



# Modern Radiation Oncology at a Crossroads: Biology, Technology and Identity

Angel Montero<sup>1</sup>, Ivica Ratosa<sup>2,3</sup>

*1 Department of Radiation Oncology, HM Hospitales, Madrid, Spain*

*2 Department of Radiation Oncology, Institute of Oncology Ljubljana, Slovenia*

*3 Faculty of Medicine, University of Ljubljana, Slovenia*

10.53011/JMRO.2025.02.01

ISSN: 2784 – 0131

**Received** December 20, 2025

**Revised** December 30, 2025

**Accepted** December 31, 2025,

**Published Online** December 31, 2025.

**\*Corresponding author:**

Angel Montero

**Email:** [angel.monteroluis@gmail.com](mailto:angel.monteroluis@gmail.com)

Copyright 2025 The Author(s).

Published by Casa Cărții de Știință

This is an open access article under a CC-BY license

## ABSTRACT:

Contemporary radiation oncology stands at a critical crossroads between technological sophistication and biological relevance. While the field has undergone a profound transformation—achieving unprecedented precision through innovations like IMRT, SABR, and AI-driven workflows—there is a growing concern that technical mastery is overshadowing clinical purpose. This paper explores the tension between a technology-driven identity and the necessity of reclaiming a biology-centered paradigm.

**KEYWORDS:** *precision medicine, Radiation Oncology, technology, tumor biology.*

## Introduction

Contemporary cancer care is inherently multidisciplinary, requiring close collaboration among oncologists from different specialties to ensure optimal treatment for each patient. Within this framework, radiotherapy remains one of the most widely used and effective therapeutic modalities, with approximately 50% of all patients with cancer requiring radiotherapy at some point during the course of their disease (1,2).

Yet radiation oncology now finds itself at a crossroads. Few medical specialties have undergone such a profound and rapid technological transformation over recent decades. Precision has become our defining hallmark, technical accuracy our

professional language, and technology the most visible expression of our identity.

Beneath this unquestionable progress, however, lies an uncomfortable question: are we advancing toward better oncologic care, or merely toward increasingly sophisticated radiation delivery? The growing debate between biology and technology in radiation oncology is not a minor academic exercise; rather, it reflects deeper concerns about the specialty's clinical leadership, professional identity, and long-term relevance.

## Where We Come From, Where We Are, and Where We Are Going

Since its discovery and subsequent consolidation as a therapeutic tool for cancer (and for several non-

malignant conditions) radiotherapy has undergone continuous evolution, becoming a highly sophisticated modality capable of delivering dose with remarkable precision to the target volume while sparing surrounding healthy tissues. In recent years, however, and with increasing intensity, radiation oncology faces the risk of becoming a technologically brilliant yet conceptually impoverished specialty if biology fails to reclaim a central role in clinical decision-making.

Overlooking, or relegating to the background, the fact that radiotherapy is fundamentally intended to cure (sometimes), relieve (often), and accompany (always) the patient, means relinquishing the medical foundations of the specialty in favor of a poorly understood technological primacy.

Radiotherapy emerged at the end of the nineteenth century from the discovery of X-rays by Wilhelm Röntgen and natural radioactivity by Henri Becquerel, alongside the pioneering work of Marie and Pierre Curie. From its earliest stages, it was grounded in a distinctly biological perspective. Early advances were driven by clinical experimentation and direct observation of biological effects, including the definition of maximum tolerated dose through the concept of the “erythema dose” and the establishment of fractionation as a therapeutic principle, based on the classical experiments of Claude Regaud and colleagues (3). These developments firmly positioned biology at the core of understanding the therapeutic effects of ionizing radiation.

At the same time, it would be both risky and inaccurate to ignore that progress in radiotherapy has been inseparable from technological development. The twentieth century—and the first quarter of the twenty-first—has been shaped by engineering, applied physics, and industrial innovation, leading to unprecedented technological advances that have turned radiotherapy into a clear success story.

Technological innovation has permeated every stage of the oncological process, from diagnosis through completion of treatment. Techniques such as intensity-modulated radiotherapy (IMRT), stereotactic radiosurgery (SRS), stereotactic ablative body radiotherapy (SABR), image-guided radiotherapy (IGRT), and adaptive radiotherapy (ART) have substantially improved treatment precision, enabling the safe irradiation of

tumors near critical organs, enhancing safety, standardizing workflows, and ensuring clinical reproducibility.

In parallel, hybrid systems such as MRI-guided linear accelerators (MR-LINAC), PET-based platforms, and workflow automation supported by artificial intelligence have improved both accuracy and efficiency. Particle therapies—using protons and carbon ions—exploit distinct physical properties, such as the Bragg peak, to achieve potentially superior dose distributions. Emerging approaches, including FLASH radiotherapy, are currently under investigation for their potential to improve normal tissue tolerance and further advance treatment personalization (4,5).

## What if we shift the focus, again?

Technological success, while undeniable, is not without risk. The more our specialty is defined by machines and algorithms, the greater the danger of becoming technology-driven rather than patient-centered. Today, we can determine *where* we irradiate with remarkable precision, yet we are not always equally clear about *whom* to treat, *how much*, *when*, and *why*. This imbalance highlights a fundamental truth: technical progress alone does not necessarily translate into clinical progress.

In contrast, a biologically driven approach seeks to understand the differential response of tumors and normal tissues to ionizing radiation, reflecting the inherent heterogeneity of patients. The integration of radiogenomics, liquid biopsy, and molecular biomarkers offers a pathway toward genuine treatment personalization, allowing radiation dose, fractionation, and therapeutic combinations—including immunotherapy and targeted agents—to be tailored to the individual characteristics of both tumor and host.

This radiobiological paradigm not only strengthens the clinical role of the radiation oncologist and the physician–patient relationship, but also expands the therapeutic potential of radiotherapy beyond geometric optimization, reframing it as a dynamic and patient-specific strategy.

Biology-centered approaches, however, come with undeniable challenges: fragmented evidence, immature or insufficiently validated biomarkers, increased conceptual complexity, and limited appeal to an industry focused on rapid, scalable

solutions. Yet for precisely these reasons, abandoning biology in favor of uncritical technologisation is not a pragmatic shortcut, but an intellectual retreat.

### **The limits of biologism and the risks of uncritical technologization: toward radiation oncology fragmentation?**

Framing the debate in radiation oncology as a simple opposition between biology and technology fundamentally misrepresents the issue. Technology refines execution but does not determine indication; biology introduces uncertainty but provides clinical meaning. Adaptive radiotherapy implemented without clear biological criteria risks becoming little more than geometric adjustment; artificial intelligence without biological grounding leads to automation without true intelligence; and proton therapy adopted without biologically informed patient selection results in high-cost treatments with, at best, marginal clinical benefit.

Radiotherapy must rest on biological principles that define who is likely to benefit, why treatment is indicated, when and how it should be delivered, and what therapeutic goals are realistic. Beyond hypothetical hierarchies, it may be more meaningful to understand why cells become “immortal,” evade regulatory and immune control, and ultimately exhaust the life of their host, or how available strategies can reverse this process and interact to maximize response, than to fine-tune a treatment to the millimeter or control the minimal variation caused by normal respiratory motion. Within this framework, technology plays a crucial—yet supporting—role: it enables and refines clinical intent, but it should never become an end in itself.

The speed and visual appeal of technological innovation, substantial industrial investment with pressure for early returns, and a degree of persistent professional insecurity—shaped by fear of rare but serious toxicities and by the public’s often negative perception of radiation—have all contributed to a growing reliance on a technological “lifeboat,” even within the specialty itself. This drift risks pushing radiation oncology toward an increasingly technical practice in which clinical judgement is subordinated to algorithms—or to other specialists—reducing radiation oncologists to highly

skilled “advanced operators” progressively distanced from their medical identity.

Swinging the pendulum in the opposite direction, toward an exclusively biologicist view, is equally unhelpful. Sound biological concepts without the technological means to deliver treatment safely and precisely would inevitably lead to clinical regression and further weaken the specialty.

If this false dichotomy persists, the most likely outcome is not synthesis but fragmentation: on one side, a nominally “clinical” branch focused on patient interaction and treatment decisions, at risk of being absorbed by other specialists; on the other, a predominantly technical branch formed by a close alliance of physicians and physicists devoted to constraining, histogramming, and other *-ing*, expertly optimizing dose distributions while becoming increasingly focused on the irradiated volume rather than the patient who, almost incidentally, contains it. Such a future would not only impoverish the discipline but would also erode its medical identity and clinical leadership. The question is whether we, as oncology and radiotherapy specialists, are prepared to accept such a (dystopian?) future.

### **From precision to purpose in radiation oncology**

The integration of biological data into clinical workflows allows a more accurate characterization of tumor heterogeneity, including the identification of radioresistant subvolumes or hypoxic regions that may benefit from targeted dose escalation. In parallel, advances in tumor biology are driving increasingly rational multimodal strategies—such as radioimmunotherapy and combinations of radiotherapy with targeted agents—in which biomarkers inform both patient selection and optimal treatment sequencing. Crucially, this biologically driven approach is only feasible when supported by advanced technologies, including adaptive radiotherapy, functional and molecular imaging (PET and MRI), and artificial intelligence—assisted planning (6–8).

The convergence of technological innovation and biological insight is therefore enabling a transition towards truly precision radiation oncology, focused on individualizing treatment for each person with cancer—the ultimate goal of any medical

intervention. We are oncologists and radiation oncologists, but above all, we are physicians. It is the humanistic foundations of medicine, rather than the allure of technology alone, that should guide our path forward.

Patients are not volumes, histograms, or targets; they are the reason our specialty exists. Without self-criticism, there is no progress, only inertia. In

this context, the next major advance in radiation oncology is unlikely to come from a new machine, but from a well-formulated clinical question. If biology does not reclaim a central role in decision-making, radiotherapy may become technically flawless yet clinically dispensable. Ultimately, treating cancer is not about delivering radiation perfectly, but about delivering it with purpose.

**ABBREVIATIONS**

- ART – adaptive radiotherapy
- IGRT – image-guided radiotherapy
- IMRT – Intensity-modulated radiotherapy
- MR-LINAC – Magnetic resonance-guided linear accelerators
- SABR – stereotactic ablative body radiotherapy
- SRS – stereotactic radiosurgery

**STATEMENTS**

**Authors' contribution:** AM and IR planned the manuscript. AM took the leading in drafting the text and IR provided critical feedback.

**Conflict of interest:** The authors declare no conflicts of interest regarding any aspect of this manuscript

**Funding:** The authors declare no source of funding for this manuscript

**REFERENCES**

1. Atun R, Jaffray DA, Barton MB, Bray F, Baumann M, Vikram B, Hanna TP, Knaul FM, Lievens Y, Lui TY, Milosevic M, Sullivan B, Rodin DL, Rosenblatt E, Van Dyk J, Yap ML, Zubizarreta E, Gospodarowicz M. Expanding global access to radiotherapy. *Lancet Oncol.* 2015 Sep;16(10):1153-86. doi: 10.1016/S1470-2045(15)00222-3. PMID:26419354.
2. Rodríguez A, Borrás JM, López-Torrecilla J, Algara M, Palacios-Eito A, Gómez-Caamaño A, Olay L, Lara PC. Demand for radiotherapy in Spain. *Clin Transl Oncol.* 2017 Feb;19(2):204-210. doi: 10.1007/s12094-016-1525-x. Epub 2016 Aug 4. PMID: 27492014.
3. Regaud C, Ferroux R. Discordance des effets de rayons X, d'une part dans le testicule, par le peau, d'autre parts dans le fractionnement de la dose. *Compt Rend Soc Biol.* 1927;97:431–434.
4. Calvaruso M, Pucci G, Alberghina C, Minafra L. Radiation Therapy Personalization in Cancer Treatment: Strategies and Perspectives. *Int J Mol Sci.* 2025 Jul 2;26(13):6375. doi: 10.3390/ijms26136375. PMID: 40650150; PMCID: PMC12250120.
5. Chandra RA, Keane FK, Voncken FEM, Thomas CR Jr. Contemporary radiotherapy: present and future. *Lancet.* 2021 Jul 10;398(10295):171-184. doi: 10.1016/S0140-6736(21)00233-6. Epub 2021 Jun 21. PMID: 34166607.
6. Yan Y, Alexander DA, Bednarz BP, Bronk LF, Chen H, Gladstone DJ, Han B, Iannuzzi CM, Li Y, Nguyen N, Mulenga N, Viscariello NN, Wang Y, Weygand J, Zlateva Y, Guan F. Innovative approaches in precision radiation oncology: advanced imaging technologies and challenges which shape the future of radiation therapy. *Front Med (Lausanne).* 2025 Oct 30;12:1686593. doi: 10.3389/fmed.2025.1686593. Erratum in: *Front Med (Lausanne).* 2025 Nov 25;12:1738811. doi: 10.3389/fmed.2025.1738811. PMID: 41244760; PMCID: PMC12613237.
7. Fiorino C, Guckemberger M, Schwarz M, van der Heide UA, Heijmen B. Technology-driven research for radiotherapy innovation. *Mol Oncol.* 2020 Jul;14(7):1500-1513. doi:10.1002/1878-0261.12659. Epub 2020 Mar 19. PMID: 32124546; PMCID:PMC7332218.
8. Webster M, Podgorsak A, Li F, Zhou Y, Jung H, Yoon J, Dona Lemus O, Zheng D. New Approaches in Radiotherapy. *Cancers (Basel).* 2025 Jun 13;17(12):1980. doi:10.3390/cancers17121980. PMID: 40563630; PMCID: PMC12190917.