding healthy tissues. These innovations not only enhance patient outcomes by reducing side effects but also create opportunities to treat tumors that were previously considered untreatable.

Keywords	*Public Health; Radionuclide; Sustainable Treatment; Waves Propagation*
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Introduction

Medicinal applications have become crucial as they significantly enhance human health and contribute to economic development. These applications contribute immensely to economic development through reduction in healthcare costs, and driving innovation in the pharmaceutical and biotechnology industries (Anyanwu *et al.,* 2024). Radiation physics is essential in medicine, enabling healthcare professionals to obtain detailed images of the human body for diagnosis. By comprehending the principles of radiation and its interaction with matter, physicists can create and refine imaging techniques that deliver critical insights into a patient's health (Decoene and Crop, 2023). The role of radiation physics in medical applications is indeed crucial, as it aids advanced imaging techniques. These techniques are essential for the diagnosis and treatment of a wide range of medical condition (Chen et al., 2011).

Applications of radiation physics in medicine include X-rays, CT scans, magnetic resonance imaging (MRI), ultrasound, and nuclear medicine. Repeated scanning and superimposition of cross-sectional X-ray images, with the digital removal of background elements, create high-resolution, three-dimensional or four-dimensional computed tomography (CT) images (Noo and Karellas, 2011). In nuclear medicine, radioactive substances are utilized to observe physiological processes within the body and to deliver targeted therapeutic doses. During these procedures, a very small amount of radioactive material is introduced into the body. The radioactive material is absorbed by the organ or tissue under investigation. The radiation emitted as the material decomposes is detected by a gamma camera, which generates digital signals to analyze the functional state of the organ. When stationary, the gamma camera produces a two-dimensional (2-D) image (Soh *et al.,* 2022; Kharfi, 2013).

Fundamentals of Radiation Physics

Radiation is the release and transmission of energy through space or a medium, usually manifesting as waves or particles. It can occur naturally, like solar radiation from the sun, or be produced artificially, as seen in medical devices or nuclear reactors. Radiation is integral to many domains, including healthcare, industry, energy generation, and scientific research (Donya *et al.,* 2014). Properties and behavior of radiation: Radiation is energy emitted in the form of waves or particles, transmitted through an intervening medium or space (Podgorsak, 2005; IAEA, 2014). Radiation may be classified as electromagnetic or particulate, with electromagnetic radiation including visible light, infrared and ultraviolet, x-rays and gamma rays (Figure 1), and particulate radiation including electrons, positrons, protons and neutrons. Electromagnetic waves can, like all waves, be characterized by their amplitude, wavelength (λ), frequency (v) and speed. The amplitude is the intensity of the wave. The wavelength is the distance between identical points on adjacent cycles. The frequency is the number of complete wave oscillations per unit time. The speed of the wave is equal to the product of the frequency and the wavelength, and its magnitude depends upon the nature of the material through which the wave travels and the frequency of the radiation.

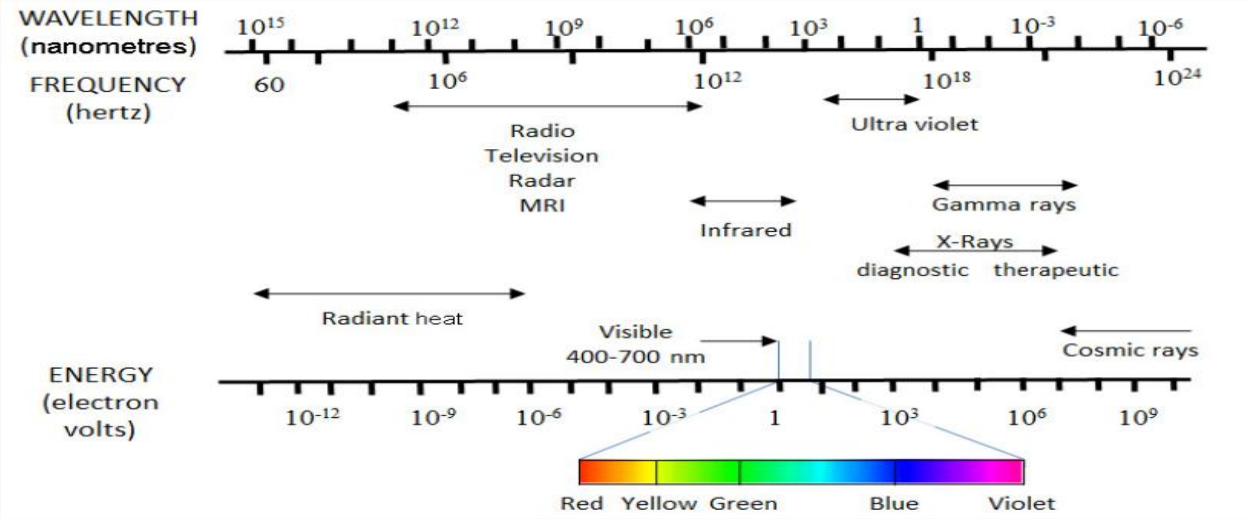

Figure 1: The electromagnetic spectrum (Dance *et al.,* 2014)

Radiation physics is the branch of physics that focuses on the study of the properties and behavior of radiation, including its generation, propagation, and interaction with matter. Its role in medical applications is crucial as it enables the development of imaging techniques that aid in the diagnosis and treatment of various medical conditions (Chen *et al*., 2021). In particular , applications of physics in medicine have been increasing in variety and quantity so that new diagnostic and treatment modalities have required that the number of physicists in hospitals be increased and their academic and clinical training suit to the demands of advanced technologies , giving rise to an interdisciplinary profession that allows addressing multiple therapeutic and diagnostic techniques, and provides the scientific basis for understanding, implementation and development of these technologies that are revolutionizing the practice of medicine, as well as the ability to establish criteria for the appropriate use of physical agents used in medicine ensuring the quality of the technical aspects involved in the processes, the effectiveness and quality of the data , thus reducing the likelihood of accidents in medical applications of radiation (Nieto, 2015; Mokobia *et al.,* 2022).

Radiation Types used in Medicine

Different radiation techniques are used in the medical field for both therapeutic and diagnostic purposes. These include particulate radiations such as electrons, fast neutrons, protons, alpha particles, and pi-mesons, as well as electromagnetic waves with a wide range of wavelengths, including radio waves, visible light, ultraviolet radiation, X-rays, and gamma rays. Among these, gamma rays and X-rays are the most commonly used (Kumar and Kumar, 2023).

X-rays: X-rays are electromagnetic waves with very short wavelengths, shorter than those of ultraviolet rays but longer than those of gamma rays. X-rays are produced when fast-moving electrons undergo sudden deceleration upon colliding and interacting with a target anode. In this process, over 99% of the electron energy is converted into heat, while less than 1% is converted into X-rays (Figure 2). An X-ray generator supplies power to the X-ray tube, which contains high-voltage transformers, filament transformers, and rectifier circuits. As the X-rays transit through the patient, they are attenuated to varying degrees as they pass through or reflect off the various tissues of the body, casting an X-ray shadow of the radiopaque tissues (such as bone tissue) on the fluorescent screen. Images arise on the screen when unattenuated or minimally attenuated X-rays from radiolucent tissues interact with atoms via the photoelectric effect, converting energy to electrons. Almost all the energy transferred to the electrons is released as heat and a smaller portion is given out as visible light (Bednarek *et al*., 2021).

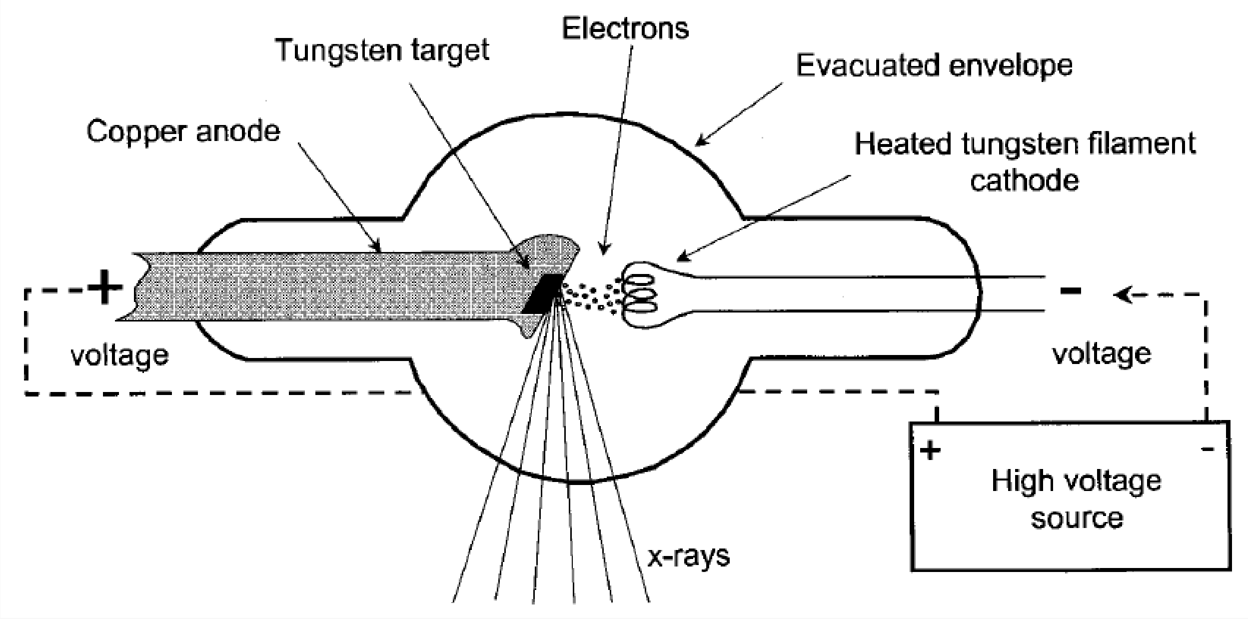

Figure 2: The X-ray tube (Bushberg *et al*., 2002)

Gamma Rays: A gamma ray (g) is a bundle of electromagnetic energy (photon) that some radionuclides' nuclei release after radioactive decay. The electromagnetic spectrum's most energetic photons are known as gamma photons. EMR, or electromagnetic radiation, includes gamma rays. Gamma rays are created when an excited radionuclide settles down after undergoing radioactive decay. Whether they came from nuclear decay or reaction, high-energy photons that are also referred to as gamma-rays are included in cosmic rays. Many of the radioisotopes in the uranium, thorium, and actinium natural radiation decay series, as well as the naturally occurring radioisotopes potassium-40 and carbon-14, emit gamma radiation (Stephan and Shmatov, 2021).

Applications of Radiation Physics in Medicine

Radiation physics is concerned with the application of physics principles and methodologies to the prevention, diagnosis, and treatment of human diseases to improve human health and well-being. Radiation physics deals with the application of the concepts and methods of physics to the prevention, diagnosis and treatment of human diseases with a specific goal of improving human health and well-being. These can include the theories associated with amplitudes, fluid pressure, frequencies and waves. Applications of these principles can be found in diagnostic radiology, nuclear medicine and radiation oncology or radiotherapy.

Radiography and Diagnostic Imaging Techniques (e.g., X-ray radiography, computed tomography)

Radiography is a diagnostic imaging procedure that produces an image of an inside body structure using ionising radiation (X-rays). Radiographs were first created by subjecting silver-containing films to ionising radiation (Fung and Ray, 2021). The various diagnostic imaging techniques being employed in Medicine today are X-ray imaging, Mammography, Fluoroscopy, Ultrasound, Magnetic resonance imaging and computed tomography. Radiography is used to diagnose disease of the chest, abdomen and musculoskeletal system. Additionally, contrast imaging studies are performed to evaluate the gastrointestinal and urinary tract. Radiography also called X-ray imaging, was the first, and for decades the only, available imaging method able to "see into the body." X-rays are a type of electromagnetic radiation that exposes tissues to ionizing radiation which accumulates in the body over the patient's lifetime. It remains among the most widely performed exams in medicine. X-ray imaging is quick, inexpensive, and can even be portable. There are several types of specialized x-ray techniques. 2D mammography utilizes x-ray technology and is the gold standard for breast imaging. 3D mammography (digital breast tomosynthesis), approved by the FDA in 2012, is rapidly gaining acceptance as an alternative for breast cancer screening. Fluoroscopy is an x-ray technique that produces images in real-time.

Fluoroscopy: fluoroscopy is a term coined by Thomas Edison during his early x-ray research. The name is derived from the fluorescence he observed while staring at a luminous plate hit with x-rays. Moving projection radiographs are produced using this technique. Fluoroscopy is most commonly used to see movement (of tissue or a contrast agent) or to guide a medical operation such as angioplasty, pacemaker implantation, or joint repair/replacement. It is an imaging technology that uses x-rays to obtain real-time moving images of an object's inside. This is used in general radiology, interventional radiology, and image-guided surgery for both diagnosis and therapy. A fluoroscope, in its most basic form, consists, of an x-ray source and a fluorescent screen, between which a patient is positioned**.** As the X-rays transit through the patient, they are attenuated to varying degrees as they pass through or reflect off the various tissues of the body, casting an X-ray shadow of the radiopaque tissues (such as bone tissue) on the fluorescent screen. Images arise on the screen when unattenuated or minimally attenuated X-rays from radiolucent tissues interact with atoms via the photoelectric effect, converting energy to electrons. Almost all the energy transferred to the electrons is released as heat and a smaller portion is given out as visible light (Bednarek *et al*., 2021).

Ultrasound: Ultrasound is a type of high-frequency sound that exceeds 20 kHz. Human ears can detect noises of frequencies ranging from 20 Hz to 20 kHz. Piezoelectric crystals packed within ultrasound transducers generate ultrasonic waves. As a result, crystals inside transducers convert electric current to ultrasound and return ultrasound beams from the body to electric currents, generating ultrasound. Crystals in modern transducers are comprised of synthetic plumbium zirconium titanate (PZT) (Choi, 2022).

Computed Tomography (CT): CT scanners were developed in 1972 by Sir Godfrey Hounsfield as an essential radiological technique used in various clinical situations. They use x-rays to generate cross-sectional, two-dimensional images of the body, acquired by rapid rotation of the x-ray tube 360° around the patient. Multislice or multidetector machines use the principles of the helical scanner but incorporate multiple rows of detector rings, allowing for multiple slices per tube rotation. The viewed image is reconstructed as a corresponding matrix of picture elements (pixels) (Podgarsak, 2005).

Magnetic Resonance Imaging (MRI): This is a medical imaging method that captures changing magnetic fields. It employs a strong external magnetic field to align protons within the tissue, which is then disrupted by the application of external Radio Frequency (RF) energy. Using the Fourier transformation, the emitted signals are measured and transformed to intensity levels. Changing the sequence of RF pulses applied and collected produces different forms of pictures. In MRI, repetition time (TR) and time to echo (TE) are critical parameters. T1 and T2 are two relaxation periods in tissue that determine how quickly excited protons return to equilibrium and how quickly they regain equilibrium or fall out of phase with each other (Podgarsak, 2005).

Radiation Therapy for Cancer Treatment

Radiation therapy is a method of delivering ionizing radiation to destroy and eliminate cancer cells. It uses high-energy photons for deep-seated tumors and electrons for superficial tumors. Medical imaging is used to ensure safe and targeted delivery of radiation and assess radiation-induced changes in the anatomy. Advancements in imaging technologies have also improved radiation delivery through advanced techniques (Shahbazian *et al*., 2020)

Physics of Cobalt-60: After Roentgen discovered X-rays in 1895, radiotherapy focused on greater photon energy and intensities. Technological advancement was slow, relying primarily on X-ray tubes, van de Graaff generators, and betatrons. The 60Co teletherapy equipment created in Canada in the 1950s was the first practical megavoltage therapy machine. This machine accelerated the search for higher photon energy, propelling the 60Co unit to the forefront of radiotherapy. Cobalt-60 (60Co) is a radioisotope synthesised and utilised in external beam radiation therapy and brachytherapy. It decays to an excited state of Nickel-60, generating high-energy gamma rays essential in radiation therapy. Cobalt 60 is used in external beam radiation therapy linear accelerators and high-dose-rate brachytherapy. It is also used in some MRI-guided external beam therapy systems. Important features of 60Co teletherapy machines include high energy X-ray emission, long half-life, high specific activity, and simple production methods (Podgarsak, 2005).

Brachytherapy: Brachytherapy is a short-distance cancer treatment using radiation from small, encapsulated radionuclide sources. It is administered by inserting sources directly into the tumor volume, providing constant doses for temporary or permanent implants. Most sources emit photons, with neutron-generating devices used in specialized settings. There are two types: intracavitary and interstitial, with temporary or permanent implants. Brachytherapy offers better-localized dose delivery over external beam radiotherapy, but it can only be used when the tumor is properly localized and small. It is used to treat 10-20% of all radiotherapy patients in a typical department (Soror *et al*., 2019)

Theranostics: It is a novel branch of nuclear medicine that aims to give both therapeutic and diagnostic imaging using the same radiopharmaceutical formulation. The term "theranostics" comes from the Greek terms "therapy" and "diagnosis." Theranostics is helping to pave the road for customised or precision medicine. It employs molecular targeting vectors (for example, peptides) marked with diagnostic and therapeutic radionuclide(s) to gather diagnostic pictures and administer a therapeutic radiation dose to the target. This can be accomplished by integrating two radionuclides (one for imaging and another for therapy) into the same formulation, such as 131I, 153Sm, 166Ho, 177Lu, 186Re, and 188Re. Diagnostic imaging gives additional information on the disease, its status, and a patient's features (Araz and Küçük, 2021)

Principles of PET: PET is based on the physical features of positron emitters, which are radioactive isotopes. When radioactive decay occurs, these radionuclides release positrons rather than gamma rays, as their name implies. Positron decay is a form of beta decay in which a positively charged particle called a beta+ particle (denoted +) is expelled from a proton-rich nucleus as it seeks to become more stable . Particles have no effect on PET.) Do PET scanners detect positrons? No, it does not. Unlike conventional nuclear medicine imaging with gamma-emitting radionuclides, photons seen in PET do not come directly from decaying nuclei. Neither are positrons being imaged. Because positrons are positively charged particles, they travel just a short distance, usually no more than a millimeter or two, before colliding with a negatively charged electron. When a positron and an electron collide, the particles annihilate, and the annihilation of the electron and positron leads to the generation of two high-energy gamma rays that travel approximately 180 degrees from one another (Wang *et al*., 2023).

Principles of SPECT: Single photon emission computed tomography (SPECT) is a three-dimensional nuclear medicine imaging technology that combines scintigraphy with computed tomography information. It allows the radionuclide distribution to be presented in three dimensions, providing more detail, contrast, and spatial information than planar nuclear imaging alone. SPECT machines use an array of gamma cameras (from one to four) that rotate around the subject on a gantry. SPECT can also be paired with a separate CT machine in a hybrid imaging technique known as single photon emission computed tomography-computerized tomography (SPECT-CT) used for attenuation correction and anatomical localization. -binding radiotracers).

Gamma Camera: A gamma camera (-camera), also known as a scintillation camera or Anger camera, is a device used to picture gamma radiation emitting radioisotopes, a method known as scintigraphy. It is a nuclear medicine diagnostic test in which radioisotopes attached to drugs travel to a specific organ or tissue (radiopharmaceuticals), the emitted gamma radiation is captured by gamma cameras, which are external detectors that form two-dimensional images in a process similar to the capture of x-ray images. When a gamma photon leaves the patient, it knocks an electron loose from an iodine atom in the crystal, resulting in a small flash of light when the dislocated electron finds a low-energy state again. The excited electron's initial phenomena are related to the photoelectric effect and (especially with gamma radiation) the Compton effect. The flash of light is detected by photomultiplier tubes (PMTs) after it has occurred. The computer reconstructs and shows a two-dimensional representation of the relative spatial count density. The distribution and relative concentration of radioactive tracer elements present in the organs and tissues examined are reflected in this reconstructed image (Fontana *et al*., 2017).

Nuclear Medicine and Molecular Imaging

Nuclear scintigraphy is an imaging procedure which provides information about body or organ systems based on the distribution pattern of a radioactive substance in the body. A radiopharmaceutical is a chemical substance that contains a radionuclide within its structure. Radiopharmaceuticals are formulated in a variety of ways to deliver the radionuclide to particular parts of the body. The radiopharmaceutical is administered intravenously and binds to the area of interest, and a gamma camera attached to a computer is then used to scan the animal for localization of the radiation ("hot spots"), indicating the site of the problem. The radioactive substance does not harm the animal and is quickly excreted from the body mainly through the urine. Nuclear scintigraphy is a useful diagnostic tool to screen or localize subtle lesions, such as incomplete fractures, degenerative changes in the spine or limbs or infection. Scintigraphy can also provide information about the relative function of an organ. Although nuclear scintigraphy does not specifically diagnose the underlying problem, it provides important information that is helpful in determining the need for further diagnostic tests and in guiding management. In scintigraphy, one of the big goals is to use the optimal radioactive dose to acquire the desired information with the least radiation dose to the patient. Nuclear medicine is a medical specialty that uses radioisotopes for diagnosis and treatment of diseases. During the procedure, a known amount of radiopharmaceutical (a radioisotope labelled with a biological carrier) is administered to the patient’s body via injection, ingestion or inhalation.

Remarkably, unlike X-ray imaging, nuclear medicine imaging detects the gamma radiation emitting from the radioisotope uptake within the body rather than radiation that is generated by the X-ray source. Besides, nuclear medicine imaging elucidates the physiological function of an organ rather than its anatomy. It is often combined with CT or MRI findings to assist a clinical diagnosis. Advanced technologies in both hardware and software have enabled hybrid imaging to be carried out. For examples, a gamma camera instrument is combined with a CT scanner to produce single-photon emission computed tomography SPECT-CT images, PET-CT or MRI scanner to produce PET-MR images. The fusion imaging technique provides more accurate information on both anatomy and physiology in

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a single study. Medical physicists ensure the quality and accuracy of image production and registration. Systematic and periodical quality control need to be included in the standard operating procedures (SOP) of a nuclear medicine department. The recent development in radiopharmaceutical has also led to more advanced imaging and treatment of various diseases at the molecular level. As an example, peptide receptor radionuclide therapy (PRRT) using 90Y-DOTATOC or 177Lu-DOTATAC (a radiolabelled somatostatin receptor) has shown very promising results in treating neuroendocrine tumours (NETs). The treatment involves the systemic administration of a radiolabelled peptide developed to target with high affinity and specificity receptors overexpressed on neuroendocrine tumours (Bodei et al., 2013). 177Lu-PSMA (prostate-specific membrane antigen) is another good example of radioimmunotherapy (RIT) that has shown good response rate and low toxicity in treating prostate cancer (Rahbar et al., 2018). The monoclonal antibody will bind specifically to an antigen associated with tumour increases the radiation dose delivered to the tumour while decreasing the dose to healthy tissues (Yeong et al., 2014). Theranostics is a new area of nuclear medicine which is expanding to provide therapeutic as well as diagnostic imaging using the same radiopharmaceutical formulation (Frangos and Buscombe, 2019).

Future Developments in Radiation Physics and Medicine

Radiation physics and medicine have grown more important in recent years in the healthcare industry. Radiation is used in a variety of medical procedures, including sterilization procedures, imaging methods, and cancer treatments. The ongoing developments in this area have paved the way for better patient care, more precise diagnoses, and targeted treatments. Future developments in radiation physics and medicine are anticipated as technology advances, and they will improve diagnostics, treatments, and patient outcomes by making significant advancements (Zokvic and D'Alimonte, 2023). Imaging technology is still developing and offering new possibilities for identifying and treating human diseases. These new developments, which include artificial and augmented intelligence, wearable scanners, virtual reality with 3D imaging, amyloid PET imaging, MRI gloves, digital radiography, cone beam computed tomography, etc., promise to improve patient care (Urlings *et al*., 2023).

Conclusion

Radiation physics plays an indispensable role in modern medicine and has a promising future in advancing healthcare. The future of medicine heavily relies on radiation physics as it continues to make significant strides in enhancing medical procedures and therapies. One of the emerging areas is molecular imaging, which involves the use of radioactive tracers to identify specific molecular targets in the body. This technique enables physicians to assess cellular events, pinpoint disease progression, and evaluate treatment responses at a molecular level. Molecular imaging has the potential to revolutionise diagnostics and aid in the development of personalised treatment strategies. Another promising aspect of radiation physics in medicine is the utilisation of proton therapy. Proton beams offer precise and controlled radiation delivery, minimising damage to healthy tissues surrounding the tumor. This type of therapy shows great potential for improving treatment outcomes by reducing side effects and producing better functional results, particularly in paediatric patients. The potential for personalised medicine and enhanced treatment modalities makes radiation physics a cornerstone of the future of medicine.

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