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Review Article

Radiation Techniques in Health and Environment†

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Abstract: Radiation science has become a cornerstone of modern medicine, offering powerful tools for both diagnosis and treatment. Diagnostic imaging technologies such as X-ray, ultrasonography, computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and gamma camera systems utilize radiation to provide high-resolution visualization of internal structures. Therapeutic applications have evolved from conventional radiotherapy to highly sophisticated techniques including Photon Beam Radiotherapy using LINAC, Gamma Knife, and CyberKnife systems. Advanced modalities such as Stereotactic Radiosurgery (SRS), and Stereotactic Body Radiation Therapy (SBRT) allow for precise delivery of high-dose radiation to tumors while minimizing exposure to surrounding healthy tissue. Emerging techniques such as FLASH radiotherapy, which delivers radiation at very high speeds, and carbon ion therapy, which is effective against resistant tumors, are bringing major improvements to cancer treatment. Cherenkov radiation is being explored for its role in treatment visualization and dosimetry, while Targeted Radionuclide Therapy (TRT) uses tumor-specific radioactive agents to deliver internal radiation precisely to cancer cells. Adaptive Radiation Therapy (ART) modifies treatment plans during therapy to account for tumor or patient changes. These developments are shaping the future of oncology, with an emphasis on precision, safety, and therapeutic efficiency. Beyond medicine, radiation is also applied in environmental protection. It is used for purifying wastewater through radiolysis, sterilizing hazardous solid waste, facilitating the breakdown of plastics, and detecting pollutants using nuclear analytical methods. These applications highlight the broader utility of radiation in supporting both health and environmental sustainability.

Keywords: Radiation, Gamma Irradiation, FLASH Radiotherapy, Targeted Radionuclide Therapy, Environmental Radiation Applications.

1. INTRODUCTION

Radiation has been a cornerstone of medical science since its discovery in the late 19th century, providing powerful tools for both diagnosis and treatment of diseases, particularly cancer [1]. Radiation therapy, the therapeutic application of ionizing radiation, is a major modality in cancer management, with nearly 50% of patients receiving radiotherapy during their illness to inhibit tumor growth and maximize curative outcomes [2]. The underlying principle of radiotherapy relies on the ability of high-energy radiation to damage the genetic material (DNA) of cancer cells, preventing their proliferation while minimizing exposure to surrounding healthy tissue [3]. The energy transported by radiation is governed by Einstein's mass-energy equivalence equation $E = mc^2$ [4], while the interaction of electromagnetic fields with biological tissues is described by Ampère-Maxwell's law, $\nabla B = \mu_0 (J + \varepsilon_0 \frac{\partial E}{\partial t})$ [5]. Furthermore, the quantum nature of radiation is captured by the Planck-Einstein relation, $E = h\nu$, linking photon energy to frequency [6] and by Einstein's photoelectric equation, $KE = h\nu - \phi$, which describes the kinetic energy of ejected electrons as a function of photon energy and the material's work function [7].

Radiotherapy not only serves curative purposes but also plays a pivotal role in palliative care,

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alleviating symptoms such as pain, obstruction, or compression caused by tumors. Thus, the integration of physics, imaging, and clinical expertise has made radiation a vital component of modern medical practice, offering both life-saving treatment and improved quality of life for patients [1].

2. MEDICAL IMAGING TECHNIQUES

2.1. X-ray

X-rays are a form of ionizing radiation with wavelengths of 0.01–10 nm, widely used in medical imaging for visualizing internal structures based on differential absorption and transmission through tissues. Modern X-ray systems, including computed radiography, flat-panel detectors, and CT, provide high-resolution 2D and 3D images essential for diagnosing fractures, bone disorders, soft tissue abnormalities, and guiding surgical or interventional procedures. Advances in detector technology and imaging techniques have improved image quality while reducing patient radiation exposure [8, 9].

2.2. Ultrasonography

Ultrasonography has rapidly advanced, offering high-resolution real-time imaging of anatomy, pathology, and blood flow. It is safe, quick, and often superior to CT or MRI in uncooperative or lean patients, though limitations exist with obesity, gas, and bone interfaces. High-quality sonography requires extensive training and expertise, while handheld devices hold promise for screening and enhancing routine clinical diagnosis [10].

2.3. Computed Tomography (CT)

Computed tomography (CT) provides high-resolution, cross-sectional images that accurately distinguish tissues, enabling precise assessment of body composition, including adipose tissue, skeletal muscle, bones, and organs. Modern multidetector CT (MDCT) allows rapid acquisition of three-dimensional volume images with sub-millimeter resolution, improving both speed and reproducibility of measurements. CT can also quantify bone mineral density and fat infiltration in muscles or liver, making it a reliable tool for clinical evaluation and research [11, 12].

2.4. Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) is a non-invasive technique that produces high-resolution images using strong magnetic fields and radiofrequency radiation, providing excellent soft tissue contrast. It is widely used in clinical diagnostics, radiotherapy planning, and pharmaceutical research to study tissue structure, tumor margins, and in vivo drug delivery [13-15].

2.5. Positron Emission Tomography (PET)

Positron Emission Tomography (PET) is a functional imaging technique widely used in oncology for tumor staging, treatment response assessment, and radiotherapy planning, providing early insights into tumor metabolism beyond anatomical imaging. PET imaging has evolved from early research tools to sophisticated clinical scanners with 3D acquisition, iterative reconstruction, and time-of-flight technology, improving sensitivity, image quality, and quantitative tumor assessment [16, 17].

3. ADVANCED RADIOTHERAPY MODALITIES

3.1. Gamma Knife

Gamma Knife radiosurgery has evolved over the past decades as a minimally invasive alternative for treating intracranial tumors, vascular malformations, and functional disorders, particularly medically refractory tumors. Its advantages include precise high-dose radiation delivery without craniotomy, making it suitable for patients unfit for invasive surgery [18].

3.2. CyberKnife

The CyberKnife system is a frameless, image-guided radiosurgery platform that integrates a compact 6-MV LINAC with a robotic arm to deliver highly precise, non-isocentric radiation beams. Real-time imaging and motion correction allow accurate targeting of both intracranial and extracranial lesions without invasive stereotactic frames. Its treatment planning software supports multimodality imaging fusion, inverse planning, and dose optimization, enabling safe irradiation of complex tumor shapes while sparing adjacent structures. Since FDA approval in 2001, CyberKnife has been widely adopted as an effective alternative to conventional surgery and radiosurgery systems such as the Gamma Knife [19-22].

3.3. LINAC

LINAC-based radiotherapy uses high-energy X-rays to precisely target tumors while sparing normal tissues. Modern techniques like IMRT and VMAT, combined with image guidance, improve dose accuracy, though CBCT has limitations in soft tissue visualization and motion management. The integration of MRI with LINAC (MR-Linac) allows real-time imaging, adaptive treatment, and better tumor targeting, enhancing efficacy and reducing toxicity [23, 24].

3.4. Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT)

Stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT) are noninvasive, high-dose radiotherapy techniques targeting cranial and extracranial tumors, respectively, using image guidance and stereotactic alignment for precise delivery. SRS typically involves a single high-dose session for brain lesions, while SBRT delivers a few large doses to extracranial tumors, including lung, liver, and prostate. Both modalities are effective in local tumor control, with ongoing studies refining their use and exploring combination with targeted systemic therapies [25].

3.5. FLASH Radiotherapy (FLASH-RT)

FLASH radiotherapy (FLASH-RT) delivers ultra-high dose-rate radiation within milliseconds, which has shown the ability to spare normal tissues while maintaining strong antitumor efficacy. Preclinical studies across multiple species and early clinical cases demonstrate reduced toxicity compared to conventional radiotherapy, making FLASH-RT a promising approach for overcoming radio-resistant tumors [26, 27].

3.6. Targeted Radionuclide Therapy (TRT)

TRT delivers cytotoxic radiation to tumor cells using radiolabeled molecules such as antibodies, peptides, or small ligands, minimizing damage to normal tissues. Common applications include I-131 for thyroid cancer, Y-90 ibritumomab tiuxetan and I-131 tositumomab for non-Hodgkin's lymphoma, and Lu-177-DOTA-TATE or Y-90-DOTA-TOC for neuroendocrine tumors [28, 29].

3.7. Adaptive Radiation Therapy (ART)

ART is a closed-loop radiotherapy approach that continuously adapts treatment plans using systematic feedback from patient-specific measurements. Unlike conventional radiotherapy that applies uniform margins based on population averages, ART customizes field margins and radiation doses to individual anatomical and positional variations, thereby enhancing both safety and effectiveness. This process employs advanced technologies such as CT imaging, electronic portal imaging devices, multileaf collimators, and computer-controlled systems to monitor changes and re-optimize treatment in real time. By accounting for organ motion, geometric target shifts, and treatment beam placement errors, ART reduces unnecessary radiation exposure to healthy tissues. It also allows for safer dose escalation by tailoring margins to the actual variability of each patient rather than generalized estimates. Ultimately, ART represents a dynamic, patient-centered strategy that refines radiation delivery and improves therapeutic outcomes [30].

4. ENVIRONMENTAL APPLICATIONS OF RADIATION

4.1. Wastewater Purification

Radiation technology, particularly gamma irradiation, has shown significant potential in purifying municipal wastewater by effectively reducing physical and organic contaminants. Laboratory studies indicate that gamma doses between 100 - 500 krad can degrade up to 88% of organic pollutants while inactivating pathogenic microorganisms, thus lowering biochemical oxygen demand (BOD) and chemical oxygen demand (COD). The method also improves sludge compactness and settling capacity, making it a promising alternative to conventional treatments. With optimized radiation parameters and pilot-scale validation, this technology can provide cost-effective and environmentally compatible wastewater treatment [31, 32].

4.2. Solid Waste Treatment

Radiation technologies have emerged as effective tools for the treatment and disinfection of solid and liquid wastes, addressing growing global concerns over pollution and public health. Techniques such as gamma irradiation, electron-beam, ultraviolet, and X-rays have been applied to sterilize sewage sludge, biomedical wastes, and industrial effluents, while also degrading toxic contaminants in soils.

Gamma irradiation, particularly using cobalt-60, has demonstrated practical efficacy in field-scale applications, providing pathogen-free, nutrient-rich sludge suitable for agricultural use. These technologies offer significant advantages, including odorless, easily handled waste and elimination of withholding periods before crop use, making radiation a promising approach for sustainable waste management [33].

4.3. Pollutant Detection

Radiation techniques, particularly laser-based absorption spectroscopy, are increasingly used to detect and quantify gaseous pollutants in the atmosphere. By targeting specific infrared absorption bands of pollutants such as carbon monoxide, nitric oxide, sulfur dioxide, and ozone, lasers provide high sensitivity and selectivity even at very low concentrations. The collimated, high-power laser beams allow long-distance transmission and multiple-pass absorption, overcoming limitations of traditional light sources and enhancing real-time environmental monitoring [34].

4.4. Plastic Waste Degradation

Radiation processing, using gamma rays or electron beams, effectively modifies the structure of synthetic and natural polymers, enhancing properties such as thermal stability, biodegradability, and mechanical strength. It facilitates plastic waste degradation, accelerates breakdown of cellulose into viscose, and improves chitin/chitosan processing without toxic chemicals.

Electron beam and gamma irradiation offer environmentally friendly alternatives to conventional chemical methods, providing cost-effective and sustainable polymer modification for industrial and environmental applications [35].

5. CONCLUSIONS

Radiation technologies have become indispensable across medicine and environmental management, offering precise, efficient, and versatile solutions. In healthcare, advances in diagnostic imaging and targeted radiotherapy improve tumor control, minimize normal tissue damage, and enable personalized treatment strategies. Environmentally, radiation applications in wastewater purification, solid waste sterilization, and pollutant detection provide sustainable and effective approaches to safeguard public health. Together, these innovations underscore the transformative potential of radiation science in enhancing both human health and environmental protection.

6. REFERENCES

1. D. Abshire and M.K. Lang. The evolution of radiation therapy in treating cancer. *Seminars in Oncology Nursing* 34(2): 151-157 (2018).
2. A. Aggarwal, G. Lewison, D. Rodin, A. Zietman, R. Sullivan, and Y. Lievens. Radiation therapy research: A global analysis 2001-2015. *International Journal of Radiation Oncology* Biology* Physics* 101(4): 767-778 (2018).
3. R. Baskar, K.A. Lee, R. Yeo, and K.W. Yeoh. Cancer and radiation therapy: current advances and future directions. *International Journal of Medical Sciences* 9(3): 193 (2012).
4. M.J. Feigenbaum and N.D. Mermin. $E= mc^2$. *American Journal of Physics* 56(1): 18-21 (1988).
5. S.E. Hil. Reanalyzing the ampère-maxwell law. *The Physics Teacher* 49(6): 343-345 (2011).
6. P.L. Ward. On the Planck-Einstein Relation. (2020). https://whyclimatechanges.com/relation.pdf.
7. C. Wan, J.M. Vaughn, J.T. Sadowski, and M.E. Kordesch. Scandium oxide coated polycrystalline tungsten studied using emission microscopy and photoelectron spectroscopy. *Ultramicroscopy* 119: 106-110 (2012).
8. M. Berger, Q. Yang, and A. Maier. X-ray Imaging. In: Medical imaging systems: an introductory guide. A. Maier, S. Steidl, V. Christlein, and J. Hornegger (Eds.). *Springer, Cham, Switzerland* pp. 119-145 (2018).
9. X. Ou, X. Chen, X. Xu, L. Xie, X. Chen, Z. Hong, H. Bai, X. Liu, Q. Chen, L. Li, and H. Yang. Recent development in x-ray imaging technology: Future and challenges. *Research* 2021: 9892152 (2021).

10. P.W. Ralls, R.B. Jeffrey, R.A. Kane, and M. Robbin. Ultrasonography. *Gastroenterology Clinics of North America* 31(3): 801-825 (2002).
11. M. Mazonakis and J. Damilakis. Computed tomography: What and how does it measure? *European Journal of Radiology* 85(8): 1499-1504 (2016).
12. D.W. Townsend. Positron emission tomography/computed tomography. *Seminars in Nuclear Medicine* 38(3): 152-166 (2008).
13. G. Katti, S. Ara, and A. Shireen. A. Magnetic resonance imaging (MRI)–A review. *International Journal of Dental Clinics* 3(1): 65-70 (2011).
14. V.S. Khoo, D.P. Dearnaley, D.J. Finnigan, A. Padhani, S.F. Tanner, and M.O. Leach. Magnetic resonance imaging (MRI): considerations and applications in radiotherapy treatment planning. *Radiotherapy and Oncology* 42(1): 1-15 (1997).
15. J.C. Richardson, R.W. Bowtell, K. Mäder, and C.D. Melia. Pharmaceutical applications of magnetic resonance imaging (MRI). *Advanced Drug Delivery Reviews* 57(8): 1191-1209 (2005).
16. A. Gallamini, C. Zwarthoed, and A. Borra. Positron emission tomography (PET) in oncology. *Cancers* 6(4): 1821-1889 (2014).
17. G. Muehllehner and J.S. Karp. Positron emission tomography. *Physics in Medicine and Biology* 51(13): 117-137 (2006).
18. Y. Higuchi, S. Matsuda, and T. Serizawa. Gamma knife radiosurgery in movement disorders: Indications and limitations. *Movement Disorders* 32(1): 28-35 (2017).
19. W. Cheng and J.R. Adler. An overview of cyberknife radiosurgery. *Chinese Journal of Clinical Oncology 3*(4): 229-243 (2006).
20. C. Ding, C.B. Saw, and R.D. Timmerman. Cyberknife stereotactic radiosurgery and radiation therapy treatment planning system. *Medical Dosimetry* 43(2): 129-140 (2018).
21. W. Kilby, M. Naylor, J.R. Dooley, C.R.M. Jr, and S. Sayeh. A technical overview of the CyberKnife system. In: Handbook of robotic and image-guided surgery. M.H. Abedin-nasab (Ed.). *Elsevier, Amsterdam* pp.15-38 (2020).
22. J.S. Kuo, C. Yu, Z. Petrovich, and M.L. Apuzzo. The CyberKnife stereotactic radiosurgery system: description, installation, and an initial evaluation of use and functionality. *Neurosurgery* 62: 785-789 (2008).
23. J.J. Lagendijk, B.W. Raaymakers, and M. Van Vulpen. The magnetic resonance imaging–linac system. *Seminars in Radiation Oncology* 24(3): 207-209 (2014).
24. X. Liu, Z. Li, and Y. Yin. Clinical application of MR-Linac in tumor radiotherapy: a systematic review. *Radiation Oncology* 18: 52 (2023).
25. B.D. Kavanagh and R.D. Timmerman. Stereotactic radiosurgery and stereotactic body radiation therapy: an overview of technical considerations and clinical applications. *Hematology/Oncology Clinics of North America* 20(1): 87-95 (2006).
26. B. Lin, F. Gao, Y. Yang, D. Wu, Y. Zhang, G. Feng, T. Dai, and X. Du. FLASH radiotherapy: History and Future. *Frontiers in Oncology* 11: 644400 (2021).
27. J. Bourhis, P. Montay-Gruel, P.G. Jorge, C. Bailat, B. Petit, J. Ollivier, W. Jeanneret-Sozzi, M. Ozsahin, F. Bochud, R. Moeckli, and J.F. Germond. Clinical translation of FLASH radiotherapy: Why and how? *Radiotherapy and Oncology* 139: 11-17 (2019).
28. D. Ersahin, I. Doddamane, and D. Cheng. Targeted radionuclide therapy. *Cancers* 3(4): 3838-3855 (2011).
29. S.V. Gudkov, N.Y. Shilyagina, V.A. Vodeneev, and A.V. Zvyagin. Targeted radionuclide therapy of human tumors. *International Journal of Molecular Sciences* 17(1): 33 (2015).
30. D. Yan, F. Vicini, J. Wong, and A. Martinez. Adaptive radiation therapy. *Physics in Medicine & Biology* 42(1): 123-132 (1997).
31. M.Y. Al-Ani and F.R. Al-Khalidy. Use of ionizing radiation technology for treating municipal wastewater. *International Journal of Environmental Research and Public Health* 3(4): 360-368 (2006).
32. R.O.A. Rahman and Y.T. Hung. Application of ionizing radiation in wastewater treatment: an overview. *Water* 12(1): 19 (2019).
33. P.H. Rathod, J.C. Patel, M.R. Shah, and A.J. Jhala. Evaluation of gamma irradiation for bio-solid waste management. *International Journal of Environment and Waste Management* 2(1-2): 37-48 (2008).
34. P.L. Hanst and J.A. Morreal. Detection and measurement of air pollutants by absorptions of infrared radiation. *Journal of the Air Pollution Control Association* 18(11): 754-759 (1968).
35. A.G. Chmielewski, M. Haji-Saeid, and S. Ahmed. Progress in radiation processing of polymers. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 236(1-4): 44-54 (2005).