Review paper

The role of training simulators in interventional radiation therapy (brachytherapy) training: A narrative review

Martina Ferioli, MD[1], Federica Medici, MD[1,2], Erika Galietta, MD[1,2], Ludovica Forlani, MD[1,2], Luca Tagliaferri, MD[3], Savino Cilla, MD[4], Silvia Cammelli, MD, PhD[1,2], Alessio G. Morganti, MD, PhD[1,2*], Milly Buwenge, PhD[1*]

[1]Radiation Oncology, Department of Medical and Surgical Sciences (DIMEC), Alma Mater Studiorum – Bologna University, Bologna, Italy, [2]Radiation Oncology, IRCCS Azienda Ospedaliero-Universitaria di Bologna, Bologna, Italy, [3]Gemelli ART (Advanced Radiation Therapy) – Interventional Oncology Center (IOC), Fondazione Policlinico Universitario «Agostino Gemelli» IRCCS, Rome, Italy, [4]Medical Physics Unit, Gemelli Molise Hospital, Campobasso, Italy

*The two authors contributed equally and share the senior authorship.

Abstract

Simulators have revolutionized medical education and training across various disciplines, offering unique advantages in skill acquisition and performance improvement. In the context of interventional radiation therapy (IRT), simulators have emerged as valuable tools for training healthcare professionals in these complex procedures. This narrative review summarized the available evidence on the use of simulators in IRT training, highlighting their impact on proficiency, engagement, and self-confidence as well as their benefits for medical physicists and radiation therapists.

A systematic search was conducted in PubMed, resulting in inclusion of 10 papers published since 2009, with 5 of them published since 2020. Publications originated from centers in USA, Ireland, Switzerland, Canada, and Japan, covering a range of IRT settings, including general, prostate, and cervical IRT.

The review demonstrated that simulators provide a controlled and realistic environment for skill acquisition, allowing healthcare professionals to practice procedures, optimize image quality, and enhance technical proficiency. The use of simulators addressed the barriers associated with limited caseload and procedural complexity, ultimately contributing to improved education and IRT training. While cost considerations may exist, simulators offer long-term cost-effective solutions, balancing the potential benefits in improving educational outcomes and patient care.

Overall, simulators play a crucial role in IRT training, enhancing the skills and competence of healthcare providers and improving access to quality IRT care worldwide. Future research should focus on evaluating the long-term impact of simulation-based training on clinical outcomes and patient satisfaction, exploring different simulation models and training approaches, and addressing region-specific barriers to optimize the utilization of IRT.

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Purpose

Simulators have emerged as valuable tools in teaching and training across diverse fields, offering unique advantages for skill acquisition and performance improvement. These advanced technological systems provide realistic and immersive environments that simulate real-world scenarios, enabling learners to engage in experiential learning and practice without the associated risks and costs. By replicating complex tasks and environments, simulators facilitate the development of cognitive, psycho-motor, and decision-making skills, allowing learners to gain proficiency, enhance their problem-solving abilities, and refine their techniques [1]. Furthermore, simulators enable repeated practice, allowing learners to overcome the limitations of time, access, and availability of resources. The ability to provide immediate feedback and performance assessment enhances self-reflection, promotes error analysis, and supports deliberate practice. Consequently, simulators have proven instrumental in a wide range of domains, including aviation, military training, engineering, emergency response, and other high-stakes professions, revolutionizing the way education and training are approached in these fields [1].

Educational simulators in medicine have become valuable tools with a wide range of medical applications.

Address for correspondence: Dr. Martina Ferioli, MD, Radiation Oncology, DIMEC, Alma Mater Studiorum – Bologna University, Via Albertoni 15, 40138 Bologna, Italy, phone: +39-051-2143564, ✉ e-mail: martina.ferioli4@unibo.it

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These simulators offer realistic and immersive environments that allow healthcare professionals, students, and trainees to practice and refine their skills in a safe and controlled setting. In surgical disciplines, simulators enable trainees to learn surgical techniques, develop hand-eye coordination, and improve procedural proficiency without risking patient safety. They are also used for training in diagnostic procedures, such as ultrasound and endoscopy, providing a platform for learners to enhance their imaging interpretation skills and procedural competence. Overall, educational simulators contribute significantly to medical education, fostering competence, confidence, and proficiency among healthcare professionals, while prioritizing patient safety [2].

Simulators are also increasingly used in radiotherapy training. Rooney *et al*. conducted a systematic literature review to clarify the type and extent of simulation-based medical education (SBME) in radiation oncology. Fifty-four publications met the inclusion criteria. SBME types included screen-based simulators, simulated environments, virtual reality and haptic systems, simulated patients, part-task trainers, and computer-based systems with mannequins. Various skill sets were addressed, such as contouring, treatment planning, and clinical decision-making. The target learning population included residents, attending physicians, medical students, and other healthcare professionals. Learner feedback was reported in 32 studies. The review provides guidance for future SBME development in radiation oncology, emphasizing the need for centralized resources and improved reporting in the literature [3].

Interventional radiation therapy (IRT, commonly known as "brachytherapy") is an important treatment modality for various cancers, including cervical and prostate cancers. However, the complexity and technical skills required for IRT procedures pose challenges in training and maintaining competency among healthcare professionals [4, 5]. Simulators have emerged as valuable tools in IRT training, offering a controlled and realistic environment for skill acquisition.

This narrative review summarized the findings from available evidence on the use of simulators in IRT training, highlighting their development, impact on proficiency, engagement, and self-confidence as well as the benefits for medical physicists and radiation therapists.

Material and methods

Search strategy

A systematic search was conducted in PubMed on July 10, 2023, using the following search terms: ("education" OR "educational" OR "training") AND ("simulator" OR "simulators") AND ("brachytherapy" OR "interventional radiotherapy" OR "interventional radiation therapy"). The search strategy aimed to identify relevant studies on the use of simulators in IRT.

Study selection

Only publications in full text and in English were included in the review, regardless of study design and without time limits. Two authors (FM, EG) independently screened the reports based on title and abstract to identify potentially relevant articles. Any disagreements between the authors were resolved through a discussion and consultation with the senior author.

Data extraction

Two authors (MF, LF) independently extracted information from the selected studies. Data was collected on study setting, methods used, and results obtained. Any discrepancies or conflicts in data extraction were resolved through discussion and consensus.

Narrative review checklist

A narrative review checklist was followed to ensure comprehensive coverage of the topic. Supplementary Table 1 provides details of the checklist items and their corresponding assessment criteria. By employing this methodology, we aimed to conduct a comprehensive review of the literature on the use of simulators in IRT. The systematic search and rigorous selection process ensured the inclusion of relevant studies, while the data extraction process allowed for the analysis of key information from the selected articles.

Results

Search results

The initial search yielded a total of 18 items. After screening the titles and abstracts, 10 papers were identified as meeting the inclusion criteria, while 8 papers were excluded. The excluded papers, along with the reasons for exclusion, are listed in Supplementary Material. All the included papers were published since 2009, with 5 of them published since 2020, indicating a recent focus on the topic. The publications were sourced from various centers worldwide, including the USA (5 papers), Ireland (2 papers), Switzerland (1 paper), Canada (1 paper), and Japan (1 paper). The selected papers covered a range of IRT settings, including 1 paper on general IRT, 6 papers on prostate IRT, and 3 papers on cervical IRT.

Literature review

The literature search identified ten relevant papers, which were reviewed for this narrative summary. The abstracts covered various aspects of simulator-based IRT training, including development of patient-derived training simulators, the use of anthropomorphic prostate simulators, virtual reality-based simulation, and ultrasound-compatible gynecologic IRT simulators. The abstracts included studies assessing the impact of simulators on proficiency, engagement, self-confidence, and technical skills among healthcare professionals involved in IRT procedures.

Goksel *et al*. observed that in IRT procedures, needle insertion is commonly performed, but accurate targeting can be challenging due to tissue displacement and needle bending caused by needle-tissue interaction. To enhance physicians' needle targeting skills, training with needle

Table 1. Main characteristics and results of the analyzed studies

Authors, year, country	Setting	Methods	Results	Conclusions
Goksel *et al.*, 2009, USA	Interstitial IRT	Comparison of three models of needle bending to improve needle insertion simulation	The angular spring is computationally the most efficient model	The angular spring model is the most accurate in modelling the bending of ORT needles
Goksel *et al.*, 2011, USA	TRUS-guided interstitial IRT of prostate cancer	Presentation of an IRT simulator with both needle insertion and TRUS probe controlled by haptic device	The simulator can be used for rehearsal, training, and treatment planning	–
Goksel *et al.*, 2013, Switzerland	TRUS-guided interstitial IRT of prostate cancer	Presentation of a virtual training system	The simulator, patient-specific, combines simulated TRUS images and haptic interactions, allowing the trainee to feel the interaction forces (both TRUS system and needle insertion)	This advanced simulator allows the physician to practice an upcoming procedure, and residents to train
Thaker *et al.*, 2014, USA	Interstitial IRT of prostate cancer	Design and implementation of a training program including a phantom-based simulator	Implants from the phantom-based simulator had a high consistency degree between trainees and uniformly high-quality of planning parameters	The training program improved the quality of IRT training and accelerated the learning curve
Fields *et al.*, 2020, USA	Intra-cavitary IRT of cervical cancer	Development of a high-fidelity, US- and CT-compatible gynecologic IRT training simulator	The model was developed in 3 months, and it did not show signs of degradation after multiple tandem insertions	The simulator may improve the access, for patients with gynecologic cancers, to more proficient radiation oncologists
Doyle *et al.*, 2021, Ireland	TRUS-guided interstitial IRT of prostate cancer	Description of the design, development and preliminary evaluation of an anthropomorphic training phantom	Iterative design process: several prototypes of a simulator including TRUS clinical patient data to design 3D-printed moulds, tissue-mimicking materials with sonographic characteristics of the prostate and overlying tissues, and haptic feedback to the user	–
Taunk *et al.*, 2021, USA	Intracavitary IRT of cervical cancer	Description of a VR-based intra-cavitary IRT simulation procedure	VR intra-cavitary IRT simulation improves residents' subjective and objective technical skills, self-confidence, and willingness to perform IRT	VR is an immersive, time-efficient, engaging, and enjoyable tool that promotes residents interest in IRT
Shaaer *et al.*, 2021, Canada	TRUS-guided interstitial IRT of prostate cancer	Design of a training environment using a phantom-based simulator	Oncologists ranked the phantom as "very good" both in terms of overall quality and elasticity	Phantoms can be a surrogate to train residents on prostate IRT
Doyle *et al.*, 2022, Ireland	TRUS-guided interstitial IRT of prostate cancer	Design of a simulation-based TRUS training workshop for medical physicists	Improved knowledge, perceived understanding of TRUS scanner, and readiness to optimize image quality	Benefit in offering a simulation training workshop to medical physicists in this setting
Tomizawa *et al.*, 2022, Japan	Intra-cavitary. interstitial IRT of cervical cancer	Development of a training simulator for intra-cavitary and interstitial IRT	Two physicians successfully applied different applicators and created CT-based treatment plans	The training simulator can be useful for training of IRT

IRT – interventional radiation therapy, TRUS – trans-rectal ultrasound, VR – virtual reality insertion simulators is valuable. Accurate needle bending models are crucial for such simulators as well as for needle path planning. In their paper, the authors proposed three different models to simulate needle deformations. The first two models incorporate geometric non-linearity and utilize a finite element method. The third model consists of rigid bars connected by angular springs. These models were compared using experimental data obtained by applying lateral tip forces on a IRT needle. Model parameters were identified, and simulation results were compared with experimental findings. These results demonstrate that the angular spring model, being computationally efficient, also provides the most accurate representation of IRT needle bending [6].

Goksel *et al*. introduced a haptic simulator for prostate IRT. The simulator enabled control of needle insertion and trans-rectal ultrasound (TRUS) probe manipulation using haptic devices. Deformable tissue modeling based on the finite element method (FEM) computed tissue interaction forces, which were rendered to the user through the haptic devices. The simulator included 3D models of needle flexibility and asymmetric tip bevel for realistic needle insertion simulation. Trainees could practice needle insertion, targeting, and 3D intra-operative TRUS placement for registration with pre-operative volume study. Computational acceleration techniques were employed for real-time haptic performance, balancing accuracy, and speed. The paper also presented a graphic card implementation for mesh adaptation operations. The authors concluded that the simulator serves as a valuable tool for training, rehearsal, and treatment planning purposes [7].

In their subsequent paper, Goksel *et al*. introduced a computer-based virtual training system for prostate IRT. The system combined ultrasound image synthesis and haptic TRUS interaction to create a comprehensive simulator. Trainees could manipulate the needle and TRUS, observe patient-specific images, and experience realistic interaction forces. The simulator incorporated validated models for tissue deformation, needle and seed appearance, and haptic feedback. It simulated various aspects of the IRT procedure, including seed unloading, fluoroscopy imaging, and TRUS plane switching. Real-time rendering techniques enabled fast image formation, and the simulator provided real-time dosimetry for immediate feedback on planning changes. The simulation was patient-specific, allowing the import of treatment plans and imaging data for practice and training purposes [8].

Thaker *et al*. developed a unique training program using a phantom-based simulator to improve the quality of education in prostate IRT and its quality assurance process. The program included practicing radiation oncologists, radiation oncology residents, and fellows of the American Brachytherapy Society. It focused on six core areas of quality assurance in prostate IRT. Trainees implanted ultrasound phantoms with dummy seeds using iodine-125 pre-operative treatment planning technique. Dosimetric parameters were compared before and after implantation. Thirty-one trainees completed the program successfully. The size, number of seeds, and total activity used were consistent among the trainees. All trainees achieved the objective of V_{100} > 95% both before and after implantation. The trainees' ability to cover the target volume with the dose was maintained regardless of initial prostate phantom volume. However, there was lower concordance for V_{150}, which may better reflect heterogeneity control. The analysis showed consistent and high-quality implants. The training program enhanced prostate IRT training, improved the learning curve, and provided valuable educational opportunities. The authors concluded that prostate phantom implantation serves as an important initial step in acquiring the skills for safe prostate IRT performance [9].

Fields *et al*. observed that existing simulators lack procedural fidelity, hindering resident training. To address this, the authors developed a high-fidelity, ultrasound- and CT-compatible gynecologic IRT training simulator. The custom-made simulator, based on a pelvic ultrasound trainer, features a cervical os, endometrial canal, and palpable hypoechoic cervical tumor. The development took approximately three months, and the material properties were suitable for ultrasound, CT, and MRI imaging. The simulator remained intact after multiple tandem insertions. This high-fidelity ultrasound-compatible simulator effectively improved resident training, leading to more proficient brachytherapists and potentially improving survival for women with advanced gynecologic malignancies. The authors concluded that future guidance include enhancing the model for interstitial training and introducing variations in anatomy for advanced technical training [10].

Taunk *et al*. stated that intra-cavitary IRT is crucial in cervical cancer treatment, but many graduating residents lack confidence due to limited caseload. The authors hypothesized that virtual reality (VR) simulation would enhance resident confidence, engagement, and proficiency. A VR training video of an intra-cavitary IRT case was created and viewed by residents using a commercial VR headset. Objective measures of implant quality were recorded during timed procedures on a pelvic simulator. Pre- and post-simulation questionnaires assessed self-confidence, procedural knowledge, and perceived usefulness. Fourteen residents participated, with improvements in confidence, assembly, insertion, and reduced implant time. Median technical proficiencies increased. Residents found VR to be a useful, immersive, engaging, time-efficient, and enjoyable learning tool, increasing their interest in IRT. The authors concluded that VR intra-cavitary IRT simulation improves residents' self-confidence, technical skills, and willingness to perform IRT [11].

Shaaer *et al*. aimed to create a training environment for prostate IRT using a phantom-based simulator. The prostate phantom was made from gelatin, graphite, and water. Radiation oncologists evaluated the phantom's image quality, haptic feedback, needle insertion quality, and compatibility with tools. The authors concluded that the phantom had good image quality and elasticity. It can serve as a training tool for residents in prostate IRT procedures [12].

Doyle *et al*. designed and evaluated a training phantom for trans-rectal ultrasound prostate IRT. The training phantom was developed using 3D-printed moulds based on clinical patient data. Tissue-mimicking materials were applied to simulate sonographic characteristics and physical response of the prostate. The design went through iterative improvements based on quantitative evaluations and feedback from an experienced IRT oncologist. The authors presented preliminary evaluation results, demonstrating potential usefulness of the training phantom [13].

In order to improve training opportunities for interstitial needle application in image-guided adaptive IRT, Tomizawa *et al*. developed a training simulator. The simulator consisted of a translucent silicone tumor phantom and acrylic tube resembling the vagina. It is compatible with CT and MRI imaging. A tumor phantom (68 × 49 × 45 mm^3) was created based on a patient with a typical bulky and irregular-shaped cervical tumor. Two physicians with different IRT skills used the simulator successfully, applying Fletcher-Suit Asian Pacific and Venezia applicators with interstitial needles. CT-based treatment plans consistent with clinical practice were created. The authors concluded that the simulator showed promising results for IRT training, but requires further research with more phantoms and practitioners to confirm its educational value [14].

Doyle *et al*. noted that ultrasound imaging training is lacking in radiation oncology programs, and there is no objective measure to assess performance. Their study presented a simulation-based training workshop for medical physicists involved in low-dose-rate prostate IRT using high-fidelity anthropomorphic TRUS simulators. The workshop incorporated a blended learning approach to optimize TRUS image quality. Results showed significant improvements in knowledge, perceived understanding of TRUS scanner operation, and readiness to optimize image quality. Focus group data explored participants' experiences and challenges with TRUS prostate IRT. The study suggests the benefit of offering simulation training workshops to medical physicists and other healthcare professionals involved in prostate IRT. The authors concluded that incorporating high-fidelity anthropomorphic TRUS simulators enables competency-based skill acquisition and continued proficiency outside the surgical environment, without direct patient exposure [15].

Discussion

Narrative

The reviewed abstracts collectively support the use of simulators as effective training tools in IRT. Simulators offer a controlled environment for skill acquisition, allowing healthcare professionals to practice procedures, optimize image quality, and enhance technical proficiency. They provide opportunities for hands-on training, independent of direct patient exposure, which is particularly valuable for medical physicists and radiation therapists. Simulators also contribute to increasing self-confidence and engagement among residents, addressing the barriers associated with limited caseload and procedural complexity.

The sub-optimal use of IRT for cervical cancer remains a significant issue on a global scale, affecting high-income, and low- and middle-income countries [4]. Barriers to the implementation of IRT are multifactorial, and vary between countries and regions. These barriers include limited infrastructure, inadequate training opportunities, resource constraints, and disparities in healthcare access. In light of our review, it is evident that the use and diffusion of educational simulators offer a promising solution to address the educational challenges in IRT. Simulators provide a safe and controlled environment for training, allowing healthcare professionals to acquire and refine the necessary skills for delivering IRT effectively. By improving education and training through simulators, we can enhance the competency of healthcare providers and ultimately increase access to quality IRT care worldwide. These efforts, combined with other initiatives, aim at addressing infrastructure and resource limitations, and hold great potential for improving the utilization of IRT globally.

However, cost can be a significant consideration when it comes to implementing IRT training simulators [16]. While specific information about the cost of IRT training simulators are not easily available, it is important to note that simulation technology in healthcare can vary widely in terms of complexity and associated costs. High-fidelity simulators with advanced features and realistic anatomical models tend to be more expensive. These simulators may incorporate imaging compatibility, haptic feedback, and advanced software capabilities, which contribute to their cost. Additionally, ongoing maintenance, updates, and technical support can also incur additional expenses.

Nevertheless, some institutions and educational programs may choose to invest in simulators as a long-term cost-effective solution, considering the potential benefits they offer in improving educational outcomes and patient care. Furthermore, cost considerations extend beyond the initial investment in simulators. Training programs also need to account for faculty training, curriculum development, and the integration of simulation into existing educational structures. Additionally, resource allocation for dedicated simulation facilities, personnel, and ongoing program evaluation should be taken into account. However, while cost can be a factor, it should be balanced against the potential benefits of IRT training simulators in improving education, patient safety, and clinical outcomes.

In conclusion, simulators play a crucial role in IRT training by providing a realistic and controlled environment for skill acquisition. Patient-derived, anthropomorphic, virtual reality-based, and ultrasound-compatible simulators have demonstrated their effectiveness in improving proficiency, engagement, self-confidence, and technical skills among healthcare professionals involved in IRT procedures. Further research is warranted to explore the educational value of simulators using larger cohorts and varied training scenarios. Simulators have the potential to revolutionize IRT training and contribute to better patient outcomes through enhanced skill acquisition and proficiency among healthcare professionals.

Summary

This narrative review identifies the use of educational simulators as a promising solution to address the educational challenges in IRT.

In terms of clinical practice, the findings emphasize the need for comprehensive training programs that incorporate simulation-based education to enhance the skills of healthcare professionals involved in IRT. By providing hands-on training opportunities, simulators can improve technical proficiency and procedural knowledge, ultimately leading to improved patient outcomes.

For policy-makers, the review underscores the importance of recognizing multifactorial barriers to IRT implementation and developing targeted interventions. Policy development should prioritize the integration of educational simulators into training curricula, ensuring access to these resources for healthcare institutions. Additionally, addressing infrastructure gaps and resource constraints is crucial to facilitate the widespread adoption of IRT, and improve cancer care services globally.

Future research in this field should focus on evaluating the long-term impact of simulation-based training on clinical outcomes and patient satisfaction. Further studies could explore the effectiveness of different simulation models, training approaches, and curricular integration strategies. Additionally, research should aim to identify additional barriers specific to different regions and develop context-specific solutions to improve the utilization of IRT. Continued collaboration between researchers, healthcare professionals, policy-makers, and educators is vital to drive advancements in IRT education and implementation, ultimately benefiting patients worldwide.

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Disclosure

The authors report no conflict of interest.

Supplementary Material is available on the journal's website.

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