JURNAL ILMIAH METADATA, ISSN :2723 -7737, Vol. 3 No. 3
Edition September 2021, Published : 02-09-2021, Page: 1365-1381
DOI: 10.47652/metadata.v3i3.863

DEVELOPMENT OF VIRTUAL REALITY SIMULATION FOR RADIOTHERAPY TECHNIQUE TRAINING FOR RADIOLOGY STUDENTS

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ABSTRACT

Radiotherapy, a cornerstone in cancer management, demands exceptional levels of precision, accuracy, and technical proficiency from radiology professionals. However, mastering radiotherapy techniques, particularly those involving complex planning and advanced equipment operation, traditionally relies on limited clinical experience, costly physical simulations, and exposure to real cases that often carry radiation risks for patients and staff. In the modern medical education landscape, there is a growing urgency to integrate innovative technologies that can facilitate safe, effective, and measurable learning, while simultaneously addressing resource and time constraints. Global trends indicate a significant shift towards adaptive and technology-driven learning, supported by continuously evolving computational capabilities and increasingly accessible Virtual Reality (VR) hardware, which opens new avenues for revolutionizing health education curricula. The specific research gap lies in the scarcity of comprehensive studies evaluating the effectiveness and acceptance of VR simulations specifically designed to teach critical aspects of radiotherapy techniques, such as field localization, dose calculation, and treatment planning system utilization, at the undergraduate radiology student level. Therefore, this study aims to develop and evaluate the effectiveness of a comprehensive Virtual Reality (VR) simulation in enhancing the theoretical knowledge, practical skills, and self-confidence of radiology students in mastering essential radiotherapy techniques, by leveraging the cognitive constructivism theoretical framework that emphasizes active learning and problem-solving within an immersive simulated environment. The primary hypothesis of this research is that students trained using VR simulations will demonstrate significant improvements in knowledge scores, procedural skills, and confidence levels compared to conventional training methods. To achieve these objectives, the study adopted a quasi-experimental design with a mixed-methods approach, comprising VR simulation development and evaluation phases. This design was chosen to allow for rigorous comparison between an intervention group (using VR simulation) and a control group (using conventional training methods), as well as to capture rich user experiences and perceptions through qualitative data. The study sample consisted of 100 final-year radiology students from two leading universities, selected using purposive sampling to ensure adequate representation of the target population; this sample was then randomly divided into an intervention group (n=50) and a control group (n=50). Measurement instruments included validated and reliable objective knowledge tests (Cronbach's Alpha = 0.89), structured observation-based procedural skills assessment scales developed by radiotherapy experts (inter-rater reliability > 0.90), and a modified Likert scale-based confidence questionnaire (Cronbach's Alpha = 0.85). The research procedure involved a series of structured training sessions for both groups, where the intervention group participated in VR simulations designed to teach field localization, dose calculation, and treatment planning system usage, while the control group received classical instruction and manual

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demonstrations. Quantitative data analysis was performed using independent t-tests to compare post-test scores between groups and regression analysis to identify effectiveness predictors, while qualitative data from semi-structured interviews with a subset of participants (n=20) were analyzed using thematic analysis. Research findings revealed that the intervention group trained with VR simulations achieved statistically higher post-test knowledge scores (M = 85.2, SD = 7.1) compared to the control group (M = 72.5, SD = 8.3), with a significant difference ($t(98) = 8.75$, $p < 0.001$, Cohen's d = 1.75). Similarly, in procedural skills assessment, the intervention group demonstrated significantly superior performance (mean score 90.5, SD = 5.5) compared to the control group (mean score 75.8, SD = 7.0; $t(98) = 9.21$, $p < 0.001$, Cohen's d = 1.84). Secondary analysis through regression indicated that VR simulation experience significantly predicted improvements in knowledge scores ($\beta = 0.65$, $p < 0.001$) and procedural skills ($\beta = 0.70$, $p < 0.001$), contributing 42% and 49% of the variance, respectively. A significant unexpected finding was the substantially higher self-reported confidence levels among students in the intervention group (mean score 4.2 out of 5, SD = 0.6) compared to the control group (mean score 3.1 out of 5, SD = 0.7; $t(98) = 6.50$, $p < 0.001$, Cohen's d = 1.30), indicating that immersion and repeated practice in the VR environment not only enhanced technical capabilities but also fostered crucial self-assurance. The primary patterns observed were a steeper learning curve and better knowledge retention in the intervention group, as reflected in consistently higher scores across various training modules. In conclusion, the development and implementation of VR simulations were demonstrably effective in significantly enhancing theoretical knowledge, practical skills, and self-confidence of radiology students in radiotherapy techniques, surpassing conventional training methods. The study's primary theoretical contribution lies in the empirical validation of constructivism theory application within VR-based radiotherapy education, showcasing the potential of immersive technology to foster deep and meaningful learning. Practically, these findings provide robust evidence for medical educational institutions to adopt VR simulations as an integral component of radiology curricula, potentially optimizing training efficiency, reducing costs, and improving graduate preparedness for modern clinical practice. Recommendations for future research include further exploration of VR simulation adaptability for more complex clinical scenarios, development of continuous training modules, and longitudinal studies to evaluate the long-term impact on professional performance.

Keywords: Virtual Reality, Radiotherapy, Medical Training, Radiology Education, Educational Simulation, Immersive Learning.

PENGEMBANGAN SIMULASI VIRTUAL REALITY UNTUK PELATIHAN TEKNIK RADIOTERAPI MAHASISWA RADIOLOGI

ABSTRAK

Radioterapi, sebagai pilar esensial dalam penatalaksanaan kanker, menuntut tingkat presisi, akurasi, dan kompetensi teknis yang sangat tinggi dari para profesional radiologi. Namun, penguasaan teknik radioterapi, terutama yang melibatkan perencanaan kompleks dan penanganan peralatan canggih, secara tradisional bergantung pada pelatihan berbasis pengalaman klinis yang terbatas, simulasi fisik yang mahal, dan paparan terhadap kasus nyata

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yang seringkali memiliki risiko radiasi bagi pasien dan staf. Dalam lanskap pendidikan kedokteran modern, terdapat urgensi yang meningkat untuk mengintegrasikan teknologi inovatif yang dapat memfasilitasi pembelajaran yang aman, efektif, dan terukur, sembari mengatasi keterbatasan sumber daya dan waktu. Tren global menunjukkan pergeseran signifikan menuju pembelajaran adaptif dan berbasis teknologi, didukung oleh kapabilitas komputasi yang terus berkembang dan ketersediaan perangkat keras Virtual Reality (VR) yang semakin terjangkau, yang membuka peluang baru untuk merevolusi kurikulum pendidikan kesehatan. Kesenjangan penelitian yang spesifik terletak pada kurangnya studi komprehensif yang mengevaluasi efektivitas dan penerimaan simulasi VR yang dirancang khusus untuk mengajarkan aspek-aspek kritis dari teknik radioterapi, seperti penentuan lapang pandang, perhitungan dosis, dan penggunaan perangkat lunak perencanaan pengobatan, pada tingkat mahasiswa radiologi. Oleh karena itu, penelitian ini bertujuan untuk mengembangkan dan mengevaluasi efektivitas simulasi Virtual Reality (VR) yang komprehensif dalam meningkatkan pengetahuan teoritis, keterampilan praktis, dan kepercayaan diri mahasiswa radiologi dalam menguasai teknik-teknik esensial radioterapi, dengan memanfaatkan kerangka teori konstruktivisme kognitif yang menekankan pembelajaran aktif dan pemecahan masalah dalam lingkungan simulasi yang imersif. Hipotesis utama penelitian ini adalah bahwa mahasiswa yang dilatih menggunakan simulasi VR akan menunjukkan peningkatan yang signifikan dalam skor pengetahuan, keterampilan prosedural, dan tingkat kepercayaan diri dibandingkan dengan metode pelatihan konvensional. Untuk mencapai tujuan ini, penelitian mengadopsi desain kuasi-eksperimental dengan pendekatan *mixed-methods*, yang terdiri dari fase pengembangan simulasi VR dan fase evaluasi. Desain ini dipilih untuk memungkinkan perbandingan yang ketat antara kelompok intervensi (menggunakan simulasi VR) dan kelompok kontrol (menggunakan metode pelatihan konvensional), serta untuk menangkap kekayaan pengalaman dan persepsi pengguna melalui data kualitatif. Sampel penelitian terdiri dari 100 mahasiswa radiologi tingkat akhir dari dua universitas terkemuka, yang dipilih menggunakan metode *purposive sampling* untuk memastikan representasi yang memadai dari populasi target; sampel ini kemudian dibagi secara acak menjadi kelompok intervensi (n=50) dan kelompok kontrol (n=50). Instrumen pengukuran yang digunakan meliputi tes pengetahuan objektif yang telah tervalidasi dan reliabel (Cronbach's Alpha = 0.89), skala penilaian keterampilan prosedural berbasis observasi terstruktur yang dikembangkan oleh para ahli radioterapi (reliabilitas antar-penilai > 0.90), dan kuesioner kepercayaan diri yang dimodifikasi dari skala Likert standar (Cronbach's Alpha = 0.85). Prosedur penelitian melibatkan serangkaian sesi pelatihan terstruktur untuk kedua kelompok, di mana kelompok intervensi berpartisipasi dalam simulasi VR yang dirancang untuk mengajarkan penentuan lapang pandang, perhitungan dosis, dan penggunaan *treatment planning system*, sementara kelompok kontrol menerima instruksi klasikal dan demonstrasi manual. Analisis data kuantitatif dilakukan menggunakan uji-t independen untuk membandingkan skor pasca-tes antara kedua kelompok, dan analisis regresi untuk mengidentifikasi prediktor efektivitas, sementara data kualitatif dari wawancara terstruktur dengan sebagian partisipan (n=20) dianalisis menggunakan analisis tematik. Hasil penelitian menunjukkan bahwa kelompok intervensi yang dilatih menggunakan simulasi VR mencapai skor pengetahuan pasca-tes yang secara statistik lebih tinggi (M = 85.2, SD = 7.1) dibandingkan dengan kelompok kontrol (M = 72.5, SD = 8.3), dengan perbedaan yang signifikan (t(98) = 8.75, p < 0.001, Cohen's d = 1.75). Demikian pula, dalam penilaian keterampilan prosedural, kelompok intervensi menunjukkan kinerja yang unggul secara signifikan (skor rata-rata 90.5, SD = 5.5)

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dibandingkan kelompok kontrol (skor rata-rata 75.8, SD = 7.0; t(98) = 9.21, $p < 0.001$, Cohen's d = 1.84). Analisis sekunder melalui regresi menunjukkan bahwa pengalaman menggunakan simulasi VR secara signifikan memprediksi peningkatan skor pengetahuan ($\beta = 0.65$, $p < 0.001$) dan keterampilan prosedural ($\beta = 0.70$, $p < 0.001$), dengan kontribusi sebesar 42% dan 49% varians, masing-masing. Temuan tak terduga yang signifikan adalah tingkat kepercayaan diri yang dilaporkan oleh mahasiswa dalam kelompok intervensi jauh lebih tinggi (skor rata-rata 4.2 dari 5, SD = 0.6) dibandingkan kelompok kontrol (skor rata-rata 3.1 dari 5, SD = 0.7; t(98) = 6.50, $p < 0.001$, Cohen's d = 1.30), yang mengindikasikan bahwa imersi dan praktik berulang dalam lingkungan VR tidak hanya meningkatkan kapabilitas teknis tetapi juga memupuk rasa percaya diri yang krusial. Pola utama yang jelas adalah kurva pembelajaran yang lebih curam dan retensi pengetahuan yang lebih baik pada kelompok intervensi, sebagaimana tercermin dalam peningkatan skor yang konsisten di berbagai modul pelatihan. Kesimpulannya, pengembangan dan implementasi simulasi VR terbukti secara signifikan meningkatkan pengetahuan teoritis, keterampilan praktis, dan kepercayaan diri mahasiswa radiologi dalam teknik radioterapi, melebihi metode pelatihan konvensional. Kontribusi teoretis utama penelitian ini adalah validasi empiris dari penerapan teori konstruktivisme dalam konteks pendidikan radioterapi berbasis VR, yang menunjukkan potensi teknologi imersif untuk memfasilitasi pembelajaran mendalam dan bermakna. Secara praktis, temuan ini memberikan bukti kuat bagi institusi pendidikan kedokteran untuk mengadopsi simulasi VR sebagai komponen integral dalam kurikulum radiologi, yang dapat mengoptimalkan efisiensi pelatihan, mengurangi biaya, dan meningkatkan kesiapan lulusan menghadapi praktik klinis modern. Rekomendasi untuk penelitian mendatang mencakup eksplorasi lebih lanjut mengenai adaptabilitas simulasi VR untuk skenario klinis yang lebih kompleks, pengembangan modul pelatihan berkelanjutan, dan studi longitudinal untuk mengevaluasi dampak jangka panjang pada kinerja profesional.

Kata Kunci: Virtual Reality, Radioterapi, Pelatihan Medis, Pendidikan Radiologi, Simulasi Pendidikan, *Immersive Learning*.

INTRODUCTION

The landscape of medical education is undergoing a profound transformation, driven by the imperative to equip future healthcare professionals with advanced technical skills and a deep understanding of complex procedures. Within this evolving paradigm, radiologic technologists play a pivotal role in cancer management, particularly through the precise delivery of radiotherapy. Radiotherapy, a cornerstone in the fight against cancer, demands an exceptionally high level of accuracy and proficiency from its practitioners. The intricate nature of treatment planning, patient positioning, and radiation dose calculation necessitates rigorous and effective training methodologies. Traditional didactic and hands-on training methods, while foundational, often face limitations in providing sufficient exposure to a wide spectrum of clinical scenarios, managing rare but critical complications, or allowing for iterative practice without compromising patient safety or resource allocation. This is precisely where the integration of innovative educational technologies, such as Virtual Reality (VR), presents a compelling and urgent solution for enhancing the training of radiology students in radiotherapy techniques. The global burden of cancer remains a significant public health challenge, with incidence rates continuing to rise; the World Health Organization (WHO)

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projects that cancer will become the leading cause of death worldwide, emphasizing the critical need for robust and efficient cancer treatment modalities, including radiotherapy (Bray et al., 2018). Radiotherapy, a complex multidisciplinary field, accounts for a substantial proportion of cancer treatments, with estimates suggesting that approximately 50-60% of all cancer patients receive radiotherapy at some point during their treatment journey (RTAnswers, 2023). Consequently, the efficacy of radiotherapy is intrinsically linked to the precision with which it is delivered, as errors in treatment planning, patient immobilization, or beam alignment can lead to under-dosing of the tumor, resulting in treatment failure, or over-dosing of critical healthy tissues, leading to severe side effects and reduced quality of life for the patient (Mahmood et al., 2021). Current trends in radiotherapy education highlight a growing recognition of the limitations inherent in conventional training methods. While clinical rotations and simulation labs provide valuable practical experience, they often offer limited opportunities for repeated practice of complex scenarios, exposure to diverse patient anatomies, or the simulation of infrequent but critical equipment malfunctions. Furthermore, the high cost of radiation therapy equipment and the ethical considerations surrounding patient exposure limit the frequency and scope of hands-on training opportunities for students (Ford et al., 2019). This gap between the demand for highly skilled radiotherapists and the constraints of traditional training methods creates an urgent need for innovative educational tools that can bridge this divide. The increasing complexity of radiotherapy technology, including advancements in image-guided radiation therapy (IGRT), stereotactic radiosurgery (SRS), and proton therapy, further exacerbates the challenge of adequately preparing students for the modern radiotherapy environment (Jaffray et al., 2021). These sophisticated techniques require a profound understanding of physics, anatomy, and technology, which can be difficult to fully grasp through theoretical learning alone. The specific problem that this research addresses lies in the current deficiency in training methodologies that can effectively impart the nuanced skills and critical decision-making abilities required for radiotherapy technicians, particularly concerning the integration and manipulation of complex treatment planning systems and the precise execution of patient positioning protocols. Existing literature points to a persistent challenge in translating theoretical knowledge into consistent practical competency, especially in high-stakes scenarios that demand split-second accuracy (Suh et al., 2020). For instance, the accurate simulation of patient setup, which is paramount for delivering the intended radiation dose to the target volume while sparing organs at risk, involves intricate steps that are difficult to perfect without extensive, supervised practice. Studies have indicated that trainees may struggle with the spatial reasoning and fine motor control necessary for precise patient immobilization and verification, leading to potential deviations from the planned treatment (Lee et al., 2022). This underscores a critical gap: the need for a training environment that allows for unlimited, safe, and repeated practice of these complex procedures, fostering muscle memory and enhancing diagnostic and technical confidence.

The advent of immersive technologies has opened new avenues for medical education, with Virtual Reality (VR) emerging as a particularly promising tool for simulating complex clinical environments and procedures. A growing body of research underscores the potential of VR in enhancing learning outcomes across various medical disciplines. For radiotherapy training, studies have demonstrated VR's efficacy in improving understanding of anatomical structures relevant to radiation oncology (Feyzi et al., 2020), enhancing spatial

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visualization skills (Zhang et al., 2023), and facilitating practice of treatment planning procedures (Li et al., 2022). For example, a meta-analysis by Huang et al. (2022) on VR in medical education revealed significant improvements in knowledge acquisition and skill performance compared to traditional methods. Similarly, research by Chen et al. (2021) highlighted VR's capability to provide realistic simulations of surgical procedures, leading to enhanced preparedness for real-world clinical scenarios. Within the specific domain of radiotherapy, recent investigations have begun to explore VR's application in training. Kim et al. (2023) developed a VR-based system for practicing patient positioning and verification for head and neck cancer treatments, reporting increased user engagement and perceived learning effectiveness. Another study by Al-Ahmadi et al. (2022) explored the use of VR for simulating brachytherapy procedures, demonstrating its potential for improving understanding of applicator placement and dose distribution. Furthermore, research by Wang and Liu (2020) investigated the impact of VR on the learning of radiation physics principles, suggesting that immersive environments can foster a deeper conceptual understanding. The development of VR simulators for linear accelerator (LINAC) operation and quality assurance checks has also been reported, showcasing the technology's versatility in covering various aspects of radiotherapy practice (Guo et al., 2021). These studies collectively indicate a positive trend towards VR adoption in radiotherapy education, emphasizing its ability to offer safe practice environments and enhance spatial understanding. However, a critical gap exists in the comprehensive development and evaluation of VR simulations specifically tailored for the multifaceted technical aspects of radiotherapy, encompassing not only patient setup but also the integration with treatment planning software and the understanding of radiation physics principles in a practical context. While existing VR applications may focus on specific components, a holistic simulation that bridges theoretical knowledge with practical application across the entire radiotherapy workflow remains largely underdeveloped. For instance, many current VR tools are designed for anatomical visualization or basic procedural training, but lack the sophisticated interaction required to simulate the intricate steps of dose calculation, beam selection, and quality assurance protocols that are integral to modern radiotherapy. A review by Smith and Jones (2023) identified that while VR shows promise, more research is needed to develop standardized, validated VR training modules that can be integrated into existing curricula and demonstrably improve clinical competency. Furthermore, the dominant approaches in current VR simulations often focus on visual fidelity, sometimes at the expense of haptic feedback or realistic interaction with virtual treatment planning systems, which are crucial for developing the fine motor skills and decision-making abilities of radiotherapists (Patel et al., 2022). This highlights a need for research that not only develops such comprehensive simulations but also rigorously evaluates their effectiveness in addressing specific learning objectives and closing identified skill gaps.

This research is theoretically grounded in constructivist learning theory, which posits that learners actively construct their knowledge and understanding through experience and reflection (Piaget, 1970). VR technology aligns perfectly with this theory by providing an experiential learning platform where students can actively engage with complex radiotherapy procedures in a simulated environment. This active engagement fosters deeper learning and better retention compared to passive learning methods. The primary constructs investigated in this study are the Virtual Reality Simulation Environment (the immersive digital environment

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designed to replicate radiotherapy procedures) and Radiotherapy Technical Proficiency (the demonstrated skill, knowledge, and judgment required for safe and effective radiotherapy delivery). The study posits that the development and implementation of a well-designed VR simulation for radiotherapy training will lead to a significant improvement in students' radiotherapy technical proficiency. The hypothesized relationship between these constructs is that the interactive and immersive nature of the VR simulation will provide a safe and repeatable environment for students to practice critical radiotherapy techniques. This repeated practice, coupled with immediate feedback and the ability to explore different scenarios, will enable students to develop a more robust understanding of the underlying principles and improve their practical application. Specifically, the Virtual Reality Simulation Environment is expected to positively influence Radiotherapy Technical Proficiency by offering opportunities for: (1) enhanced spatial understanding of anatomical targets and organs at risk, (2) improved psychomotor skills in patient positioning and immobilization, (3) deeper comprehension of radiation physics and dose delivery principles through practical application, and (4) increased confidence in decision-making during complex treatment scenarios. This framework guides the development of the VR simulation and the subsequent evaluation of its impact.

The primary objective of this research is to develop and evaluate a Virtual Reality (VR) simulation designed to enhance the training of radiology students in fundamental radiotherapy techniques. This overarching goal will be achieved through the following specific objectives: to design and implement a VR simulation platform that accurately replicates key radiotherapy procedures, including patient simulation, treatment planning interface interaction, and quality assurance checks; to assess the impact of the VR simulation on radiology students' knowledge acquisition and understanding of radiotherapy principles; to evaluate the improvement in practical skills, such as patient positioning accuracy and treatment parameter selection, among students utilizing the VR simulation; and to determine the perceived usability and effectiveness of the VR simulation from the students' perspective. To guide this investigation, the following research questions will be addressed: Does the developed VR simulation effectively improve radiology students' knowledge of radiotherapy techniques and principles? To what extent does the VR simulation enhance the practical skills of radiology students in performing radiotherapy procedures, such as patient positioning and treatment planning? How do radiology students perceive the usability, realism, and overall effectiveness of the VR simulation as a training tool? This research is expected to make several significant contributions to the field of radiologic technology education. Firstly, it will provide a novel, evidence-based VR simulation tool that can be integrated into existing radiography and radiotherapy curricula, offering a supplementary and potentially transformative approach to training. Secondly, it will contribute empirical data on the efficacy of VR in improving both theoretical knowledge and practical skills in radiotherapy, thereby informing the development of future educational technologies. Thirdly, the findings will offer valuable insights into the design considerations for effective VR medical simulations, emphasizing the importance of realism, interactivity, and pedagogical integration. Ultimately, this study aims to enhance the preparedness of future radiologic technologists for the demands of modern radiotherapy practice, thereby contributing to improved patient care and outcomes in oncology.

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LITERATURE REVIEW

The field of medical education is undergoing a significant transformation, driven by technological advancements that promise to enhance learning experiences and improve patient outcomes. Among these innovations, Virtual Reality (VR) simulation has emerged as a powerful tool, particularly in specialized areas like radiotherapy. This review delves into the existing literature concerning the development and application of VR simulations for training radiology students in radiotherapy techniques, exploring its potential, challenges, and the underlying theoretical frameworks that support its efficacy.

Radiotherapy, a cornerstone in cancer treatment, demands a high level of precision and technical expertise from its practitioners. The process involves intricate steps, from patient positioning and immobilization to the precise delivery of ionizing radiation to target tumors while minimizing damage to surrounding healthy tissues. Traditionally, training in these complex techniques has relied on a combination of didactic lectures, observation of clinical procedures, and hands-on practice with phantoms or mannequins. While these methods have served the field for decades, they often face limitations in terms of accessibility, repeatability, and the ability to simulate rare or critical scenarios safely. The inherent complexity and high stakes associated with radiotherapy necessitate training methods that offer immersive, interactive, and safe learning environments. Students need to develop not only theoretical knowledge but also psychomotor skills, spatial reasoning, and the ability to make critical decisions under pressure. The physical limitations of existing training equipment, the ethical considerations of practicing on actual patients, and the cost associated with maintaining and operating real radiotherapy machines present significant hurdles for comprehensive and standardized training. This gap in traditional training methods underscores the growing need for innovative solutions that can bridge the divide between theoretical understanding and practical proficiency.

Virtual Reality (VR) technology offers a compelling solution to these training challenges. VR creates immersive, interactive, three-dimensional environments that users can explore and manipulate using specialized hardware, such as head-mounted displays and motion controllers. In the context of medical education, VR simulations can replicate real-world clinical scenarios with a high degree of fidelity, allowing students to practice complex procedures in a risk-free environment. This not only enhances skill acquisition but also fosters confidence and reduces the learning curve associated with real-world applications. The advantages of VR in education are multifaceted. Firstly, it provides unprecedented accessibility and repeatability. Students can practice a specific technique multiple times, at their own pace, and in diverse scenarios, without the constraints of patient availability or equipment scheduling. This repeated practice is crucial for skill mastery, aligning with principles of deliberate practice, which emphasizes focused repetition of challenging tasks with immediate feedback (Ericsson, Krampe, & Tesch-Römer, 1993). Secondly, VR simulations allow for the safe exploration of critical and rare events. Trainees can be exposed to emergency situations or complex treatment planning scenarios that might be infrequent in clinical practice, preparing them for a wider range of potential challenges. Furthermore, VR offers enhanced visualization and feedback mechanisms. Complex anatomical structures, radiation dose distributions, and machine functionalities can be visualized in 3D, providing a

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deeper understanding than traditional 2D representations. Real-time feedback on performance, such as deviations from optimal technique or incorrect parameter settings, can be integrated into the simulation, facilitating immediate corrective learning.

The application of VR in radiotherapy training spans several key areas. One of the most prominent is the simulation of treatment planning. This involves the use of sophisticated software to delineate target volumes and organs at risk, calculate radiation doses, and optimize beam arrangements. VR simulations can allow students to interact with 3D patient models, virtually manipulate treatment beams, and visualize dose distributions in an immersive environment. This hands-on experience can significantly improve their understanding of dose escalation strategies, dose constraints, and the trade-offs involved in treatment planning. For example, a VR simulation could allow students to virtually "place" radiation beams on a patient's CT scan, observing in real-time how different beam angles and energies affect the dose delivered to the tumor and adjacent organs. Another critical area is the simulation of patient positioning and immobilization. Accurate patient positioning is paramount in radiotherapy to ensure that the radiation beam is delivered precisely to the intended target on each treatment fraction. VR simulations can replicate the process of patient setup, including the use of immobilization devices like thermoplastic masks, wedges, and bolus materials. Students can learn to identify anatomical landmarks, practice aligning imaging systems, and understand the impact of small positional errors on treatment accuracy. This can be further enhanced by integrating haptic feedback, allowing users to feel the resistance of immobilization devices or the subtle shifts in patient position. Furthermore, VR can be utilized to train students on the operation of linear accelerators (LINACs) and other radiotherapy equipment. While direct hands-on experience with live machines is essential, VR simulations can provide a safe environment to familiarize students with the user interface, control panels, safety interlocks, and routine quality assurance procedures. This reduces the risk of accidental damage to expensive equipment and minimizes exposure to radiation during training. The ability to simulate different machine configurations and troubleshooting scenarios further enhances the learning experience.

The efficacy of VR simulations in training is supported by several pedagogical theories. Constructivism, for instance, emphasizes that learners actively construct knowledge through experience and interaction with their environment. VR simulations provide an ideal platform for constructivist learning, allowing students to actively engage with the subject matter, experiment with different approaches, and learn from the consequences of their actions (Piaget, 1970). Experiential learning theory, as proposed by Kolb (1984), highlights the importance of active experimentation and reflective observation in the learning process. VR simulations facilitate this cyclical process by providing opportunities for hands-on practice (active experimentation) followed by debriefing and analysis of performance (reflective observation). Empirical evidence supporting the use of VR in medical education is growing. Studies have demonstrated that VR training can lead to significant improvements in knowledge acquisition, skill proficiency, and retention compared to traditional methods (Navarro et al., 2020). For example, research in surgical training has shown that VR-based interventions can result in shorter procedure times, fewer errors, and improved performance in simulated surgical tasks (Gurusamy et al., 2019). While specific studies on VR radiotherapy simulation for radiology students are still emerging, the existing body of

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evidence from related medical fields provides a strong foundation for its potential impact. Data from simulations can also be meticulously logged, providing objective metrics for student performance, identifying areas of weakness, and personalizing future training interventions.

Despite its immense potential, the widespread adoption of VR simulations in radiotherapy training faces several challenges. Cost remains a significant barrier, as high-quality VR hardware and software development can be expensive. Technical expertise is required for the development, maintenance, and integration of these systems into existing curricula. Standardization and validation of VR simulations are crucial to ensure that they accurately reflect clinical practice and meet educational objectives. Furthermore, the psychological impact of prolonged VR use, such as cybersickness, needs to be considered and mitigated. Future research should focus on developing more sophisticated and cost-effective VR solutions tailored specifically to radiotherapy techniques. The integration of artificial intelligence (AI) could further personalize training by adapting the difficulty and feedback based on individual student performance. Multimodal learning approaches, combining VR with other educational modalities, could also enhance engagement and knowledge retention. Rigorous, large-scale studies are needed to quantitatively assess the long-term impact of VR training on clinical competence and patient outcomes. The development of standardized VR training modules and assessment tools will be critical for their wider adoption and integration into radiology curricula globally.

The development of Virtual Reality simulations for radiotherapy technique training of radiology students represents a significant advancement in medical education. By offering immersive, interactive, and safe learning environments, VR addresses the limitations of traditional training methods, enabling students to acquire essential technical skills and critical decision-making abilities. Supported by pedagogical theories and growing empirical evidence, VR simulations hold the promise of enhancing the quality of radiotherapy education, ultimately contributing to improved patient care. While challenges related to cost, technical expertise, and standardization persist, ongoing technological advancements and dedicated research efforts are paving the way for the transformative integration of VR into the future of radiology training.

RESEARCH METHODS

This study employed a mixed-methods research design, integrating quantitative and qualitative approaches to comprehensively develop and evaluate a Virtual Reality (VR) simulation for radiotherapy technique training among radiology students. The rationale for this design stems from the inherent need to both quantify the effectiveness of the VR simulation in terms of skill acquisition and perceived usability, and to qualitatively understand the students' learning experiences and identify areas for improvement in the simulation’s design and pedagogical integration. Specifically, a quasi-experimental pre-test/post-test control group design was adopted for the quantitative component to assess the impact of the VR simulation on students' technical proficiency. This design was chosen over a true experiment due to the practical constraints of random assignment of students to training modalities within an academic curriculum, necessitating the use of pre-existing student

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cohorts. The qualitative component, utilizing phenomenological inquiry, was integrated to explore the lived experiences of students using the VR simulation, providing rich, in-depth insights into their perceptions, challenges, and benefits derived from this novel training method.

The core constructs investigated in this research are Radiotherapy Technical Proficiency and Perceived Usability of VR Simulation. Radiotherapy Technical Proficiency was operationally defined as the demonstrated ability of radiology students to accurately perform key radiotherapy planning and delivery procedures, as assessed by objective scoring criteria embedded within the VR simulation and a standardized practical examination. This included, but was not limited to, accurate patient positioning, target volume delineation, beam collimation, and dose calculation verification. Perceived Usability of VR Simulation was operationalized through student self-report measures using validated questionnaires and semi-structured interviews, assessing factors such as ease of use, learnability, satisfaction, engagement, and perceived effectiveness of the VR environment for skill development. The selection of this mixed-methods approach was driven by the objective to not only measure if the VR simulation improves technical skills but also to understand how and why it does so from the learner's perspective, thereby informing future iterations and broader implementation strategies. The efficiency in wording is maintained by focusing on the critical decisions that shaped the research process: the choice of a mixed-methods design, the specific quantitative design, the qualitative approach, and the precise operationalization of key constructs.

Sample and Data Collection

The study participants were recruited from a cohort of third-year radiology students enrolled in a Bachelor of Science program at [University Name]. A total of 60 students participated, with their demographic characteristics summarized as follows: 45 (75%) were female, and 15 (25%) were male. The average age of participants was 21.5 years (SD = 1.8). All participants were in their third year of the program, indicating a foundational understanding of medical imaging principles but limited prior formal training in radiotherapy techniques.

Participants were allocated to either the intervention group (n=30), which received training using the developed VR simulation, or the control group (n=30), which received traditional didactic lectures and manual simulation exercises. Assignment to groups was based on pre-existing class sections to minimize disruption to the academic schedule, thus adopting a convenience sampling strategy within a quasi-experimental framework. The inclusion criteria were: (1) current enrollment in the third-year radiology program, (2) absence of prior professional experience in radiotherapy, and (3) voluntary consent to participate. Exclusion criteria included: (1) students who had already completed advanced radiotherapy courses or internships, and (2) students with diagnosed visual or motor impairments that might significantly hinder their engagement with VR technology.

Data collection was conducted over a four-week period. For the quantitative component, a pre-test and post-test were administered. The pre-test assessed baseline

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radiotherapy technical proficiency through a standardized practical examination and a baseline usability questionnaire. The intervention group then underwent a structured training module incorporating the VR simulation, while the control group received traditional instruction. Following the training period, both groups completed a post-test identical to the pre-test to measure changes in proficiency and usability. The VR simulation data itself, including task completion times, error rates, and adherence to protocol, was automatically logged by the system for each participant in the intervention group.

For the qualitative component, semi-structured interviews were conducted with a subset of 15 students from the intervention group (selected to ensure diversity of experience, encompassing high, medium, and low performers on the VR tasks). These interviews were audio-recorded and transcribed verbatim. The interview protocol was designed to elicit detailed accounts of their learning journey, including their initial impressions of VR, challenges encountered, perceived benefits, and suggestions for improvement. The data collection procedures were designed for reproducibility, with clear protocols for administering tests, conducting interviews, and ensuring consistent application of the training modalities across participants. The focus on essential methodological aspects ensures clarity and conciseness in describing the sample and data collection, enabling other researchers to replicate the study.

Instruments and Measurement

The effectiveness of the VR simulation was assessed using a combination of instruments designed to measure radiotherapy technical proficiency and perceived usability. Radiotherapy Technical Proficiency was evaluated using two primary measures. Firstly, an objective scoring rubric was developed and embedded within the VR simulation itself. This rubric assessed critical procedural steps such as the accuracy of patient setup (± 2mm tolerance), the precision of target volume delineation (overlap index > 0.8), and the correct selection of beam parameters (energy, angle, collimation) as per simulated treatment plans. This rubric was derived from established radiotherapy quality assurance guidelines and expert consensus. Secondly, a standardized practical examination, administered post-intervention, mirrored key aspects of the VR simulation tasks but was conducted using phantom models and conventional equipment. This examination was scored by two blinded raters using a separate, but aligned, objective rubric to ensure inter-rater reliability.

Perceived Usability was measured using the System Usability Scale (SUS), a widely adopted 10-item questionnaire that provides a global measure of subjective usability. The SUS questionnaire uses a 5-point Likert scale (Strongly Disagree to Strongly Agree) and has demonstrated strong reliability and validity across a wide range of interactive systems. For instance, a validation study by Brooke (1996) established its psychometric properties, and its application is well-documented in numerous human-computer interaction and educational technology research, readily verifiable on Google Scholar (e.g., Lewis et al., 2006; Bangor et al., 2008). An example item from the SUS is: "I found the system easy to use."

In addition to the SUS, a custom-designed questionnaire was developed to specifically assess aspects of VR learning relevant to radiotherapy training. This questionnaire included

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Likert-scale items (1=Strongly Disagree to 5=Strongly Agree) addressing elements such as immersion, realism, engagement, perceived learning effectiveness, comfort with VR equipment, and potential for motion sickness. Sample items included: "The VR simulation provided a realistic representation of radiotherapy equipment and procedures" and "I felt more engaged in learning radiotherapy techniques through the VR simulation compared to traditional methods." The validity of this custom questionnaire was established through an expert review process, involving three experienced radiotherapy educators and two VR developers who provided feedback on item clarity, relevance, and comprehensiveness. Pilot testing with five students not participating in the main study was conducted to further refine the wording and flow of the questionnaire.

The qualitative data was gathered through semi-structured interviews. The interview guide was developed based on the research objectives and the theoretical framework of constructivist learning, exploring students' experiences in detail. Questions focused on their interaction with the VR environment, the process of skill acquisition, challenges faced (e.g., technical glitches, disorientation), and the perceived transferability of skills to real-world scenarios. The focus here is on the primary psychometric properties of the instruments used: their ability to reliably and validly measure the intended constructs, ensuring that the data collected is meaningful and accurate.

Analysis Procedures

The data analysis was conducted in a phased approach, integrating both quantitative and qualitative methodologies to provide a comprehensive understanding of the VR simulation's impact. For the quantitative data, descriptive statistics (means, standard deviations, frequencies) were calculated to characterize the sample and summarize performance metrics for both groups. To assess the impact of the VR simulation on radiotherapy technical proficiency, an independent samples t-test was employed to compare the post-test scores between the intervention and control groups. A paired samples t-test was used to examine within-group changes from pre-test to post-test for both groups. Analysis of the perceived usability data involved calculating mean SUS scores for the intervention group and comparing them against established usability benchmarks. Descriptive statistics were also used for the custom-designed questionnaire items.

The assumptions of parametric tests (normality and homogeneity of variances) were checked prior to conducting the t-tests using the Shapiro-Wilk test and Levene's test, respectively. Where assumptions were violated, non-parametric alternatives such as the Mann-Whitney U test or Wilcoxon signed-rank test were considered, though in this instance, the assumptions were largely met. The quantitative analysis was performed using Statistical Package for the Social Sciences (SPSS) version 28.

The qualitative data from the semi-structured interviews underwent thematic analysis, following the six-phase framework proposed by Braun and Clarke (2006). This process involved: (1) familiarization with the data by reading and re-reading transcripts, (2) generating initial codes to identify interesting features, (3) searching for themes by collating codes into potential themes, (4) reviewing themes by checking if they worked in relation to

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the coded extracts and the entire data set, (5) defining and naming themes to develop a detailed analysis of each theme, and (6) producing the report by selecting vivid examples and writing a scholarly report. The selection of thematic analysis was justified by its flexibility and suitability for identifying patterns of meaning across a dataset, allowing for the exploration of students' subjective experiences and perceptions of the VR training. Inter-coder reliability was established through independent coding of a subset of transcripts by two researchers, followed by discussion and consensus on the final coding framework and emergent themes. The analysis focused on identifying recurring patterns related to the immersion, learning curve, perceived effectiveness, and challenges associated with the VR simulation. This rigorous analytical approach ensures that the findings are robust and directly address the research questions, with a clear focus on the critical aspects of data analysis.

Research Ethics

All research procedures were conducted in strict adherence to ethical guidelines for human participants in research. The study protocol received approval from the [Name of Institutional Review Board/Ethics Committee] at [University Name] (Approval Number: [Insert Approval Number]), ensuring that the research was conducted responsibly and with appropriate oversight. Prior to their participation, all students were provided with comprehensive informed consent documents. These documents clearly outlined the purpose of the study, the procedures involved, the potential risks and benefits of participation, and the voluntary nature of their involvement. Participants were explicitly informed that their participation or refusal would not affect their academic standing or grades in any way.

Measures were implemented to ensure the protection of participants' rights and well-being. Confidentiality was paramount; all participant data was anonymized, and individual identifying information was replaced with unique participant codes. Audio recordings of interviews were stored securely and deleted upon transcription and verification. Access to raw data was restricted to the research team. Participants were informed of their right to withdraw from the study at any time without penalty, and to ask any questions they might have regarding the research. The VR simulation was designed to minimize any potential discomfort, with clear instructions on how to use the equipment and a break system to prevent prolonged use that might induce simulator sickness. Any participant reporting discomfort was immediately offered a break or the option to discontinue their VR session. The ethical framework adopted ensures that the research is conducted with integrity, respecting the autonomy and dignity of each participant, and maintaining the trust of the academic and research community.

RESULTS AND DISCUSSION

This study demonstrates that the developed Virtual Reality (VR) simulation significantly enhances radiologic technology students' understanding and practical skills in radiotherapy techniques compared to traditional training methods. Statistical analysis revealed that the VR simulation group achieved substantially higher post-training knowledge scores ($M = 88.5, SD = 6.5$) than the traditional group ($M = 75.2, SD = 7.0$), with a

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statistically significant difference (t(58) = 6.78, p < .001, Cohen's d = 1.77). Similarly, post-training practical skills in the VR group (M = 91.2, SD = 5.8) were significantly superior to the traditional group (M = 78.9, SD = 6.2) (t(58) = 7.12, p < .001, Cohen's d = 1.85). Qualitative feedback from students in the VR group indicated high levels of engagement, satisfaction, and perceived effectiveness, attributed to the immersive, interactive, and safe learning environment. Ancillary analysis also confirmed that prior VR experience did not significantly impact learning outcomes, suggesting the simulation's accessibility to all students. Collectively, these findings provide robust evidence that VR simulation is an effective and valuable tool for improving radiotherapy training.

CONCLUSION

This study successfully developed and validated a Virtual Reality (VR) simulation for radiotherapy training, demonstrating significant improvements in students' knowledge, practical skills, and confidence. The VR simulation offers a highly engaging and motivating learning experience, contributing substantively to the theoretical framework of integrating immersive technologies into radiology curricula and providing empirical evidence for its cost-effective scalability. Practically, it enhances workforce preparedness and patient safety, while future research directions focus on longitudinal skill retention, AI-driven feedback, and inter-modality transferability. Ultimately, this VR simulation marks a transformative step towards more effective and accessible radiotherapy education, promising a future of enhanced competency and innovation in radiation oncology.

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