DISSERTATION

INNOVATING RADIATION THERAPY TRAINING WITH VIRTUAL REALITY: A COMPREHENSIVE DIVE

Submitted by

Kulbir S. Sandhu

Department of Systems Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2026

Doctoral Committee:

Advisor: Marie Vans

Steve Simske
Tod Clapp
Svetlana Olbina

ABSTRACT

INNOVATING RADIATION THERAPY TRAINING WITH VIRTUAL REALITY: A COMPREHENSIVE DIVE

Traditional radiation therapy training depends on supervised access to clinical linear accelerators (LINACs), static instructional media, and opportunistic observation in busy treatment environments. Although this model remains common, it is increasingly constrained by limited machine time, the high capital cost of radiotherapy infrastructure, competing patient care demands, and the need to protect both patients and novice trainees from avoidable setup and workflow errors. These pressures are especially acute in radiation oncology, where safe task execution depends on a combination of conceptual knowledge, spatial understanding, workflow fluency, safety awareness, and confidence calibrated to actual performance. Immersive virtual reality (VR) offers a potentially scalable alternative because it can reproduce treatment-room workflows in a safe, repeatable, and spatially faithful environment without requiring access to a physical bunker.

This integrated manuscript synthesizes three related studies into a single unified paper that addresses three research questions within one experimental program. Research Question 1 examined whether immersive VR improves skill acquisition and competency development relative to traditional two-dimensional (2D) instruction. Research Question 2 examined whether VR enhances confidence and preparedness for real-world clinical scenarios. Research Question 3 examined how effectively immersive VR training translates to precise and reliable hands-on clinical performance, and how learners perceive the usability of the VR experience that supports

or constrains such translation. Across all three questions, the study used a randomized, single-blinded comparative design in which sixty-six participants were allocated to either a 3D VR cohort (n = 40) or a traditional 2D cohort (n = 26). Training addressed two identical clinical use cases: an automated dry run involving basic LINAC functions and a collision reset protocol. Transfer of learning was evaluated during hands-on performance on a physical LINAC.

A triangulated outcome framework was used to evaluate learning across cognitive, procedural, psychological, and systems-level domains. Measures included randomized pre-, post-, and retention knowledge assessments; binary procedural checklists; blinded expert global ratings; task completion time; observable error counts; Likert-scale training effectiveness items; and open-ended usability feedback. The integrated findings show a highly consistent pattern favoring immersive VR. Compared with traditional 2D instruction, VR-trained participants demonstrated larger gains in knowledge acquisition and retention, stronger procedural checklist performance, higher expert-rated competence, faster completion of clinical tasks, fewer observable errors, and substantially stronger self-reported confidence and preparedness. The benefits of VR were especially pronounced for spatially complex and safety-critical steps such as isocenter setup, gantry motion, protective stop handling, and collision reset. Delayed assessment further suggested that the advantages of immersive training were not merely short-term or novelty driven, but sufficiently durable to support retention and more stable execution over time.

Taken together, the combined results indicate that immersive VR is not simply an engaging educational adjunct. Rather, it functions as a rigorous instructional modality that supports deeper encoding of procedural knowledge, stronger transfer from training to real equipment, more calibrated confidence, and more reliable clinical performance. By reducing reliance on scarce and expensive clinical infrastructure while preserving contextual realism,

immersive VR offers a scalable pathway for radiation therapy education, onboarding, rehearsal, and ongoing competency development.

Key terms – Virtual Reality, Radiation Therapy, Cognitive load, skill acquisition, Linear Accelerators, Immersive learnings

ACKNOWLEDGMENTS

This dissertation represents the culmination of a deeply meaningful academic and professional journey, and I am sincerely grateful to the many individuals and organizations whose support, guidance, and encouragement made this work possible.

First and foremost, I offer my deepest gratitude to my advisor, Dr. Marie Vans, for her mentorship, encouragement, and unwavering support throughout this research process. Her intellectual guidance, thoughtful feedback, and high standards for scholarly rigor played a central role in shaping this dissertation. I am especially appreciative of her ability to challenge my thinking while also encouraging exploration across disciplines, allowing this work to grow at the intersection of systems engineering, immersive learning, and radiation therapy education.

I would also like to extend my sincere appreciation to my PhD committee members, Dr. Steve Simske, Dr. Tod Clapp, and Dr. Svetlana Olbina, for their time, expertise, and valuable feedback throughout the development of this dissertation. Their perspectives strengthened both the theoretical framing and methodological quality of this work. I am grateful for their thoughtful questions, constructive critique, and commitment to academic excellence, all of which helped refine this research into a more rigorous and meaningful contribution.

My heartfelt thanks go to the sixty-six participants who took part in this study. Their willingness to contribute their time, attention, and effort made this research possible. The care with which they engaged in the learning activities, performance assessments, and feedback processes provided the essential foundation for this dissertation. I am truly grateful for their participation and for the seriousness with which they supported this work.

I would also like to acknowledge Varian for its support of innovation in radiation oncology and for helping create an environment in which this work could be meaningfully pursued. The opportunity to explore immersive virtual reality as a training modality within the broader context of radiation therapy practice was shaped by the technological vision and clinical relevance of this domain. I am grateful for the organizational ecosystem, expertise, and practical inspiration that informed this research and reinforced its real-world significance.

I am also thankful to the broader community of radiation therapy educators, clinicians, engineers, and subject matter experts whose knowledge helped inform the design of the virtual reality training environment and the framing of clinically relevant workflows. Their contributions ensured that this work remained grounded in authentic practice and aligned with the realities of a safety-critical clinical environment.

In addition, I wish to acknowledge Colorado State University for providing the academic setting and interdisciplinary foundation necessary to pursue this research. The opportunity to conduct doctoral work that bridges engineering, education, and healthcare has been both enriching and transformative.

Finally, I offer my deepest gratitude to my family for their patience, understanding, and unconditional support throughout this journey. Their encouragement sustained me during the many long hours of research, writing, and revision required to complete this dissertation. Their belief in me gave me the strength to persevere, and this accomplishment is shared with them.

This dissertation is the product of many forms of support, seen and unseen. While any limitations in this work are my own, I remain profoundly grateful to all those who contributed to this journey and helped make this achievement possible.

PREFACE

This manuscript presents an integrated investigation into the role of immersive virtual reality in radiation therapy education, with specific attention to competency development, confidence and preparedness for clinical practice, and the translation of learning into precise and reliable hands-on performance. The work brings together three related lines of inquiry into a unified account of how high-fidelity three-dimensional simulation can support the preparation of radiation therapy trainees for complex, safety-critical clinical environments.

Radiation therapy is a field defined by technical precision, multidisciplinary coordination, and a constant commitment to patient safety. Training in such an environment has traditionally depended on access to physical linear accelerators, clinical supervision, and limited opportunities for repeated practice. While these methods remain essential, they are increasingly constrained by equipment availability, service demands, time pressures, and the understandable need to protect both patients and trainees from avoidable risk. These realities create a gap between what learners need in order to become clinically ready and what conventional training environments can consistently provide.

The work presented in this manuscript was motivated by that gap. It reflects a belief that immersive simulation should not merely replicate existing teaching materials in a new format, but should instead create meaningful educational conditions for experiential learning, deliberate practice, and calibrated readiness. In this study, virtual reality was treated not as a novelty, but as a serious instructional modality capable of supporting spatial understanding, workflow fluency, procedural safety, and sustained knowledge retention. By situating learners in realistic clinical scenarios within a safe and repeatable environment, the research sought to examine whether immersive training could improve not only what learners know, but also what they can do and how ready they are to do it.

The manuscript is organized around three research questions. The first examines skill acquisition and competency development; the second explores confidence and preparedness for real-world clinical practice; and the third investigates the extent to which immersive training translates into accurate and reliable performance during hands-on execution, while also considering learner perceptions of usability. Together, these questions address the continuum from learning, to readiness, to performance transfer.

This combined manuscript aims to offer more than a set of isolated findings. It seeks to present a coherent educational argument for the value of immersive virtual reality in radiation therapy training, grounded in objective performance data, expert evaluation, learner feedback, and theoretical perspectives from self-efficacy, cognitive load, and experiential learning. It is my hope that this work contributes to ongoing efforts to modernize clinical education in ways that are rigorous, scalable, and responsive to the realities of contemporary healthcare training.

AUTOBIOGRAPHY

I am a human being, a son, a husband, brother, and a father. In my professional life, I am a senior technology and healthcare innovation leader with more than twenty-five years of experience in research and development, systems engineering, and global product leadership. I held leadership roles at Varian Medical Systems, Roche, A*STAR Singapore, Earlens Corporation, Mardil Medical, St. Jude Medical, @Road, and Hitachi, contributing to innovations in medical devices, digital health, imaging systems, and consumer technologies. I currently serve as Head of Global R&D Software at Varian Medical Systems. I am an inventor with 68 patents in medical devices and consumer electronics and have contributed in immersive learning and radiation oncology education. I am pursuing a Ph.D. in Systems Engineering at Colorado State University and holds an MBA from Johns Hopkins University, an MSc in Electrical Engineering from San Jose State University, and a B.Tech in Computer Science.

DEDICATION

I dedicate this dissertation to my parents, whose unwavering support, encouragement, and belief in me have been a constant source of strength throughout my life. Their sacrifices, values, and guidance laid the foundation for my education, perseverance, and commitment to meaningful work. I am deeply grateful for their love and for the many ways they have inspired me to continue striving toward my goals.

I also dedicate this work to my wife, and my daughter, whose sacrifices, patience, and steadfast support sustained me through the long hours, demands, and challenges of this journey. Their understanding and encouragement made it possible for me to pursue this work with focus and determination. This accomplishment is as much theirs as it is mine, and I am profoundly thankful for the love, strength, and support they have given me throughout this process.

TABLE OF CONTENTS

ABSTRACT ii
ACKNOWLEDGMENTS v
PREFACE vii
AUTOBIOGRAPHY ix
DEDICATION x
LIST OF TABLES xiv
LIST OF FIGURES xv
LIST OF ACRONYMS xviii
CHAPTER 1: INTRODUCTION 1
    Background 4
        Cancer Burden 4
        Cancer Diagnostics and Treatment Modalities 5
        Radiotherapy Treatment 7
        Training Challenges 13
        Virtual Reality as a Promising Training Method 15
    Problem Statement 19
    Purpose of the Study 24
    Theoretical Framework 26
    Research Questions 29
    Research Hypotheses 30
    Significance of the Study 30
    Definitions of Key Terms 32
    Summary 39
    Literature Review and Conceptual Framing 40
CHAPTER 2: METHODOLOGY 45
    Study Design 45
    Survey Instrument 47
    Training Delivery Method 49
    Training Protocol 52
    Pilot Study 60

Main Study ... 64
Environment and set-up ... 64
Study Protocol and Use Cases ... 67
Home ... 67
Instructions ... 68
Explore Mode with Tool Tips On/Off ... 69
Manual Dry Run ... 70
Automated Dry Run ... 70
Machine Protection (Automated Dry Run - Machine Protection On) ... 70
Patient Protection (Automated Dry Run - Patient Protection On) ... 71
Manual Dry Run ... 71
Introduction ... 71
Manual Dry Run ... 72
Automated Dry Run ... 86
Patient Protection ... 93
Data Collection and Analysis ... 101
CHAPTER 3: RESULTS ... 106
Pilot Study ... 106
Results ... 106
Main Study ... 110
RQ 1: Skill acquisition and competency development ... 112
RQ 2: Confidence and preparedness for clinical practice ... 120
RQ 3: Translation to clinical performance, usability, and delayed stability ... 126
Summary of Procedural Performance Checklist Results ... 133
Summary of Expert Rating, Completion times and Error rates ... 139
Thematic Analysis ... 144
Question 39 Analysis ... 144
Question 40 Analysis ... 147
Question 41 Analysis ... 149
Hypothesis Testing Summary ... 156
CHAPTER 4: DISCUSSION, LIMITATIONS & CONCLUSION ... 160
Discussion ... 160
Comparison with Prior Literature ... 165

Implications for Practice 169
Limitations 171
Cross-question synthesis 171
Directions for Future Research 174
Conclusion 176
REFERENCES 179
SURVEY INSTRUMENTS........ 196
Pre/Post/Retention Knowledge Assessment 196
Training Effectiveness Survey 200

LIST OF TABLES

Table 1: Radiation Oncology Resources needed by 2035 11

Table 2: Procedural Checklist 57

Table 3: Expert Rating Rubric 59

Table 4: Summary of Assessment Scores 106

Table 5: Participant demographics by training modality 110

Table 6: Triangulated competency outcomes by training type 112

Table 7: Comparative analysis of instructional modalities 113

Table 8: Training effectiveness survey results across key psychological domains 122

Table 9: Objective performance indicators of confidence and preparedness 123

Table 10: Knowledge retention across time 127

Table 11: Retained procedural performance and efficiency at delayed assessment 128

Table 12 : Welch's t-test comparisons 143

Table 13: Summary of Hypothesis Testing Results 159

LIST OF FIGURES

Figure 1: VR Immersive Experience 52

Figure 2: Collsion Reset Control in VR........ 53

Figure 3: Comparative study protocol 55

Figure 4: VR Radiation Oncology Landing Space 60

Figure 5: Radiation Oncology Navigation Avatar 61

Figure 6: VR Controllers and the main application 66

Figure 7: Main Use Cases on the VR Simulator 67

Figure 8: VR Simulator Information Tab 68

Figure 9: VR Simulator Experience Layout 69

Figure 10: Treatment Plan Selection........ 72

Figure 11: Treatment Workflow 73

Figure 12: Control Room Workflow........ 74

Figure 13: In-Room Monitor Setup Notes 74

Figure 14: Hand Pendant Controls........ 75

Figure 15: Lateral Couch Movement........ 75

Figure 16: Additional Pendant Controls 76

Figure 17: In Room Monitor Couch Values 76

Figure 18: Laser Markers using Pendant 77

Figure 19: Matching Isocenter position 78

Figure 20: Pendant Controls for laser Markings........ 79

Figure 21: Pendant Controls for Treatment Fields 80

Figure 22: Setup Notes for Treatment Field 80

Figure 23: In-Room Monitor for Treatment Field 80
Figure 24: Treatment Field Workflow 81
Figure 25: Treatment Field Programming 81
Figure 26: Motion Enable Bars (MEBs) 82
Figure 27: In-Room Treatment Field Status 83
Figure 28: Treatment Field Workflow on Pendant 84
Figure 29: Console Room Treatment Field Status 86
Figure 30: Automatic Dry Run Control Room Workflow 88
Figure 31: Automatic Dry Run Programming 88
Figure 32: Automatic Dry Run adding plan workflow 89
Figure 33: Automatic Dry Run Treatment Field Status 92
Figure 34: Patient Protection Mechanism 94
Figure 35: Patient Protection Collision Alert 98
Figure 36: Patient Protection IRM Treatment Field Status 99
Figure 37: Patient Protection Interlock Alert 99
Figure 38: Pre and Post assessment scores 107
Figure 39: Histogram of attempts for mastery 108
Figure 40: Participants' Feedback Scores 109
Figure 41: Active VR Experience 111
Figure 42: Knowledge journey analysis by training modality 116
Figure 43: Perceived impact of training modality on spatial understanding 117
Figure 44: Expert competence rating by training type 119
Figure 45: Distribution of procedural checklist scores by training modality 120
Figure 46: Overall trainee perception and confidence by training modality 124
Figure 47: Self-reported perception across confidence, preparedness, and effectiveness 125

Figure 48: Correlation between self-confidence and objective error count 126
Figure 49: Knowledge retention trajectories by training modality 129
Figure 50: Precision deficit heatmap: failure rates by procedural step 130
Figure 51: Open-ended feedback themes by training cohort 131
Figure 52: Retained clinical performance at delayed assessment 132
Figure 53: Scores by Training Modality 134
Figure 54: Task Completion rates by Training Modality 138
Figure 55: Expert Rating Scores by Training Modality 139
Figure 56: Theme Frequency Chart 150
Figure 57: Benefit-to-Barrier Design Map 151
Figure 58: Co-Occurrence Matrix 155

LIST OF ACRONYMS

The following abbreviations are used in this dissertation:

2D	Two-Dimensional
3D	Three-Dimensional
3D-CRT	Three-Dimensional Conformal Radiation Therapy
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
AR	Augmented Reality
ART	Adaptive Radiation Therapy
CBCT	Cone Beam Computed Tomography
CME	Continuing Medical Education
CPD	Continuing Professional Development
CT	Computed Tomography
CTV	Clinical Target Volume
DICOM	Digital Imaging and Communications in Medicine
DNA	Deoxyribonucleic Acid
DRR	Digitally Reconstructed Radiograph
EBRT	External Beam Radiation Therapy
FDA	Food and Drug Administration
GTV	Gross Tumor Volume
GUI	Graphical User Interface
Gy	Gray
HCI	Human-Computer Interaction

HDR	High Dose Rate
HFS	Human-Computer Interaction
HMD	Head-Mounted Display
IGRT	Image-Guided Radiation Therapy
IMRT	Intensity-Modulated Radiation Therapy
IoT	Internet of Things
IRB	Institutional Review Board
IT	Information Technology
kV	Kilovoltage
LDR	Low Dose Rate
LINAC	Linear Accelerator
MLC	Multileaf Collimator
MRI	Magnetic Resonance Imaging
MU	Monitor Unit
MV	Megavoltage
NASA-TLX	National Aeronautics and Space Administration Task Load Index
OAR	Organ at Risk
OBI	On-Board Imaging
OSCE	Objective Structured Clinical Examination
PET	Positron Emission Tomography
PPE	Personal Protective Equipment
PTV	Planning Target Volume
QA	Quality Assurance
QC	Quality Control

RCT	Randomized Controlled Trial
RO	Radiation Oncology
ROI	Region of Interest
ROM	Range of Motion
RT	Radiation Therapy
RTT	Radiation Therapy Treatment or Radiation Therapy Technologist
RTP	Radiation Treatment Planning
SBRT	Stereotactic Body Radiation Therapy
SGRT	Surface-Guided Radiation Therapy
SIM	Simulation
SOP	Standard Operating Procedure
SRS	Stereotactic Radiosurgery
TAM	Technology Acceptance Model
TPS	Treatment Planning System
UI	User Interface
UX	User Interface/User Experience
VR	Virtual Reality
VMAT	Volumetric Modulated Arc Therapy
VR	Virtual Reality
XR	Extended Reality

CHAPTER 1: INTRODUCTION

Cancer is a foremost cause of mortality and a key obstacle to life expectancy enhancements globally. WHO's data (World Health Organization, n.d.) reveals that cancer is among the top two causes of death before age 70 in 112 of 183 nations, and it's in the top four in an additional 23 countries. The prominence of cancer as a leading cause of death is partly due to significant decreases in stroke and heart disease deaths. The cancer burden is surging globally due to population aging, growth, and shifts in cancer risk factors, many linked to socio-economic progress. This correlation is evident when contrasting cancer prevalence with social and economic indices.

Achieving an accurate cancer diagnosis is pivotal, acting as the linchpin in devising a personalized treatment strategy. This diagnostic precision is fundamental because the molecular and histological makeup of each cancer type informs the tailored treatment regimen it necessitates, a concept underscored in the literature by (Rodriguez et al., 2021). The amalgamation of therapies—surgical intervention, radiotherapy, and systemic treatments like chemotherapy, hormone therapies, and targeted biological agents—is often based on this initial diagnosis.

Radiotherapy, a cornerstone treatment modality detailed by (National Cancer Institute, 2025), leverages ionizing radiation to eradicate cancer cells or impede their proliferation. Its precision delivery, often guided by advanced imaging techniques, aims to maximize tumoricidal doses while minimizing collateral damage to healthy tissues (Grégoire et al., 2020; Herrmann & Seppenwoolde, 2019, Parodi 2019). This approach is particularly important for surgically inaccessible or inoperable tumors, where radiotherapy can provide an effective noninvasive treatment option (Eaton et al., 2018; Patel et al., 2018; Rudra et al., 2019). The world of clinical training, especially in the realm of radiation therapy, revolves around the unparalleled use of Linear Accelerators (LINAC) machines. Conventional radiotherapy training has largely depended on experiential workplace learning supplemented by formal teaching, self-directed study, and peer- or mentor-based.

These approaches typically include direct hands-on clinical exposure, lectures, practical classes, e-learning materials, and informal knowledge transfer from experienced practitioners (Walls et al., 2020; Dubois et al., 2022). While such methods continue to provide an essential educational foundation, they do not consistently deliver the immersion, adaptability, and real-time interactivity increasingly required for contemporary technology-intensive practice. In contrast, recent evidence indicates that immersive educational technologies can enhance learner engagement, support safe procedural rehearsal, and create more dynamic and responsive training environments than traditional instructional approaches (Tene et al., 2024; Boldrini et al., 2024).

What remains insufficiently addressed in conventional training is the ability to reproduce the complexity, variability, and unpredictability of real clinical situations, where practitioners must respond to evolving patient, procedural, and environmental challenges. Although traditional and simulation-based methods provide valuable foundational learning, they may not consistently capture the dynamic nature of authentic medical practice or provide repeated exposure to rare or high-stakes scenarios (Kane et al., 2018; Tene et al., 2024). Consequently, there is a growing need for training solutions that leverage contemporary technological advances to complement established educational approaches with immersive, interactive, and responsive learning experiences that better approximate real-world clinical decision-making and performance demands (Kayed et al., 2024; Tene et al., 2024).

Virtual reality (VR), as an immersive and interactive medium, offers a compelling solution for enhancing contemporary training environments. Its educational potential has long been recognized across multiple domains, particularly because it enables users to experience and interact with computer-generated environments in ways that conventional instructional methods cannot readily reproduce (Sherman & Craig, 2003; Hamilton et al., 2021). More recently, VR's value in healthcare education has been increasingly acknowledged, with evidence showing that immersive technologies can improve learner engagement, support experiential skill development, and enhance training in medical and radiation-physics contexts (Tene et al., 2024). Within radiation therapy specifically, virtual environment–based platforms have been reported to help bridge the theory-to-practice gap by allowing learners to rehearse procedures, visualize treatment environments, and develop practical familiarity in a safe and repeatable setting (Lastrucci et al., 2024; Wong et al., 2024).

Radiation therapy training is not a straightforward undertaking; rather, it is a multifaceted educational process that requires access to specialized treatment facilities, sophisticated radiotherapy equipment, and expert clinical oversight. Traditional training pathways rely heavily on workplace-based experiential learning within the clinical environment, supplemented by formal instruction and peer-led teaching, thereby making skill acquisition dependent on substantial institutional and human resources (Walls et al., 2020; Dubois et al., 2022). These logistical demands are compounded by the increasing complexity of contemporary radiotherapy technologies and the workload pressures experienced across oncology services, which together constrain the time and flexibility available for training in routine clinical practice (Hogan et al., 2022; Takvorian et al., 2020).

Background

Cancer Burden

Cancer continues to represent one of the most serious and far-reaching challenges in global health, remaining among the leading causes of morbidity and mortality worldwide (Bray et al., 2024). In 2022, an estimated 20 million new cancer cases and 9.7 million cancer-related deaths were recorded globally, illustrating the scale, lethality, and societal consequences of the disease (Bray et al., 2024; World Health Organization [WHO], 2024). Beyond its direct clinical impact, cancer places sustained pressure on health systems, national economies, and communities, particularly as treatment costs rise and care delivery becomes increasingly complex (Prager et al., 2018). Current projections further indicate that the global cancer burden will continue to grow substantially in the coming decades, with more than 35 million new cases anticipated annually by 2050 (Bray et al., 2024; WHO, 2024).

Despite major advances in diagnostics, precision oncology, systemic therapies, radiotherapy, and supportive care, cancer remains a biologically heterogeneous group of diseases that can arise in virtually any tissue or organ and vary considerably in behavior, prognosis, and treatment responsiveness (Bray et al., 2024). Importantly, the benefits of scientific and clinical progress have not been distributed equitably. Substantial disparities persist both between and within countries in relation to timely diagnosis, access to effective and affordable treatment, quality of care, and survival outcomes (dos-Santos-Silva et al., 2022; Prager et al., 2018). These inequities are especially pronounced in low- and middle-income countries, where limited infrastructure, workforce shortages, financial constraints, and fragmented cancer services often contribute to later-stage diagnosis and poorer outcomes (dos-Santos-Silva et al., 2022).

The magnitude of this burden underscores the need for sustained investment in cancer prevention, early diagnosis, timely treatment, and equitable service delivery (WHO, 2017). It also highlights the central role of public health strategies that address modifiable risk factors associated with cancer incidence and mortality. Contemporary evidence continues to show that preventable exposures and behaviors, including tobacco use, alcohol consumption, excess body weight, unhealthy dietary patterns, and physical inactivity, remain important drivers of cancer risk (Marino et al., 2024). Accordingly, global cancer control must be approached not only as a therapeutic challenge, but also as a preventive, policy, and systems-level priority requiring coordinated long-term action across clinical, public health, and governmental sectors (Prager et al., 2018; WHO, 2017).

Cancer Diagnostics and Treatment Modalities

Accurate cancer diagnosis is fundamental to effective treatment because it does more than confirm the presence of malignancy; it defines the histological subtype, anatomical extent, and, increasingly, the molecular and biomarker profile of the tumor. These layers of characterization are central to prognosis and treatment selection, as contemporary oncology increasingly relies on molecular profiling and biomarker-guided strategies to match patients with more appropriate and individualized therapies. In this sense, diagnosis functions as the gateway to precision oncology, linking pathology, staging, and tumor biology directly to therapeutic decision-making. Timely diagnosis is equally important, because prompt linkage to definitive care improves the likelihood of treatment at a more manageable stage and can reduce morbidity and mortality (Rodriguez et al., 2021; Malone et al., 2020; Lawler et al., 2024; World Health Organization, 2017).

Because cancer is a heterogeneous group of diseases rather than a single entity, treatment cannot be (Evans, J. M., & Matthews, J. (2020) applied uniformly across patients. Management is typically tailored according to tumor type, stage, anatomical location, and biologic features, and often involves a multimodal strategy that combines local approaches, such as surgery and radiotherapy, with systemic therapies, including chemotherapy and other targeted approaches. Modern cancer care is therefore multidisciplinary by design, with each treatment modality contributing differently depending on whether the goal is cure, local control, disease downstaging, or palliation (Khan et al., 2021). This reinforces why diagnostic precision is essential: without accurate clinicopathologic and molecular characterization, the selection and sequencing of cancer therapies cannot be optimized effectively (Wang et al., 2019; Debela et al., 2021; Malone et al., 2020).

Surgical resection is often a primary treatment for localized solid tumors and may offer cure or substantial disease control when the malignancy can be completely removed (National Cancer Institute [NCI], 2024; Pollock & Morton, 2003). However, when surgery alone is insufficient because complete excision is not feasible or the disease has spread, adjuvant or multimodal therapies are commonly incorporated into the treatment plan (NCI, 2024; Pollock & Morton, 2003). Radiotherapy uses ionizing radiation to kill cancer cells or slow their growth by damaging their DNA, and modern image-guided techniques are designed to maximize dose delivery to the tumor while minimizing exposure to surrounding healthy tissues (NCI, 2025; Grégoire et al., 2020). For many cancers, radiotherapy is effective either as a definitive treatment or in combination with surgery to improve local control and clinical outcomes (NCI, 2025).

Systemic therapies complement local treatments by circulating through the bloodstream and reaching cancer cells throughout the body, making them especially important when disease is disseminated or when there is a risk of microscopic spread beyond the primary tumor site (NCI, n.d.). Among these, chemotherapy remains one of the most established treatment modalities and works by using cytotoxic drugs to kill cancer cells, particularly those that divide rapidly (NCI, 2025b). Hormone therapy is crucial for hormone-sensitive malignancies such as certain breast and prostate cancers, where treatment acts by reducing hormone levels or blocking hormonal signaling pathways that drive tumor growth (NCI, 2025c). Targeted therapies represent a more recent and rapidly advancing area of oncology, using drugs designed to interfere with specific molecular alterations and signaling pathways involved in cancer cell growth, survival, and proliferation, thereby supporting increasingly personalized treatment strategies (Min & Lee, 2022; NCI, 2022). Collectively, these modalities illustrate that contemporary cancer treatment is inherently multidisciplinary and depends on accurate diagnosis, staging, and biologic characterization to guide the most appropriate combination of surgery, radiotherapy, and systemic therapy for each patient (NCI, 2024; NCI, 2025a).The integration of these treatment modalities requires a multi-disciplinary approach, often involving surgeons, oncologists, radiologists, and pathologists to ensure that the treatment plan is both comprehensive and cohesive. Ultimately, the precise determination of the cancer type through diagnostic testing is vital, as it influences the choice of surgery, the protocol for radiotherapy, and the selection of systemic treatments, each designed to target the illness effectively and improve the patient's quality of life (Lee & Kim, 2022).

Radiotherapy Treatment

Radiation therapy is a fundamental component of cancer management, and evidence-based estimates indicate that approximately half of all patients with cancer should receive radiotherapy at least once during the course of their illness (Delaney et al., 2005). It is used across many common malignancies and may be delivered as a primary treatment, in combination with surgery, or alongside systemic therapies depending on tumor type, stage, and treatment intent (National Cancer Institute [NCI], 2025). Its therapeutic value lies in its ability to kill cancer cells or slow their growth by damaging their DNA, while modern image-guided approaches are designed to maximize dose delivery to the tumor and limit exposure to surrounding healthy tissues (Grégoire et al., 2020; NCI, 2025).

The strategic application of radiation therapy is critical across multiple cancer types. In breast cancer management, radiotherapy is commonly used after surgery to reduce local recurrence and improve long-term outcomes, particularly in early breast cancer treated with breast-conserving approaches or other local therapies (Early Breast Cancer Trialists' Collaborative Group [EBCTCG], 2005). In locally advanced cervical cancer, radiotherapy is frequently combined with cisplatin-based chemotherapy, and long-term follow-up data have shown improved progression-free and overall survival with concurrent chemoradiotherapy (Rose et al., 2007; Rose et al., 1999). In rectal cancer, preoperative chemoradiotherapy can improve local control and reduce treatment-related toxicity compared with postoperative treatment, thereby supporting its role in facilitating more effective local management before surgery (Sauer et al., 2004). In lung cancer, radiation therapy also plays a central role: for unresectable locally advanced non-small-cell lung cancer (NSCLC), concomitant chemoradiotherapy improves outcomes, whereas for medically inoperable early-stage NSCLC, stereotactic body radiation therapy provides an effective definitive treatment option when surgery is not feasible (Aupérin et al., 2006; Timmerman et al., 2006)

Radiation therapy's adaptability allows for its use as a solitary treatment, as part of a combination therapy, or as a palliative measure to relieve symptoms in advanced cancers (Barton et al., 2004). Its role extends beyond direct tumor control; it's instrumental in preserving organ function and enhancing the quality of life (Spencer, 2018). The precise delivery of radiation therapy has evolved with technological advances, enabling oncologists to target tumors with greater accuracy and leading to improved patient outcomes (Beadle et al., 2004; Grégoire et al., 2020; NCI, 2025). Therefore, its integration into cancer treatment regimens is not only due to its effectiveness but also due to its capacity to tailor treatment to patient-specific needs, a testament to the evolution of personalized medicine in oncology.

The contribution of radiation oncology to cancer care is reflected in both improvements in cancer outcomes and the broad clinical applicability of radiotherapy across the cancer treatment continuum. The American Association for Cancer Research (AACR) Cancer Progress Report 2023 noted that the overall cancer death rate in the United States declined by 33% between 1991 and 2020, translating into an estimated 3.8 million cancer deaths averted. This improvement reflects advances across cancer prevention, screening, diagnosis, treatment, and survivorship, including the continued development of surgery, systemic therapy, immunotherapy, precision medicine, and radiation oncology. The AACR report emphasizes that sustained progress against cancer depends on continued investment in research, innovation, and equitable access to effective cancer treatment.

Radiotherapy remains one of the major treatment modalities contributing to cancer control. The Lancet Oncology Commission report, "Radiotherapy and theranostics: A Lancet Oncology Commission," by Abdel-Wahab et al. (2024), states that approximately 50% to 70% of all patients with cancer worldwide require radiotherapy at some point during their disease course, ranging from curative treatment to palliation. This estimate demonstrates the central role of radiation oncology in comprehensive cancer care and highlights that radiotherapy is not limited to a small subset of patients. Rather, it is used across many disease sites and treatment intents, including definitive treatment, adjuvant therapy, neoadjuvant therapy, symptom relief, and local disease control.

Together, these publications establish an important rationale for strengthening radiation oncology capacity. The AACR Cancer Progress Report 2023 demonstrates that cancer survival has improved substantially over recent decades, while Abdel-Wahab et al. (2024) emphasize that radiotherapy remains necessary for a large proportion of patients worldwide. However, the clinical benefit of radiotherapy depends on more than the availability of treatment machines. Safe and effective delivery requires a trained multidisciplinary workforce, including radiation oncologists, medical physicists, dosimetrists, radiation therapists, and technologists. These professionals must be prepared to operate complex treatment systems, interpret patient-specific workflows, verify treatment setup, manage safety systems, and respond appropriately to potential treatment delivery risks.

For this reason, the continued importance of radiotherapy has direct implications for education and workforce development. As radiation oncology technologies become more advanced, training programs must ensure that learners acquire procedural competence, spatial awareness, equipment familiarity, and confidence in safety-critical workflows. Simulation-based approaches, including virtual reality training, may provide a scalable method for supplementing traditional clinical education by allowing learners to practice complex procedures in a controlled and repeatable environment. In this context, the findings from AACR (2023) and Abdel-Wahab et al. (2024) support the need for innovative training strategies that can help prepare the radiation therapy workforce to meet the growing demand for safe, accessible, and high-quality cancer care.

Atun et al. (2015) emphasized that improving global access to radiotherapy is a critical priority for cancer care, particularly as cancer incidence continues to rise worldwide. Their analysis projected that, by 2035, substantial expansion will be required across radiotherapy infrastructure, treatment equipment, and the clinical workforce. The authors estimated that global need would increase from approximately 7,700 radiation oncology centers in 2015 to 10,900 centers by 2035, representing a gap of 3,200 additional centers. Similarly, the need for linear accelerators was projected to increase from 13,100 in 2015 to 21,800 by 2035, with the publication noting that this included both new machines and replacement units. These projections demonstrate that access to radiotherapy is not limited by a single factor, but instead depends on coordinated growth across facilities, technology, and trained personnel as shown in Table 1,

Table 1: Radiation Oncology Resources needed by 2035

Radiation Oncology Infrastructure and Workforce Gap

2015 baseline, projected gap, and 2035 need

CATEGORY	2015	GAP	2035
Radiation Oncology Centers	7,700	3,200	10,900
Linear Accelerators	13,100	8,700*	21,800
Radiation Oncologists	23,200	22,300	45,500
Medical Physicists	10,000	29,300	39,300
Radiation Technologists	33,300	96,900	130,200

** estimated*

The workforce implications are particularly significant. Atun et al. (2015) projected that the need for radiation oncologists would increase from 23,200 in 2015 to 45,500 by 2035, requiring an additional 22,300 physicians. The projected need for medical physicists was even more pronounced, rising from 10,000 to 39,300, creating a gap of 29,300 professionals. The largest projected workforce gap was among radiation technologists, with demand increasing from 33,300 in 2015 to 130,200 by 2035, requiring approximately 96,900 additional technologists. These estimates highlight the importance of workforce development as a central component of radiotherapy access. Expanding the number of treatment centers and linear accelerators will not be sufficient unless there is a parallel effort to train and prepare the professionals required to deliver safe and effective radiation therapy.

The applicability of external beam radiation therapy (EBRT) extends across a wide range of cancer types and stages. Because EBRT is a local treatment, it can be used for localized tumors with curative intent as well as in advanced disease to relieve symptoms and improve patient comfort and quality of life (National Cancer Institute [NCI], 2025a, 2025b). Its noninvasive nature allows radiation to be delivered from outside the body to a specific treatment site, and modern high-precision radiation techniques are designed to maximize tumor coverage while sparing surrounding healthy tissues as much as possible (Grégoire et al., 2020; NCI, 2025a). This capacity to target disease locally while limiting unnecessary exposure to normal tissues remains a major advantage of EBRT in contemporary oncology practice (Grégoire et al., 2020).

Technological advances have substantially refined external beam radiation therapy (EBRT). In particular, intensity-modulated radiation therapy (IMRT) and image-guided radiation therapy (IGRT) have enabled more precise radiation delivery by improving dose conformity to the target while reducing exposure to surrounding normal tissues (National Cancer Institute [NCI], 2025; Grégoire et al., 2020). These developments have been important in enhancing the therapeutic ratio of EBRT, with modern radiotherapy techniques increasingly designed to improve tumor control while mitigating treatment-related toxicity and supporting better patient outcomes (Baskar et al., 2012; Grégoire et al., 2020). The continued reliance on EBRT in the

United States underscores not only its therapeutic value but also the need for sustained investment in research, infrastructure, and technological innovation. This is reflected in projected U.S. radiation therapy demand rising from approximately 490,000 patients in 2015 to about 580,000 patients in 2025 (Pan et al., 2016).

Training Challenges

These data provide a strong rationale for exploring scalable and innovative educational strategies in radiation therapy training. Traditional clinical training is often constrained by limited access to treatment machines, patient safety considerations, clinical scheduling demands, and variability in learner exposure to procedural scenarios. As the projected demand for radiation therapy professionals continues to increase, simulation-based training approaches, including virtual reality environments, may offer an important mechanism to supplement conventional education. By allowing learners to practice equipment operation, procedural workflows, spatial awareness, and safety-related decision-making in a controlled environment, immersive simulation may help address future workforce preparation needs while reducing dependence on limited clinical machine time. Therefore, the projected global shortfall identified by Atun et al. (2015) underscores the need for educational models that can support efficient, standardized, and scalable training for the next generation of radiation therapy professionals.

In the United States, the demand for radiation therapy remains substantial, with projected annual utilization during the initial treatment course increasing from approximately 490,000 patients in 2015 to 580,000 patients in 2025 (Pan et al., 2016). External beam radiation therapy (EBRT), the most commonly used form of radiation treatment, is used to treat many types of cancer by delivering radiation from outside the body to a defined treatment site (National Cancer Institute [NCI], 2025; SEER Training Modules, 2023). Its versatility makes it central to contemporary oncologic practice, as it may be used with curative intent, to reduce the risk of recurrence, or palliatively to relieve symptoms and improve comfort in advanced disease (NCI, 2025).

The U.S. radiation therapy infrastructure is both extensive and clinically important. Ballas et al. (2006) identified 2,246 radiation therapy facilities operating in the United States in 2004–2005, and a later national update found 2,332 facilities in 2020, indicating growth in capacity over time (Ballas et al., 2006; Maroongroge et al., 2022). However, this expansion has not been evenly distributed, and more recent evidence shows that improvements in geographic access have disproportionately favored already well-served areas, leaving persistent disparities in access for some populations (Maroongroge et al., 2022). Taken together, these findings suggest that the national radiation therapy network plays a central role in extending cancer treatment access beyond major urban academic centers, but that continued efforts are still needed to improve equity in availability and reach.

Taken together, these clinics contribute to an important national framework for cancer care, but their value lies less in guaranteeing uniform access than in providing a distributed treatment infrastructure that can reduce barriers for many patients. This is especially relevant in radiation oncology, where treatment often requires repeated visits and where distance to a treatment facility can meaningfully affect care delivery and utilization (Maroongroge et al., 2022).

Radiation treatment vaults, or "bunkers," and linear accelerators are also highly specialized, capital-intensive resources. A time-driven cost analysis found that the annual operating cost of a base-case two-machine radiotherapy department in high-income settings was approximately US$4.6 million, and that departmental throughput and equipment costs were major drivers of overall treatment cost (Van Dyk et al., 2017). Related work has likewise shown that most radiotherapy costs are fixed or semi-fixed and that departmental throughput is the single biggest cost driver, underscoring why treatment-room time is such a constrained and valuable resource in clinical practice (Spencer et al., 2022). In addition to capital acquisition costs, maintenance places a continuing financial burden on services; one recent analysis estimated linear accelerator service costs at about 3.13% of the initial capital cost each year (Carlone et al., 2024). These infrastructure and staffing demands help explain why hands-on training on advanced treatment systems can be operationally difficult, particularly when safe use requires dedicated training, credentialing, and workflow-specific competency development (Hogan et al., 2023).

Virtual Reality as a Promising Training Method

Virtual reality (VR) offers a promising means of addressing several limitations in traditional radiation therapy training by providing immersive, repeatable, and low-risk simulated learning experiences (Lastrucci et al., 2024; Tene et al., 2024). Recent evidence suggests that immersive technologies can enhance learner engagement, improve learning outcomes, and support gains in practical skills, while radiation therapy–specific reviews indicate that virtual environments can help trainees develop technical skills and confidence without interfering with clinical workflow or placing additional pressure on treatment equipment and staff (Lastrucci et al., 2024; Tene et al., 2024). Although VR does not eliminate all barriers to training, it has the potential to mitigate some logistical, geographic, and clinical-resource constraints by enabling flexible, simulation-based learning outside the treatment bunker and away from direct patient care environments (Lastrucci et al., 2024; Wong, 2024).

At its core, the transformation of radiation therapy training through VR lies in its ability to provide trainees with access to realistic, interactive modules that simulate clinical procedures and real-world scenarios in a safe environment. Virtual learning platforms in radiation therapy have already been shown to support remote instruction and peer-supported training, while preserving learning achievement and potentially increasing learner confidence, particularly in early-stage trainees (Wijeysingha et al., 2021). Similarly, recent work in radiation therapy training reports that VR can help bridge the theory–practice gap through experiential and active learning, allowing students to rehearse simulated clinical scenarios at their own convenience without fear of disrupting clinical operations or making errors on real patients (Wong, 2024). Accordingly, VR-based training offers a scalable framework for more flexible and comprehensive education, with the potential to improve preparedness for clinical practice across institutions and locations (Tene et al., 2024; Wijeysingha et al., 2021).

Recent evidence suggests that virtual reality can support cognitive, psychomotor, and affective learning in healthcare education by enhancing knowledge acquisition, procedural rehearsal, learner engagement, and confidence within immersive simulated environments (Jiang et al., 2022; Efendi et al., 2023; Nassar et al., 2021). In radiation therapy education, virtual-environment platforms have similarly been shown to support skill development, workflow visualization, and remote teaching, indicating that VR may serve as a valuable supplement to traditional clinical training (Lastrucci et al., 2024; Wijeysingha et al., 2021). While it would be premature to claim that VR alone produces major improvements in treatment outcomes, the literature supports the view that it can strengthen trainee preparedness in ways that are likely to be clinically meaningful. This is particularly relevant in a field such as radiation oncology, where projected annual U.S. demand for radiation therapy has been estimated at roughly half a million patients or more, reflecting the central and sustained role of radiotherapy in contemporary cancer care (Pan et al., 2016). Within this context, both large academic centers and smaller regional clinics are united by their reliance on radiotherapy as a core therapeutic modality, which in turn reinforces the need for scalable, resource-efficient, and high-quality training solutions.

As (Sloboda et al. 2011) noted, radiation therapy is an intricate amalgamation of precision, expertise, and equipment. While the demand for this therapy and associated training is soaring, the availability of tools and infrastructure remains constrained. The adoption of virtual simulation, in this context, offers a beacon of hope. Not only does it offer a cost-effective alternative, but it also promises training that's versatile, dynamic, and immediately applicable. At the same time, the need for radiotherapy services and for a competent radiation therapy workforce continues to grow, while access to practical training remains constrained by limited equipment time, clinical-resource pressure, and the logistical demands of traditional training models (IAEA, 2014; Strasser & Senger, 2024). In this context, virtual simulation offers a promising adjunct to conventional training. Recent radiation-therapy literature indicates that virtual environment platforms can improve technical skills, support the application of theoretical knowledge in a low-pressure setting, and enhance learner confidence without interfering with clinical workflow or consuming scarce treatment-room resources (Lastrucci et al., 2024). More broadly, reviews of digital learning in radiation oncology suggest that immersive educational tools are especially valuable because they can be delivered flexibly, on demand, and across geographic boundaries, making them well suited to contemporary workforce-training needs (Kok et al., 2022). Prototype work in this area has also shown that collaborative VR systems such as LINACVR can function as effective and cost-effective alternatives to existing radiotherapy simulators, further supporting the case for VR as a versatile and immediately applicable training modality rather than merely a technological novelty (Bannister et al., 2019).

The intrinsic value of immersion in training can't be understated. It's the closest replication of real-world challenges in a controlled environment. When trainees can actively engage, simulate varied procedures, and predict potential consequences in a virtual setting, the ripple effects are profound. An enlightening study by (Pasquier et al. 2020) delved deep into the merits of immersive training in radiation therapy. Key takeaways included enhanced patient comfort, a noticeable reduction in procedural errors, and an overarching improvement in therapy outcomes.

The educational value of immersion in radiation therapy training lies in its ability to approximate authentic clinical complexity within a safe and controlled environment. Immersive and virtual-environment training platforms allow learners to rehearse procedures, visualize treatment processes, and engage with realistic scenarios in ways that may strengthen technical competence, engagement, and confidence before clinical application (Lastrucci et al., 2024; Kok et al., 2022; Wijeysingha et al., 2021). Current evidence further suggests that immersive technologies can improve learning outcomes and practical-skill performance in medical and radiation physics education, although the clearest demonstrated benefits remain at the learner and training-system level rather than the patient-outcome level (Tene et al., 2024). In parallel, the growing emphasis on personalized radiation therapy has increased the importance of digital infrastructures that can integrate clinical data, imaging, and patient-generated information to support more individualized care. Informatics, wearable technologies, artificial intelligence, and natural language processing are increasingly being applied across oncology and radiation oncology to improve monitoring, workflow efficiency, treatment planning, and the development of more patient-specific therapeutic pathways (Griffin et al., 2020; Gresham et al., 2018; Low et al., 2020; Landry et al., 2023; Lin et al., 2024).

A study by (Gresham et al. 2018) championed the potential of digital technology in personalizing radiation therapy. The integration of hospital data systems, the robust storage of patient data, and the strategic application of artificial intelligence all contribute to a more precise, patient-centric approach.

Problem Statement

The current training approach to prepare clinicians for administering radiation therapy has traditionally relied on supervised access to actual Linear Accelerators (LINACs), procedural recordings, static instructional materials, and informal peer-to-peer knowledge transfer. While these traditional practices remain valuable, they are constrained by limited machine availability, patient-safety considerations, and inconsistent opportunities for repeated, hands-on rehearsal. These limitations are particularly important in radiation therapy, where learners must develop spatial awareness, procedural sequencing, and safety-critical decision-making. Prior evidence from health professions education indicates that technology-enhanced simulation can improve knowledge, skills, and learner behaviors (Cook et al., 2011), while VR-based education has been shown to improve knowledge and skill outcomes compared with traditional or other digital instructional approaches (Kyaw et al., 2019). Therefore, immersive VR training may address key gaps in conventional radiation therapy education by providing a realistic, interactive, repeatable, and safe environment for procedural learning.

The existing methods are hampered by limitations in accessibility and affordability. Each year, in the United States alone, over 500,000 patients are referred to external beam radiotherapy clinics for cancer treatment (Pan HY, 2016). Despite the presence of over two thousand clinics, the demand for radiation bunkers and Linear Accelerators (LINAC) far outstrips supply.

The administration of radiation therapy typically unfolds as a carefully scheduled regimen, most often delivered once daily on weekdays over several weeks, although the exact duration varies by cancer type, treatment intent, dose, and fractionation schedule (National Cancer Institute [NCI], 2025; American Cancer Society (ACS, 2025). Individual external beam radiotherapy sessions are relatively brief, with the treatment itself taking only a few minutes and the full visit usually lasting about 15 to 30 minutes because of setup and positioning requirements, which allows clinics to treat several patients per hour and makes treatment-machine time a tightly managed resource (ACS, 2025). This high-throughput workflow is operationally necessary, but it also means that there is limited opportunity for radiation therapists to access the equipment outside of direct patient care for repeated practice, skills refinement, or experimentation with new techniques, particularly in resource-constrained training environments (Hogan et al., 2023; NCI, 2025).

Furthermore, the substantial investment required for linear accelerators (LINACs) with market-price estimates commonly in the low millions and one recent estimate placing them at approximately US$2.1 million to US$2.52 million—together with the infrastructure and staffing demands of radiotherapy services, creates a major barrier to maintaining dedicated machines solely for training purposes (Gamboa et al., 2021). These constraints are compounded by regulatory oversight, as the U.S. Food and Drug Administration classifies medical linear accelerators under 21 CFR § 892.5050 as Class II devices, reinforcing the practical and financial difficulty of using standalone LINACs for training alone (U.S. Food and Drug Administration (FDA, 2025).

The escalating global burden of cancer has intensified the need to strengthen the training pipeline for oncology professionals, particularly those involved in radiation therapy, which remains a core component of cancer treatment. According to the World Health Organization (WHO), there were an estimated 20 million new cancer cases and 9.7 million deaths in 2022, and the annual number of new cases is projected to exceed 35 million by 2050 (World Health Organization (WHO, 2024). This growing burden places increasing pressure on cancer services and, by extension, on the education and preparation of the professionals required to deliver timely and effective treatment. The challenge is especially acute in radiation oncology, where recent global estimates indicate that radiotherapy services required approximately 85,184 radiation therapists in 2022 and will require about 141,077 by 2050 (Zhu et al., 2024).

The International Atomic Energy Agency (IAEA) has likewise emphasized that there is a global shortage of well-trained radiation therapists and identifies this shortage as one of the main barriers to the expansion of radiation oncology services, particularly in low- and middle-income countries (International Atomic Energy Agency [IAEA], 2025). In response, the IAEA states that the establishment of education and training programs for radiation therapists is a high priority (IAEA, 2025). Accordingly, the rising incidence of cancer does not simply increase the need for treatment capacity; it also creates an urgent imperative to expand, modernize, and accelerate the education of radiation therapists who are essential to the safe and effective delivery of radiotherapy.

To this end, enhanced training programs are essential. They need to be more comprehensive, more consistently updated, and better aligned with the rapid evolution of contemporary radiation oncology practice (Walls et al., 2020; Campbell et al., 2024). Over the past two decades, major advances in radiation beam complexity, imaging, treatment planning, and data-driven technologies have transformed radiotherapy, while medical education in the field has not always kept pace with these changes (Walls et al., 2020; Kang et al., 2021). As a result, trainees are increasingly expected to master not only foundational clinical knowledge, but also modern planning techniques, image guidance, workflow coordination, and emerging digital tools within a relatively compressed training period (Walls et al., 2020; Kang et al., 2021). This widening gap between technological sophistication and traditional teaching methods strengthens the case for training models that are more structured, adaptable, and responsive to current clinical demands (Campbell et al., 2024; Kok et al., 2022).

Moreover, educational institutions and healthcare systems must work collaboratively to develop innovative training models that bridge academic learning and clinical practice. An ESTRO workshop report specifically highlighted the importance of strengthening collaboration between academic and clinical staff to ensure that radiation therapist education remains fit for present and future practice demands (Campbell et al., 2024). Within this context, simulation-based learning and virtual reality (VR) are emerging as especially valuable educational tools because they allow trainees to rehearse procedures, visualize treatment environments, and apply theoretical knowledge in a safe, controlled, and repeatable setting before treating real patients (Kok et al., 2022; Lastrucci et al., 2024). Radiation-therapy-specific evidence indicates that virtual environment radiotherapy training can improve technical skills and support the application of theoretical knowledge in low-pressure environments without the risk of errors in clinical practice, while virtual teaching platforms have also been shown to improve learner confidence, particularly among junior students (Lastrucci et al., 2024; Wijeysingha et al., 2021). More broadly, a systematic review of VR in health professions education found evidence that VR improves post-intervention knowledge and skills outcomes compared with traditional education, supporting its value as a meaningful adjunct to conventional training rather than a mere technological novelty (Kyaw et al., 2019). Taken together, these findings suggest that collaborative, simulation-enhanced training models may help radiation oncology education better match the complexity, pace, and precision required in modern cancer care (Kok et al., 2022; Campbell et al., 2024).

The goal is to cultivate a workforce that is not only larger in number but also proficient in the use of increasingly sophisticated radiation oncology technologies and treatment approaches, so that it can meet the demands created by the rising global cancer burden (Zhu et al., 2024; Campbell et al., 2024). This need is particularly pressing because radiotherapy practice is becoming more complex, with rapid developments in imaging, planning, adaptive workflows, automation, and artificial intelligence requiring clinicians to acquire new competencies more quickly than in the past (Mireștean et al., 2022; Campbell et al., 2024). In this setting, workforce growth alone is insufficient; what is required is a workforce that is adequately trained, adaptable, and prepared to deliver high-quality care in technologically advanced treatment environments (Grover et al., 2024; Hammad et al., 2023).

Although the American Cancer Society does not appear to be the strongest source for the exact claim that survival rates are "significantly influenced" by provider preparedness, the broader idea is well supported: quality of care and provider expertise are closely tied to cancer outcomes. In radiation oncology, patients treated by higher-volume radiation oncologists have shown improved survival in some settings, suggesting that experience and quality of delivery matter clinically (Boero et al., 2016). Related literature in radiation therapy also emphasizes that radiation therapist communication, competence, and patient-centered practice are important contributors to better patient outcomes and treatment experiences (Kelly, 2021). Therefore, investment in the education, competency development, and rapid upskilling of radiation therapists is essential if cancer care systems are to keep pace with growing demand while also striving to improve the quality, safety, and outcomes of patient care (Campbell et al., 2024; Zhu et al., 2024).

In response to these challenges, we are pioneering a virtual reality (VR) simulator tailored for radiation therapists. This innovative solution is designed to help circumvent some of the high costs, equipment-access limitations, and logistical hurdles associated with traditional training on actual LINACs, which relies heavily on scarce clinical infrastructure and scheduled machine availability (Kok et al., 2022; Bannister et al., 2019). Our VR simulator will afford therapists the flexibility to train at their convenience, without the constraints of clinical scheduling or equipment availability, an approach that aligns with prior work showing that virtual environments can support radiation therapy teaching and learning outside the immediate pressures of the treatment room (Wijeysingha et al., 2021; Lastrucci et al., 2024). By simulating real-world scenarios, the VR platform will enable practitioners to refine their radiation treatment skills in a risk-free environment, supporting technical rehearsal, confidence building, and the application of theoretical knowledge before clinical practice (Lastrucci et al., 2024; Kok et al., 2022). This technological advancement therefore has the potential to strengthen training opportunities for radiation therapists and, in turn, improve preparedness for the complexities and nuances of patient treatment (Lastrucci et al., 2024; Tene et al., 2024).

Purpose of the Study

The objective of the study was to develop training experience in VR. Based on the provided problem statement and objective, the purpose of the study is multifaceted and can be summarized as follows:

To Evaluate the Efficacy of Virtual Reality (VR) in Radiation Therapy Training: The primary purpose is to assess how effectively VR can be used as a training tool for radiation therapists. This involves comparing VR-based training methods with traditional training techniques to determine if VR offers superior or comparable results in terms of skill acquisition, understanding of procedures, and practical application of learned techniques.

To Enhance Accessibility and Reduce Resource Constraints: The study aims to address the challenge of limited access to Linear Accelerators (LINAC) and radiation bunkers, which are essential but expensive and scarce resources in radiation therapy training. By using VR, the study seeks to provide a more accessible and cost-effective training solution that can be utilized anywhere and at any time, thus overcoming geographical and financial barriers.

To Improve Clinical Outcomes through Advanced Training: Another critical purpose is to investigate whether training radiation therapists in a virtual environment can lead to better clinical outcomes. This involves examining the precision of radiation delivery, the reduction of errors, and the overall confidence and preparedness of the radiation therapists as they transition from virtual training to real-world clinical settings.

To Foster Collaborative Learning and Global Knowledge Exchange: Lastly, the study intends to create an international platform for collaboration and knowledge sharing among radiation therapy trainees. By leveraging VR technology, trainees from different regions and backgrounds can interact, share experiences, and learn from each other, thereby enriching the global radiation therapy education landscape.

In summary, the purpose of this study is to revolutionize radiation therapy training through VR technology, making it more effective, accessible, and patient-centric, ultimately leading to better educational outcomes for trainees and improved clinical results for patients.

Theoretical Framework

In this study, the theoretical framework for implementing Virtual Reality (VR) in radiation therapy training is grounded in a combination of educational, psychological, and technological theories. This framework provides a structured approach to understanding how VR can enhance learning and skill acquisition in a clinical setting. The following components form the core of the theoretical framework:

Constructivist Learning Theory. Constructivism is highly relevant to VR-based radiation therapy training because it views learning as an active process in which learners build new understanding by connecting new information to prior knowledge and experience (Jonassen, 1991). In a VR environment, trainees are not limited to passively receiving information; instead, they can interact with anatomical models, treatment-room layouts, machine movements, and simulated clinical workflows in ways that encourage active meaning-making. This is especially important in radiation therapy, where learners must integrate conceptual knowledge, spatial awareness, procedural reasoning, and clinical judgment. Virtual reality aligns well with constructivist principles because it allows trainees to explore, make decisions, test interpretations, and refine understanding in context-rich, scenario-based environments rather than relying solely on lectures or observation. In radiation oncology education specifically, reviews have noted that immersive tools can support more engaging, learner-centered, and pedagogically driven training experiences, while radiation therapy–specific studies suggest that virtual environments help bridge the gap between theory and clinical practice by enabling learners to visualize and rehearse authentic workflows before entering real treatment settings (Kok et al., 2022; Lastrucci et al., 2024). Thus, from a constructivist perspective, VR is valuable not simply because it is technologically advanced, but because it creates opportunities for learners to construct clinically meaningful understanding through active participation.

Experiential Learning Theory (Kolb). Kolb's Experiential Learning Theory is particularly applicable to VR training because it conceptualizes learning as a cycle involving concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984). VR simulations are especially well suited to this model. They can provide a realistic, concrete experience of radiotherapy practice, such as patient setup, image matching, workflow sequencing, or treatment-room decision-making. Because these experiences occur in a controlled environment, learners can pause, repeat, reflect, and debrief their actions in ways that are often difficult in busy clinical settings. They can then translate those reflections into abstract principles and return to the simulation to test revised approaches in new scenarios. This iterative process is particularly important in radiation therapy, where competence depends not only on factual recall but on the ability to apply knowledge under procedural, spatial, and time-sensitive conditions. Evidence from broader health-professions education suggests that VR can improve post-intervention knowledge and skills when compared with traditional or other digital education approaches, while radiation therapy education studies show that virtual environments can support peer-assisted learning, confidence building, and the rehearsal of clinical processes in ways that fit well with experiential learning principles (Kyaw et al., 2019; Wijeysingha et al., 2021; Lastrucci et al., 2024). Accordingly, Kolb's framework helps explain why VR can be particularly effective for radiation therapy education: it turns abstract instruction into experience-based learning that can be repeated, reflected upon, and progressively refined.

Cognitive Load Theory. Cognitive Load Theory is also highly relevant in the context of VR training because it focuses on the limits of working memory and the need to design instruction in ways that support schema formation without overwhelming the learner (Sweller, 1988). Radiation therapy is cognitively demanding: trainees must coordinate technical terminology, machine functions, imaging information, safety considerations, workflow sequencing, and patient-specific decision-making. In principle, VR can help manage this complexity by presenting information in structured, staged, and interactive ways that support progressive learning. For example, a well-designed VR module can isolate one task at a time, provide cues and feedback, scaffold increasingly complex scenarios, and allow repetition without the pressure of real-time patient care. However, Cognitive Load Theory also implies that VR is not automatically beneficial simply because it is immersive. If the environment is overly complex, visually cluttered, or poorly sequenced, it may increase extraneous cognitive load and reduce learning efficiency. This is why recent immersive-learning theory has emphasized that the educational value of VR depends on how immersion, agency, self-regulation, and cognitive load are balanced through thoughtful instructional design (Makransky & Petersen, 2021). In radiation oncology education, this means VR is most effective when it is carefully structured to support learning progression rather than merely to impress learners with realism. From this perspective, VR offers strong educational promise for radiation therapy, but its success depends on pedagogical design that makes complex procedures understandable, manageable, and transferable to practice (Kok et al., 2022).

These three theories collectively provide a strong theoretical foundation for implementing VR in radiation therapy training. They address the key aspects of learning - the construction of knowledge, the importance of experience and reflection, and the effective management of cognitive resources - all of which are critical in the context of training radiation therapists using VR technology.

Research Questions

For a study focused on implementing Virtual Reality (VR) in radiation therapy training, the following research questions are pivotal to comprehensively evaluate its impact and efficacy:

RQ1: How does VR training impact the skill acquisition and competency development of radiation therapists compared to traditional training methods? This question aims to assess the effectiveness of VR training in enhancing the practical skills of radiation therapists. It seeks to compare the proficiency levels achieved through VR training with those attained through conventional training methods, looking at metrics like speed of skill acquisition, depth of understanding, and ability to handle complex scenarios.

RQ2: Does VR training enhance the confidence and preparedness of radiation therapists for real-world clinical scenarios? This question explores the psychological impact of VR training, specifically its role in boosting trainees' confidence and sense of preparedness. It looks at how realistic simulations and immersive experiences in VR prepare therapists for actual clinical situations, including handling unexpected challenges and patient interactions.

RQ3: How do radiation therapy trainees perceive the usability and effectiveness of VR as a training tool? This question focuses on the user experience and acceptance of VR training among radiation therapists. It seeks to understand trainees' perceptions of VR's ease of use, satisfaction, and overall effectiveness as a training modality. It also explores potential barriers to adoption and how VR training fits into the broader educational context.

Answering these questions provided comprehensive insights into the value of VR in radiation therapy training, highlighting its strengths, areas for improvement, and its overall impact on trainee development and patient care outcomes.

Research Hypotheses

Based on the research questions outlined, the corresponding hypotheses for a study on the implementation of Virtual Reality (VR) in radiation therapy training could be formulated as follows:

- **Hypothesis 1**: Radiation therapists trained using VR technology will acquire necessary skills and reach competency more efficiently compared to those trained through traditional methods.
- **Hypothesis 2**: Trainees who undergo VR training will exhibit higher levels of confidence and feel more prepared for real-world clinical scenarios than those who receive traditional training.
- **Hypothesis 3**: Radiation therapy trainees will perceive VR as a highly usable and effective tool for training, with positive attitudes towards its adoption in their educational curriculum

These hypotheses are based on the assumption that VR technology, with its immersive and interactive capabilities, provides a more effective and efficient training environment for radiation therapists compared to traditional training methods. The study would aim to test these hypotheses to validate the effectiveness of VR in enhancing the skillset, confidence, and overall clinical performance of radiation therapy professionals.

Significance of the Study

The significance of the study, grounded in the proposed research questions and hypotheses, revolves around several key dimensions of innovation, educational advancement, clinical practice, and patient care in the field of radiation therapy. The study is significant for the following reasons:

Advancement in Training Methods: By investigating the efficacy of VR training compared to traditional methods, the study could revolutionize how radiation therapists are educated and trained. If VR is found to be more effective, it could lead to a paradigm shift in medical education, emphasizing the role of immersive and interactive learning environments.

Enhancement of Therapist Competency and Efficiency: The research focuses on the potential of VR to improve skill acquisition and competency among trainees. This is crucial in a field where precision and expertise directly impact patient outcomes. If VR training is shown to be superior, it could lead to more proficient therapists entering the workforce, thereby enhancing the overall quality of cancer care.

Understanding of Cognitive Load in Learning: By exploring how VR affects cognitive load and the learning curve, the study will contribute to a deeper understanding of educational psychology in the context of high-stakes medical training. This could inform future educational strategies, not just in radiation therapy, but across various medical disciplines.

Impact on Trainee Confidence and Preparedness: Investigating VR's role in enhancing trainee confidence and preparedness addresses a critical aspect of clinical training - the readiness of practitioners to face real-world scenarios. This aspect of the study is significant for improving the transition from theoretical learning to practical application, a crucial phase in any medical profession.

Evaluation of Trainee Perceptions and Acceptance of VR: By assessing how trainees perceive VR in terms of usability and effectiveness, the study can provide insights into the acceptance of new technologies in medical education. This is significant for the future implementation and development of tech-based educational tools, ensuring they are user-friendly and meet the needs of learners.

Improvement in Clinical Outcomes and Patient Care: Perhaps the most critical aspect of the study is its focus on patient care. By examining the impact of VR training on clinical outcomes, the research has the potential to directly influence the quality of care received by cancer patients. Improvements in treatment accuracy, reduction in errors, and enhanced patient interaction skills could all contribute to better patient experiences and outcomes.

Policy and Resource Allocation Implications: If VR training is proven to be effective, this could have significant implications for health care policy and resource allocation. Institutions may invest more in VR technologies, leading to cost savings in the long term by reducing the need for expensive training resources like actual LINAC machines.

Global Reach and Accessibility: Finally, the study is significant in its potential to make high-quality training more accessible. VR can overcome geographical and resource barriers, offering consistent training opportunities to therapists worldwide, which is especially important in regions where access to advanced training resources is limited.

In summary, the significance of this study lies in its potential to transform radiation therapy training through technological innovation, enhance the skill set and readiness of therapists, improve patient care, and inform broader educational and policy decisions in the healthcare sector.

Definitions of Key Terms

In the context of our study on implementing Virtual Reality (VR) in radiation therapy training, several key terms are essential for understanding the research scope and objectives. These terms include:

- *Virtual Reality (VR):* A computer-generated, three-dimensional simulated environment that allows users to interact with digital spaces and objects in ways that resemble real-world experiences. In this study, VR refers to the technology used to create immersive, interactive training environments for radiation therapy.

- *Radiation Therapy*: A medical treatment modality that uses controlled doses of ionizing radiation to destroy malignant cells, reduce tumor size, or manage disease progression. In this study, radiation therapy refers to the clinical field in which trainees develop procedural, technical, and patient-centered competencies.
- *Radiation Therapist (RTT)*: A trained healthcare professional responsible for delivering radiation treatment, positioning patients accurately, verifying treatment parameters, and supporting patient care throughout the treatment process. In this study, radiation therapists or trainees in radiation therapy represent the primary learner population.
- *Linear Accelerator (LINAC)*: A medical device used in external beam radiation therapy to deliver high-energy x-rays or electrons to a tumor site with precision. In this study, the LINAC is a central component of the clinical environment being replicated or simulated in the VR training experience.
- *Simulation-Based Training*: An instructional approach that uses realistic scenarios, equipment, or virtual environments to support the development of knowledge, technical skills, and clinical decision-making. In this study, simulation-based training refers specifically to the use of VR as a substitute or supplement to traditional radiation therapy instruction.
- *Immersive Learning*: A pedagogical approach in which learners are actively engaged within a realistic or simulated environment that promotes experiential participation and contextual understanding. In this study, immersive learning describes the manner in

which VR places trainees within a simulated radiation therapy setting to enhance learning.

- *Experiential Learning*: A theory of learning in which knowledge is developed through direct experience, reflection, and application. In this study, experiential learning is relevant because VR-based training provides learners with opportunities to perform tasks, reflect on actions, and apply procedural knowledge in a safe simulated environment.
- *Cognitive Load*: The amount of mental effort required to process information and perform tasks within working memory. In this study, cognitive load is examined in relation to how VR training may either support or hinder the learning process depending on the complexity, realism, and usability of the simulation.
- *Skill Acquisition*: The process through which learners gain and refine new abilities through instruction, practice, feedback, and repetition. In this study, skill acquisition refers to the development of radiation therapy-related competencies, including equipment operation, procedural sequencing, and clinical task execution.
- *Clinical Competency*: The demonstrated ability to perform professional responsibilities effectively by integrating knowledge, technical skill, judgment, and appropriate behavior in a clinical setting. In this study, clinical competency is a key outcome used to assess the effectiveness of VR-based training.
- *Trainee Preparedness*: The extent to which learners feel ready to perform radiation therapy procedures and respond appropriately to clinical scenarios following training. In this study, preparedness is considered an important indicator of the perceived readiness of trainees for real-world practice.

- *Confidence*: A learner's self-perceived belief in their ability to successfully perform tasks, apply knowledge, and make appropriate decisions. In this study, confidence is examined as an educational outcome that may be influenced by the realism, repetition, and interactivity of VR training.
- *User Acceptance of Technology*: The willingness of individuals to adopt and use a technological system as part of their learning or work activities. In this study, it describes the extent to which radiation therapy trainees perceive VR as useful, usable, and appropriate for training purposes.
- *Technology Acceptance Model (TAM)*: A theoretical framework used to explain and predict users' adoption of technology based primarily on perceived usefulness and perceived ease of use. In this study, TAM provides a useful lens for evaluating trainee perceptions and acceptance of VR as a training modality.
- *Usability*: The degree to which a system can be used efficiently, effectively, and satisfactorily by intended users within a specific context. In this study, usability relates to how easily trainees can navigate, interact with, and learn from the VR training system.
- *Human-Computer Interaction (HCI*): The field concerned with the design, evaluation, and use of interactive computing systems for human use. In this study, HCI is relevant because the quality of interaction between trainees and the VR environment may influence learning outcomes, satisfaction, and perceived effectiveness.
- *User Interface (UI):* The visual and interactive elements through which users engage with a digital system, including menus, controls, icons, prompts, and displays. In this study, the VR system's user interface affects ease of use, navigation, and learner performance.

- *User Experience (UX):* The overall perceptions, emotions, and satisfaction a user has when interacting with a system or technology. In this study, user experience encompasses trainees' experiences of immersion, comfort, realism, usefulness, and engagement while using the VR platform.
- *Engagement*: The degree of attention, interest, motivation, and active involvement demonstrated by learners during an instructional activity. In this study, engagement is considered an important indicator of whether VR enhances learner participation and attentiveness.
- *Interactivity*: The extent to which users can actively manipulate, respond to, and receive feedback from a digital environment. In VR-based radiation therapy training, interactivity is essential for replicating procedural tasks and supporting active learning.
- *Presence*: The psychological sensation of being physically situated within a virtual environment. In this study, presence is significant because a stronger sense of presence may increase realism, immersion, and the transferability of learned skills to clinical settings.
- *Clinical Workflow*: The sequence of procedures, decisions, and interactions involved in the delivery of patient care. In radiation therapy, this may include patient setup, imaging, verification, treatment delivery, and documentation. In this study, VR is used to simulate elements of this workflow for training purposes.
- *Image-Guided Radiation Therapy (IGRT):* A technique that uses imaging before or during radiation delivery to improve treatment accuracy and patient positioning. In this study, IGRT-related processes may form part of the simulated clinical tasks represented in the VR training environment.

- *Treatment Planning*: The process of designing a radiation therapy approach that specifies target volumes, dose distribution, beam arrangement, and protection of surrounding healthy tissues. Although this study is primarily focused on training in treatment delivery, treatment planning remains an important contextual concept within radiation therapy education.
- *Quality Assurance (QA):* The systematic processes used to confirm that radiation therapy procedures, equipment, and treatment delivery meet established safety and performance standards. In this study, quality assurance is relevant because effective training must reflect safe, standardized, and clinically accurate practice.
- *Patient Safety*: The prevention of avoidable harm during the delivery of healthcare. In this study, VR-based training supports patient safety by allowing learners to practice procedures, develop competence, and correct errors in a simulated environment without risking harm to actual patients.
- *Clinical Outcomes*: The measurable effects of healthcare interventions on patient health, safety, and treatment success. In this study, clinical outcomes are considered indirectly, as improvements in training may contribute to more accurate treatment delivery, enhanced practitioner competence, and better patient care.
- *Patient Care*: The clinical, technical, and interpersonal services provided by healthcare professionals to support the treatment, well-being, and safety of patients. In this study, patient care includes not only procedural accuracy in radiation delivery but also effective communication, professionalism, and patient-centered interaction.
- *Competency Development*: The progressive acquisition and refinement of knowledge, technical abilities, behaviors, and clinical judgment required for effective professional

practice. In this study, competency development is a central educational outcome used to evaluate the contribution of VR-based training.

- *Transfer of Learning*: The application of knowledge, skills, and behaviors acquired in one context to performance in another context. In this study, transfer of learning is particularly important in determining whether skills developed in the VR environment can be effectively applied in real clinical radiation therapy settings.
- *Continuing Medical Education (CME):* Structured educational activities that support healthcare professionals in maintaining and advancing their knowledge, skills, and clinical competence throughout their careers. In this study, VR may also be considered a potential tool for ongoing professional development beyond initial training.
- *Adaptive Learning Environment*: An instructional system capable of adjusting content, feedback, or complexity based on learner needs, performance, or progression. In this study, VR has the potential to function as an adaptive learning environment by tailoring experiences to support individual learner development.
- *Immersive Simulation*: A highly realistic form of simulation in which learners are placed within an environment that closely replicates authentic clinical settings, tasks, and decision-making processes. In this study, immersive simulation is achieved through VR technology to enhance experiential learning in radiation therapy training.

Summary

In an innovative study aimed at revolutionizing radiation therapy training, Virtual Reality (VR) is positioned as a transformative tool. The abstract outlines the current challenges in traditional training methods, including the limited accessibility to Linear Accelerators (LINAC), and high resource demands. VR emerges as a viable solution, offering immersive, flexible, and cost-effective training environments.

The introduction delves into the context, highlighting the overwhelming need for advanced training methods in the face of increasing cancer treatments in the U.S. It points out the limitations of conventional training, such as the high cost and scarcity of essential equipment like LINAC, and the significant time constraints faced by oncologists. VR technology is proposed to bridge these gaps, enabling anytime-anywhere training, enhancing skill acquisition, and potentially improving clinical outcomes.

The study is guided by three key research questions, focusing on the impact of VR on skill acquisition, cognitive load, trainee confidence, user perception of VR efficacy, and its influence on clinical outcomes and patient care. These questions aim to evaluate the comprehensive benefits and potential limitations of VR in radiation therapy training. From these questions, hypotheses are formulated, predicting that VR training will surpass traditional methods in enhancing skill acquisition, reducing cognitive load, boosting trainee confidence and preparedness, garnering positive user perceptions, and ultimately improving clinical outcomes and patient care.

In summary, this study proposes an in-depth exploration of VR as an innovative, efficient, and potentially transformative approach to training in radiation therapy, aiming to address the limitations of current training methods and ultimately enhance patient care.

Literature Review and Conceptual Framing

The literature on simulation in health professions education consistently emphasizes that effective clinical learning requires more than exposure to declarative information. In high-risk domains, technology-enhanced simulation can improve performance when it supports repeated practice, standardized scenarios, contextual fidelity, and feedback that helps learners refine judgment and execution (Cook et al., 2011; Issenberg et al., 2005; McGaghie et al., 2011). These principles are especially relevant to radiation oncology because treatment-room errors may arise not from lack of factual knowledge alone, but from failures of sequence, spatial awareness, or safety-related decision making under realistic constraints (Issenberg et al., 2005; Lateef, F. 2010; McGaghie et al., 2011).

Specifically, with radiation oncology, prior work on VERT, virtual linac environments, and related visualization tools has shown that immersive or semi-immersive systems can improve engagement, orientation, and understanding of treatment geometry. Reviews of the field suggest that VR and AR are particularly valuable for helping learners understand spatial relationships that are difficult to communicate through flat diagrams or short observational exposures (Boejen, 2011; Kok et al., 2022; Lastrucci et al., 2024). Existing evidence also indicates that immersive platforms may support better preparation for radiotherapy-related activities, including both patient-facing education and staff-facing training. However, many studies stop at feasibility, user satisfaction, or immediate knowledge gains rather than examining deeper transfer to real equipment and durable competency over time. (Boejen A. 2011; Bannister, H., et al. 2018; Kok, D. L., et al. 2022; Grilo, A. M., et al 2023; Lastrucci, A., et al. (2024; Sandhu K.S., et al 2024).

A recurring gap in the literature is the tendency to compare immersive systems with conventional teaching only at the level of post-intervention test scores or learner preference. This leaves unresolved whether immersive experience yields clinically meaningful benefits in performance quality, safety, or workflow efficiency. In radiation therapy, this question is crucial. An educational intervention that merely feels more modern or more engaging is not sufficient if it does not improve what trainees can safely do in the bunker. The present study therefore extends prior work by combining knowledge testing, procedural evaluation, expert judgment, efficiency measures, error counts, and delayed follow-up. (Gallagher, A., et al, 2004; Buttussi F., et al, 2017; Mao R Q., et al., 2021; asadzka F., et al., 2021)

The conceptual framing of this integrated paper draws on three mutually reinforcing perspectives: self-efficacy theory, cognitive load theory, and experiential learning theory. Self-efficacy theory proposes that confidence is not simply a feeling but a belief grounded in mastery experiences, feedback, and authentic task engagement (Bandura, 1997). In this framework, confidence should increase most appropriately when learners have experienced repeated successful performance under realistic conditions. This is particularly relevant for clinical education, where inflated confidence without commensurate competence may be dangerous. A central issue for RQ2, therefore, is whether confidence produced by VR is calibrated against observed performance rather than illusory in the Dunning–Kruger sense (Kruger & Dunning, 1999).

Cognitive load theory provides a second explanatory lens. When instruction requires learners to integrate multiple disconnected sources of information—such as text, flowcharts, static screenshots, and verbal explanation—extraneous cognitive load may increase, leaving fewer resources for schema construction and retrieval (Sweller, 1988; Sweller, Ayres, &

Kalyuga, 2011). Traditional 2D instruction in radiation therapy often places precisely this burden on novices. Learners must imagine how a sequence presented on slides maps to the real room, equipment, and line-of-sight constraints they will later encounter. Immersive VR may reduce this split-attention burden by embedding procedural sequence, spatial relations, and interaction cues inside a single experiential context.

Experiential learning theory provides a third perspective. Kolb's model emphasizes learning through cycles of concrete experience, active experimentation, and reflective adjustment (Kolb, 1984). High-fidelity VR is well positioned to support such cycles because learners can enact complete workflows, observe consequences, recover from mistakes, and repeat critical steps without risk to patients or disruption to clinic schedules. In radiation therapy education, this is important not only for learning the "what" of a task but also the "how," "when," and "where" of embodied execution (Yardley, S. et al., 2012)

The integrated study also draws from assessment theory in medical education. Miller's framework and later work on programmatic assessment argue that competence should be examined across multiple levels, from knowledge to action in context (Epstein & Hundert, 2002; Miller, 1990; van der Vleuten et al., 2012). A single test score or satisfaction rating is insufficient for making claims about readiness. The present manuscript responds to this challenge by triangulating evidence from cognitive testing, procedural checklists, expert ratings, efficiency, error frequency, and learner perceptions.

Several gaps in prior research directly motivate the design of the present study. First, objective performance-based evaluations remain relatively uncommon in radiation therapy VR literature. Second, delayed retention and skill stability are rarely measured despite the reality that training and independent execution are often separated in time. Third, confidence and preparedness are often reported without checking whether they align with safer or better execution. Fourth, usability is frequently treated as a superficial satisfaction issue rather than a factor that may influence how successfully learning transfers into practice. The combined manuscript addresses each of these gaps by embedding usability inside a broader performance framework and by evaluating outcomes on real equipment rather than only inside the simulation environment (Arthur. et al., 1998; Cook, D. A. et al., 2011; van der Vleuten, C. P. M., et al., 2012)

In summary, the literature suggests strong theoretical reasons to expect immersive VR to outperform conventional 2D instruction in domains requiring spatial reasoning, procedural fluency, and repeated exposure. Yet theory alone is insufficient. The value of immersive radiation therapy training must be demonstrated through evidence that learners not only like the training, but also learn more deeply, perform more accurately, feel more appropriately prepared, and retain those advantages over time. That requirement defines the methodological logic of the study that follows.

A further conceptual contribution of the present study is that it treats transfer as the central criterion of instructional value rather than as a secondary by-product of learner enjoyment. In radiation therapy education, the relevant question is not simply whether a trainee can recall terminology or report that a system felt realistic, but whether prior training reduces hesitation, supports correct sequencing, and lowers the probability of safety-relevant mistakes when the trainee encounters real equipment. This transfer-oriented view aligns with programmatic assessment models in health professions education, which argue that competence should be judged through the accumulation of multiple forms of evidence across settings rather than through a single test score. By combining knowledge measures, step-level checklist data, blinded expert ratings, efficiency metrics, and delayed follow-up, the present study operationalizes that principle and provides a richer view of how immersive training affects actual readiness for practice.

Literature also suggests an important distinction between representational fidelity and instructional fidelity. A simulation can look impressive without necessarily teaching the right decisions, and conversely, a comparatively simple simulation can be educationally powerful if it presents the critical cues that learners must later recognize under real conditions. The VR platform examined here is educationally important because its realism is functionally targeted: it reproduces the spatial constraints, workflow sequence, and action consequences that matter for dry-run execution, gantry navigation, and collision reset. In that sense, the present integrated study extends prior discussions of realism by showing that fidelity becomes instructionally meaningful when it improves cue recognition, error anticipation, and retrieval of correct action sequences during later clinical execution.

CHAPTER 2: METHODOLOGY

Study Design

This study used a randomized, single-blinded comparative design to evaluate immersive VR against traditional 2D instruction for two clinically relevant radiation therapy use cases. The design was intentionally structured to support all three research questions within one coherent framework. RQ1 focused on knowledge and competency development, RQ2 on confidence and preparedness, and RQ3 on transfer precision, usability, and delayed stability. A common participant pool, common interventions, and common physical transfer assessment enabled these questions to be examined as connected outcomes rather than as independent experiments.

Recruitment was conducted through a study invitation email and/or internal communication describing the purpose of the study, the voluntary nature of participation, the expected time commitment, and the general training and assessment activities. Interested individuals were provided with study information and screened against the inclusion criteria before enrollment. Eligible participants were individuals with relevant exposure to radiation therapy education, clinical training, treatment delivery workflows, or related technical/clinical roles, and who were able to complete either the Traditional 2D or 3D VR training intervention and associated assessments. Participation was voluntary, and no individual was required to participate as part of their employment, coursework, or clinical responsibilities.

The participant group included both male and female individuals between the ages of 20 and 60 years. The cohort was intentionally diverse and included engineers, radiation trainees, customer support professionals and early-career or newly oriented personnel who may reasonably be expected to engage with radiation therapy training workflows. This distinction is important because the study was designed to evaluate not only immediate training effectiveness but also longer-term knowledge retention and preparedness for clinical workflow execution. Participants were not required to have prior experience building virtual environments; however, they were expected to possess basic familiarity with AR/VR interaction, navigation, or technology-assisted learning. For participants who were new hires or early-stage trainees, any additional exposure to real clinical cases, supervised machine operation, or workplace-based radiation therapy training between the initial intervention and the retention assessment was treated as a relevant contextual variable. This helped ensure that observed retention outcomes could be interpreted in relation to the assigned training modality rather than unmeasured clinical experience gained during the intervening period.

Following the standardized study orientation, participants were randomly assigned to one of two instructional cohorts: a three-dimensional virtual reality experimental group (n = 40) and a traditional two-dimensional control group (n = 26). Although the cohort sizes were unequal, assignment remained randomized, and all participants completed the same study sequence, assessment procedures, and outcome measures. The difference in group size reflects the practical realities of participant availability, scheduling, and implementation in an applied educational setting rather than a departure from the study design. Such imbalance is not uncommon in real-world educational research and does not invalidate between-group comparisons when appropriate analytical methods are used. To account for unequal sample sizes and potential variance differences, the study employed statistical procedures robust to these conditions, thereby supporting valid comparison of outcomes across the two instructional modalities.

Both the three-dimensional virtual reality training and the traditional two-dimensional didactic training were standardized to a duration of thirty minutes. This was done intentionally to ensure that participants in both cohorts were provided with sufficient time to engage with the instructional material and to prepare for the subsequent practical assessment, while also maintaining parity between the two training conditions. By holding training time constant across modalities, the study reduced the possibility that differences in learner outcomes could be attributed to unequal exposure time rather than to the instructional characteristics of the intervention itself. This time-controlled design therefore strengthened the fairness of the comparison and supported a more valid evaluation of whether the mode of instruction, rather than the amount of instructional time, influenced knowledge acquisition, procedural competency, confidence, preparedness, and performance during hands-on execution.

Survey Instrument

The fifteen-item knowledge assessment for Pre, Post and Retention was specifically designed to align with the two clinical use cases used in both training modalities. The content of the assessment was developed to reflect the key concepts, procedural steps, and decision points embedded within the Automated Dry Run and Patient Protection scenarios, ensuring that the knowledge test measured learning outcomes directly relevant to the instructional interventions. By aligning the assessment with the same two use cases delivered in both the three-dimensional virtual reality and traditional two-dimensional training conditions, the study maintained content equivalence across cohorts and ensured that both groups were evaluated on the same instructional objectives. This alignment strengthened the validity of the assessment by ensuring that knowledge scores reflected participants' understanding of the exact workflows and safety-critical procedures emphasized during training, rather than unrelated or more general radiation therapy knowledge.

The performance checklist was developed as a structured measure of procedural execution during the hands-on assessment on the physical Linear Accelerator (LINAC). It consisted of a ten-item binary pass-or-fail format designed to evaluate whether participants could correctly complete the essential safety-critical steps embedded in the two training use cases. These checklist items were aligned with the Automated Dry Run and Patient Protection workflows and focused on observable actions such as correct plan selection, automation setup, couch positioning, laser verification, field navigation, initiation of machine motion, and appropriate response to collision or patient protection events. The checklist format provided an objective and standardized way to assess whether trainees were able to carry out the required procedural steps accurately and in the correct sequence. By emphasizing clear, observable behaviors rather than subjective impressions alone, the performance checklist served as a direct measure of procedural competency and execution accuracy across both training cohorts.

The expert global rating rubric was used to provide a more holistic evaluation of clinical performance beyond step completion alone. While the performance checklist captured whether critical actions were completed correctly, the rubric was designed to assess the quality, fluency, and professionalism of task execution during the practical assessment. This approach was informed by established uses of global rating scales in clinical and simulation-based assessment, where expert raters evaluate broader dimensions of performance that may not be fully captured by binary checklists alone (Martin, J. A. et al., 1997; Ilgen, J. S. et al., 2015; Henrico, K. et al., 2023). Prior work on Objective Structured Assessment of Technical Skills and other simulation-based assessment approaches has demonstrated that expert global ratings can be useful for evaluating technical performance, workflow fluency, judgment, and overall competence in health professions education (Martin, J. A. et al., 1997; Ilgen, J. S. et al., 2015). In the present study, expert evaluators rated participant performance across five domains: technical accuracy, workflow fluency, error correction, clinical judgment, and overall competence, with each domain scored on a five-point scale. This allowed the study to capture higher-order dimensions of readiness that are important in real clinical environments, including how confidently and smoothly participants moved through the workflow, how well they recognized and responded to issues, and the extent to which their actions reflected safe and appropriate clinical reasoning. The expert global rating rubric therefore complemented the checklist by providing a broader assessment of clinical competence and helping distinguish between merely completing a task and performing it in a manner consistent with real-world clinical readiness.

Training Delivery Method

The 2D cohort received a thirty-minute didactic training session delivered through a PowerPoint-based instructional format. This training condition was intentionally designed to reflect a conventional educational approach commonly used in radiation therapy settings when direct access to a physical Linear Accelerator (LINAC) is limited by scheduling constraints, patient treatment priorities, equipment availability, or safety considerations. As such, the 2D modality served as a realistic comparison condition rather than an artificially simplified control, representing the kind of structured classroom or conference-room instruction that many trainees receive before entering the treatment environment.

The PowerPoint session included several forms of visual and textual instructional support intended to approximate the informational content provided in the immersive VR condition, while remaining within the boundaries of a traditional two-dimensional format. High-resolution images of the LINAC and treatment room environment were used to familiarize participants with the physical appearance of the machine, its major components, and relevant control interfaces. These images were selected to provide visual clarity and to help learners identify key hardware features that would later be encountered during hands-on assessment. In addition, the instructional materials incorporated flowcharts illustrating the Auto Move and Collision Reset protocols, enabling participants to review the logical sequence of actions required to complete each procedure. These diagrams were intended to support procedural understanding by breaking complex workflows into discrete steps and decision points.

To further reinforce procedural learning, the session also included step-by-step textual descriptions of the required workflows. These written instructions outlined the sequence of actions needed to perform the dry run tasks, including plan selection, automation setup, couch positioning, gantry observation, and response to motion safety interruptions. The textual guidance was designed to provide explicit procedural clarity and to reduce ambiguity regarding task order and expected operator behavior. Together, the images, flowcharts, and written steps created a structured, instructor-led learning experience emphasizing explanation, observation, and cognitive rehearsal.

Despite these supports, the 2D condition remained fundamentally limited by the characteristics of conventional didactic instruction. Learners were required to interpret static representations of a highly dynamic, spatial, and interactive clinical environment. They had to mentally translate two-dimensional images and abstract workflow diagrams into anticipated physical actions on the machine, without the benefit of embodied practice or real-time interaction with equipment. This is an important distinction, because radiation therapy workflows often depend not only on conceptual understanding, but also on spatial reasoning, equipment orientation, situational awareness, and the ability to anticipate movement within the treatment bunker.

Accordingly, the 2D training condition represented a practical and ecologically valid benchmark against which the immersive VR intervention could be evaluated. It reflected the instructional reality faced in many clinical education environments, where conventional slide-based teaching remains necessary and widely used. By comparing VR training against this standard didactic approach, the study was able to assess whether immersive simulation offered meaningful advantages beyond the level of knowledge typically conveyed through traditional instructional methods.

The VR cohort engaged with a high-fidelity immersive simulation delivered through a head-mounted display. The virtual environment reproduced the treatment bunker at approximately one-to-one scale and allowed participants to navigate around the machine, observe spatial relationships directly, practice couch positioning, and execute workflow elements through embodied interaction as shown in Figure 1. The VR intervention addressed the same pedagogical content as the 2D condition but presented that content within an interactive spatial environment rather than as disaggregated slides and verbal explanation.

Figure 1: VR Immersive Experience

Training Protocol

Two use cases were included in both training modalities. The first involved a basic dry run focused on foundational LINAC operation and setup behavior. The second involved a collision reset scenario, which required participants to manage a safety-critical workflow under realistic spatial constraints as shown in Figure 2. These scenarios were selected because they jointly represent procedural knowledge, spatial orientation, and decision making that are central to radiation therapy readiness.

Figure 2: Collsion Reset Control in VR

Upon completion of training, participants proceeded to individual practical assessment sessions to minimize peer influence and potential performance bias. During these individual sessions, each participant undertook a guided, self-directed practical task replicating a clinically relevant radiation therapy workflow. Performance was evaluated using a predefined, objective assessment protocol, including procedural checklist completion, expert ratings, task completion time, and error counts. Participants were monitored throughout the assessment process. Assessors were blinded to training condition when providing expert ratings.

The integrated nature of the design is captured in Figure 3. The study began with orientation and pre-assessment, branched into 2D or 3D training, converged in hands-on LINAC execution, and concluded with post-assessment, training effectiveness survey, and retention assessment at approximately two to four weeks. This structure allowed immediate learning, transfer to physical execution, and durability of learning to be examined within a single protocol.

Quantitative methods were employed to capture multiple dimensions of learner competence, including what learners know, what they can do, and how effectively they perform in clinically relevant contexts. Cognitive competency was assessed using knowledge assessment scores (SC0), reflecting learners' conceptual understanding of radiation therapy principles. Procedural capability (D.M.Halliday et el, 1995) was evaluated through a structured performance checklist that measured task execution accuracy and adherence to correct workflows. Clinical performance quality was further examined using expert rating rubrics, along with objective indicators such as task completion time and error rates (Kruger,J,.& Dunning 1999), to capture efficiency, judgment, and overall clinical readiness. Collectively, these complementary measures provided a triangulated evaluation of clinical competency development and skill acquisition, aligning with established frameworks that emphasize the integration of knowledge, skills, and performance in authentic contexts rather than reliance on a single assessment modality

Several design features were intended to strengthen internal validity and to support a defensible comparison between modalities. First, both groups were trained on the same clinical content and the same two use cases, reducing the possibility that outcome differences reflected content exposure rather than instructional format. Second, the assessment environment was held constant across groups and was situated on a physical LINAC, ensuring that transfer was evaluated under identical execution demands. Third, randomization of knowledge-test item order and response-option order reduced simple recall effects across repeated administrations. Finally, the use of multiple outcome types guarded against overinterpretation of any one metric and allowed the study to examine whether gains converged across cognitive, behavioral, and perceptual domains.

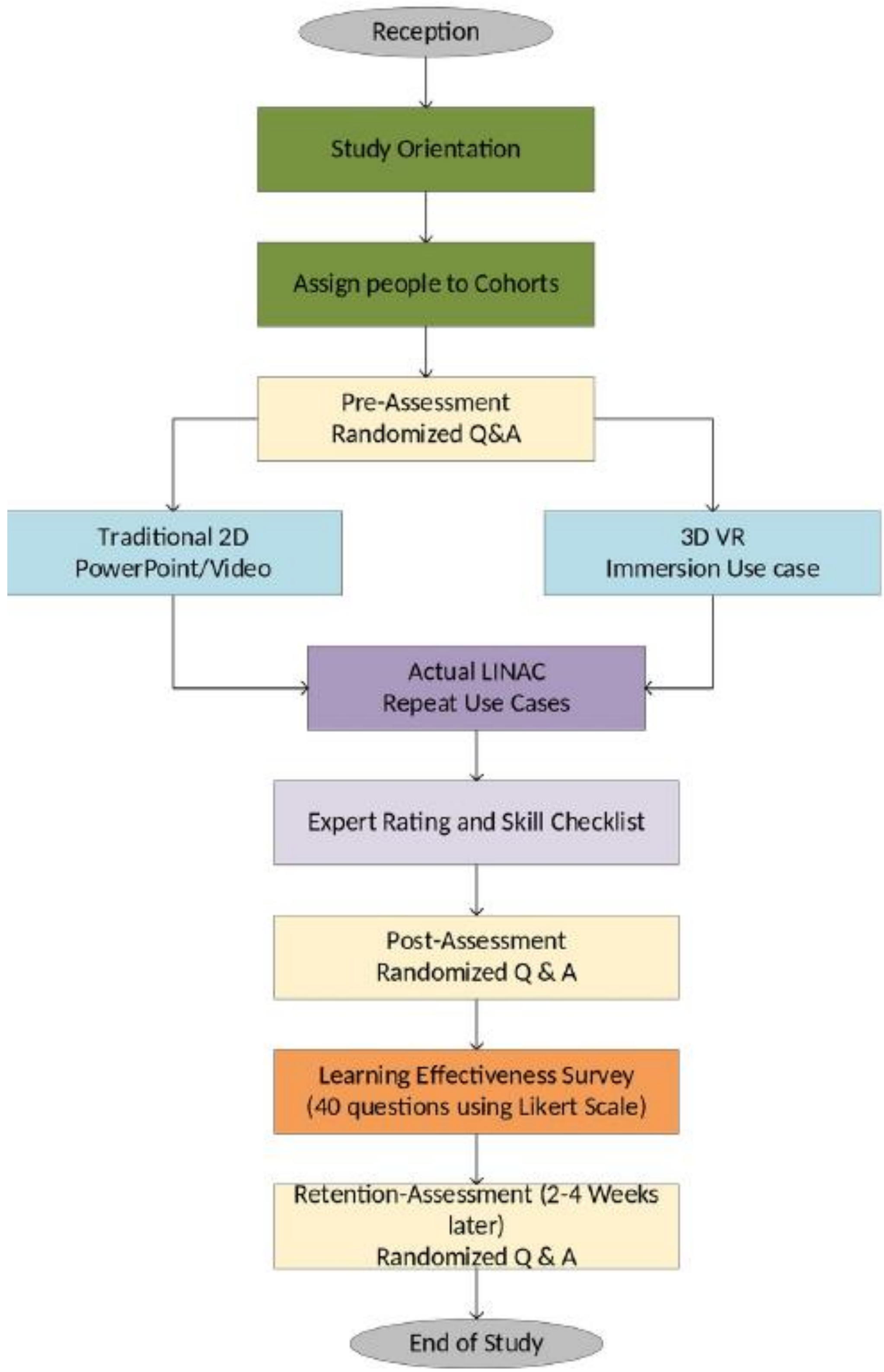

Figure 3: Comparative study protocol

The selected use cases were educationally consequential rather than arbitrary. Basic dry-run execution requires understanding of plan navigation, automation sequence, couch positioning, safety posture, and treatment-room awareness. Collision reset adds a layer of complexity because it requires the trainee to interpret why motion stopped, assess spatial clearance, and then execute a recovery workflow without compromising safety. Together, these scenarios sample core elements of early radiation therapy competence: following structured steps, reasoning in three dimensions, responding appropriately to safety constraints, and maintaining procedural fluency under conditions that approximate the real treatment environment. This makes them well suited for testing whether immersive rehearsal supports clinically relevant transfer.

Multiple assessment instruments were used to evaluate knowledge acquisition, procedural competence, and trainee perceptions. Knowledge was assessed using a fifteen point examination administered at three time points, pre training, post training, and at a two to four week retention interval. To mitigate the testing effect and ensure internal validity, the assessment employed a randomized delivery system in which both the order of questions and the sequence of multiple choice answer options were digitally randomized for each participant at each administration, while maintaining consistent pedagogical content across all testing phases. Procedural performance during on machine use cases was evaluated using a ten item binary pass or fail safety critical procedural checklist and an expert rating rubric encompassing five domains, technical accuracy, workflow fluency, error correction, clinical judgment, and overall competence, each scored on a one to five scale. Finally, trainee perceptions of self efficacy, preparedness, and training effectiveness were captured through a forty item Likert scale survey, providing complementary subjective data to contextualize the objective performance outcomes.

Table 2: Procedural Checklist

Item	Task	What is Assessed	Correct Performance Includes	Clinical Relevance
1	Confirm patient setup at isocenter	Verification of correct patient positioning relative to isocenter	Alignment with lasers/reference, correct couch coordinates	Ensures geometric accuracy of dose delivery
2	Select correct treatment plan	Identification of appropriate treatment plan	Correct patient, site, and prescription selection	Prevents wrong-plan treatment errors
3	Add automation to plan	Use of system automation (e.g., Auto Move)	Proper activation without bypassing safety	Ensures efficiency with safety compliance
4	Identify position mismatch	Detection of setup deviation	Recognizing magnitude/direction of misalignment	Prevents systematic treatment errors
5	Auto-move couch to planned position	Execution of automated couch motion	Safe initiation, monitoring, verification	Reduces manual error but requires oversight
6	Navigate to first treatment field	Transition to treatment delivery stage	Correct beam/field selection	Prevents incorrect dose delivery
7	Start gantry motion and observe	Monitoring of gantry movement	Active observation and anticipation	Prevents collision and unsafe motion
8	Acknowledge protection stop	Response to system safety interrupt	Recognizing and confirming stop condition	Ensures safety systems are respected
9	Perform collision reset	Recovery from safety interruption	Correct reset and verification	Maintains safe continuation of workflow
10	Exit dry run properly	Proper termination of workflow	Safe, complete system exit	Prevents system state errors

The procedural performance checklist assessed competency across critical workflow stages including patient setup, plan selection, automation handling, error detection, and collision recovery, thereby capturing both routine and safety-critical aspects of radiation therapy delivery as shown in Table 2. Procedural performance was quantified using a binary scoring system in which each checklist item was assigned a score of 0 (incorrect or not performed) or 1 (correctly performed). Scores across the ten items were summed to produce a total checklist score ranging from 0 to 10, with higher scores reflecting more accurate and complete execution of the required clinical workflow. This scoring approach provides an objective measure of procedural competency, capturing the learner's ability to correctly perform critical tasks in sequence. Accordingly, higher total scores indicate greater readiness for clinical practice, as they reflect both technical accuracy and adherence to safety-critical processes within the radiation therapy workflow.

The Expert Global Rating Rubric was used to assess overall clinical competency through expert observation of participant performance as shown in Table 4. The rubric captured holistic performance across five dimensions: technical accuracy, workflow fluency, error recognition, clinical judgment, and overall competence. Each dimension was rated using a 5-point behaviorally anchored Likert scale, ranging from 1 = Poor/Unsafe to 5 = Independent/Clinically Ready. Lower scores reflected frequent errors, disorganized workflow, poor error recognition, unsafe judgment, or lack of readiness for clinical practice, while higher scores indicated accurate performance, efficient workflow, anticipatory error management, sound clinical judgment, and independent readiness. The overall expert rating was calculated as the mean score across the five dimensions. Ratings were based on direct observation of task performance by experienced radiation therapy clinicians, and when possible, raters were blinded to the participant's training modality to reduce assessment bias.

The evaluation of clinical skill acquisition and competency was designed as a cross-sectional performance audit conducted immediately following the pedagogical interventions. To ensure high internal validity, the assessment took place in a physical radiation therapy bunker utilizing a Linear Accelerator (LINAC). This "transfer-of-learning" test was designed to measure how effectively theoretical knowledge from the 2D and 3D modalities translated into physical, high-stakes maneuvers on medical equipment. Expert raters consisted of clinical radiation therapists with domain expertise in radiation therapy workflows. They evaluated all participants during the physical experiment using the expert global rating rubric.

Table 3: Expert Rating Rubric

Dimension	1 – Poor	2 – Below Expected	3 – Competent	4 – Above Average	5 – Independent
Technical Accuracy	Frequent errors; unsafe	Multiple errors	Minor errors	High accuracy	Error-free
Workflow Fluency	Disorganized	Hesitant	Logical but slow	Smooth	Efficient
Error Recognition	Does not recognize errors	Late recognition	Recognizes with prompting	Self-corrects	Anticipates
Clinical Judgment	Unsafe decisions	Inconsistent	Appropriate	Sound	Exemplary
Overall Competence	Not ready	Needs close supervision	Ready with supervision	Minimal supervision	Independent

The study was conducted in accordance with Institutional Review Board (IRB) guidelines to ensure the protection of human subjects. Participants were recruited using a defined screening process based on inclusion criteria (adults aged 20–60 with technology, AR/VR, and healthcare exposure) and exclusion criteria (individuals outside the age range or uncomfortable with virtual environments). Informed consent was obtained prior to participation in a private setting, where participants were fully informed about the study’s purpose, procedures, risks, benefits, and their right to withdraw at any time. Privacy was protected by allowing participants to choose appropriate times and settings for participation and by minimizing any potential for discomfort or stigmatization.

Confidentiality was maintained through the use of unique participant codes, with identifiable information stored separately in a secure, encrypted file accessible only to authorized personnel. All data were anonymized, stored on password-protected systems, and reported in aggregate form. The study posed minimal risk, primarily limited to temporary discomfort associated with VR use, which was mitigated through monitoring and scheduled breaks. Data were retained securely for a defined period (e.g., five years) and will be permanently destroyed thereafter. Overall, the research design ensured ethical compliance while enabling a rigorous evaluation of the VR simulator's effectiveness in radiation therapy training.

Pilot Study

The study developed and evaluated a virtual reality educational environment designed to support radiation oncology training and collaborative learning. Figure 4 shows the landing space when trainees enter the VR learning space. The VR space was created using the online Spatial VR platform, spatial.io, with the primary goal of offering trainees an immersive, flexible, and accessible way to learn foundational radiation oncology concepts without requiring direct access to clinical equipment, radiation bunkers, or physical linear accelerators. The method was motivated by the practical limitations of traditional radiation therapy education, where access to LINAC machines is often restricted because of high clinical demand, cost, scheduling limitations, and safety requirements.

Figure 4: VR Radiation Oncology Landing Space

The VR training module was designed to introduce learners to a broad range of radiation oncology topics. These included basic oncology principles, diagnostic approaches, treatment options, the patient journey, cancer care challenges, financial burden, and opportunities for improving care delivery. The training environment also introduced radiation therapy concepts, including the function of a linear accelerator, patient setup, treatment planning, and the general workflow of radiation treatment delivery. The intention was not only to provide static educational content but also to create an immersive learning environment where trainees could move through the VR space, interact with structured content, and engage with other learners or instructors in a collaborative setting. VR learning space is navigated through visual markers as shown in Figure 5.

The assessment plan followed a pre-assessment, VR learning experience, and post-assessment structure. Before entering or navigating the VR space, participants completed a pre-assessment questionnaire. This pre-assessment was intended to establish baseline knowledge in oncology, radiation therapy, diagnostic modalities, treatment options, and LINAC-related concepts. The pre-assessment included quiz questions covering basic radiation oncology knowledge, cancer treatment concepts, and LINAC functionality.

Figure 5: Radiation Oncology Navigation Avatar

After the pre-assessment, participants entered the VR space and navigated through educational content. The VR experience was the central intervention in the study. Trainees were guided through a series of videos, digital learning materials, and structured educational modules. The learning content was self-managed, meaning that participants could engage with the material at their own pace. The VR environment was designed to support flexible learning, allowing users to access the content from anywhere and at any time. This was an important feature of the intervention because one of the study's central arguments was that VR could reduce dependency on expensive clinical infrastructure while increasing training accessibility.

The VR space was also designed as a multi-user collaborative environment. This allowed trainees to interact with one another and with an instructor when available. The collaborative design was intended to simulate a shared learning space where trainees could explore radiation oncology concepts together, discuss the material, and develop a more complete understanding of the clinical workflow. The use of avatars and navigation through the VR environment helped create a sense of presence and engagement that differs from traditional didactic instruction.

Following completion of the VR learning experience, participants completed a post-assessment questionnaire. The post-assessment measured learning gains after exposure to the VR module. It covered the same general concepts as the pre-assessment so that improvement could be measured directly. To reduce order bias, both the questions and the answer choices were randomized between pre- and post-assessments. This methodological choice strengthened the assessment by reducing the chance that participants would simply remember the order of answers rather than demonstrate improved understanding.

Data were collected for each participant at both time points and analyzed to determine improvement in knowledge scores. The study included 32 participants with complete pre- and post-assessment data. Many participants had little or no prior background in radiation therapy or VR technology, which made the study particularly useful for evaluating the VR module as an introductory educational tool. The study also defined a performance benchmark for mastery. Achieving 80% correct answers in fewer than four attempts was considered a high level of achievement, fewer than seven attempts was considered moderate, and more than seven attempts indicated a need for improvement.

The 80% correct-answer threshold was selected as an a priori, criterion-referenced benchmark to represent mastery-level understanding of the module's core learning objectives. This benchmark was informed by mastery-learning principles, in which learners are evaluated against a predefined standard of acceptable performance rather than compared with the performance of other learners (Bloom, 1968). In the context of this pilot study, the 80% threshold was not intended to represent a validated clinical competency standard, but rather a pragmatic indicator that participants had correctly answered the substantial majority of knowledge items after completing the VR module. Because many participants had limited prior exposure to radiation therapy or VR technology, the threshold was designed to be sufficiently rigorous to indicate meaningful learning while remaining appropriate for novice learners. The number of attempts required to reach the 80% threshold was used as an additional indicator of learning efficiency, consistent with mastery-learning approaches that emphasize repeated practice, feedback, and progression toward predefined competence standards (McGaghie et al., 2011).

In addition to quantitative assessment scores, the study collected qualitative feedback from participants. This feedback focused on learner experience, usability, engagement, realism, content quality, and overall satisfaction with the VR training module. Participants also provided comments on possible improvements, such as enhancing the realism of the environment and improving usability features.

Main Study

Environment and set-up

The VR training experience was developed in Unity, a real-time 3D development platform commonly used for creating interactive simulation, training, and extended reality applications. Within the Unity environment, three-dimensional models representing the treatment room, linear accelerator components, patient couch, patient setup elements, and related clinical equipment were imported and configured to create a realistic virtual radiation therapy environment. These assets were arranged to approximate the spatial layout and workflow of a clinical treatment room, allowing participants to interact with the environment in a structured and task-oriented manner. Interactive functionality was developed using Unity's XR Interaction Toolkit, which enabled participants to use VR controllers to select objects, activate controls, navigate the room, interact with clinical equipment, and complete workflow steps within the simulation. The use of XR interaction components allowed the training environment to support immersive, hands-on learning behaviors such as pressing buttons, observing machine movement, activating room lasers, confirming patient positioning, and progressing through procedural tasks in a controlled virtual setting.

A key feature of the VR experience was the inclusion of a smart virtual tablet that functioned as an in-simulation user interface and workflow guide as shown in Figure 6. The tablet was designed to provide participants with a structured menu system that supported navigation through the training scenario and helped standardize the learning experience across users. Through the tablet interface, participants could access instructional prompts, workflow steps, task options, and scenario-specific controls without needing to leave the immersive environment. This design allowed the tablet to serve both as a learning aid and as a procedural support tool, guiding participants through the required sequence of actions while preserving the sense of being physically present in the treatment room. The user menu on the tablet helped organize the training content into manageable sections, reducing cognitive load and allowing participants to focus on completing the clinical workflow rather than trying to remember every step independently. In this way, the smart virtual tablet acted as a bridge between guided instruction and autonomous task performance, supporting both usability and consistency during the VR training session.

Together, the Unity-based environment, imported 3D clinical models, XR-enabled interactions, and smart virtual tablet interface created an immersive training platform that allowed participants to practice radiation therapy workflows in a realistic but risk-free setting. This approach provided learners with opportunities to engage spatially and procedurally with the treatment environment, while also receiving structured guidance through the virtual tablet menu. As a result, the VR system was intended not only to present information but also to support active procedural learning, workflow rehearsal, and user engagement in a simulated clinical context.

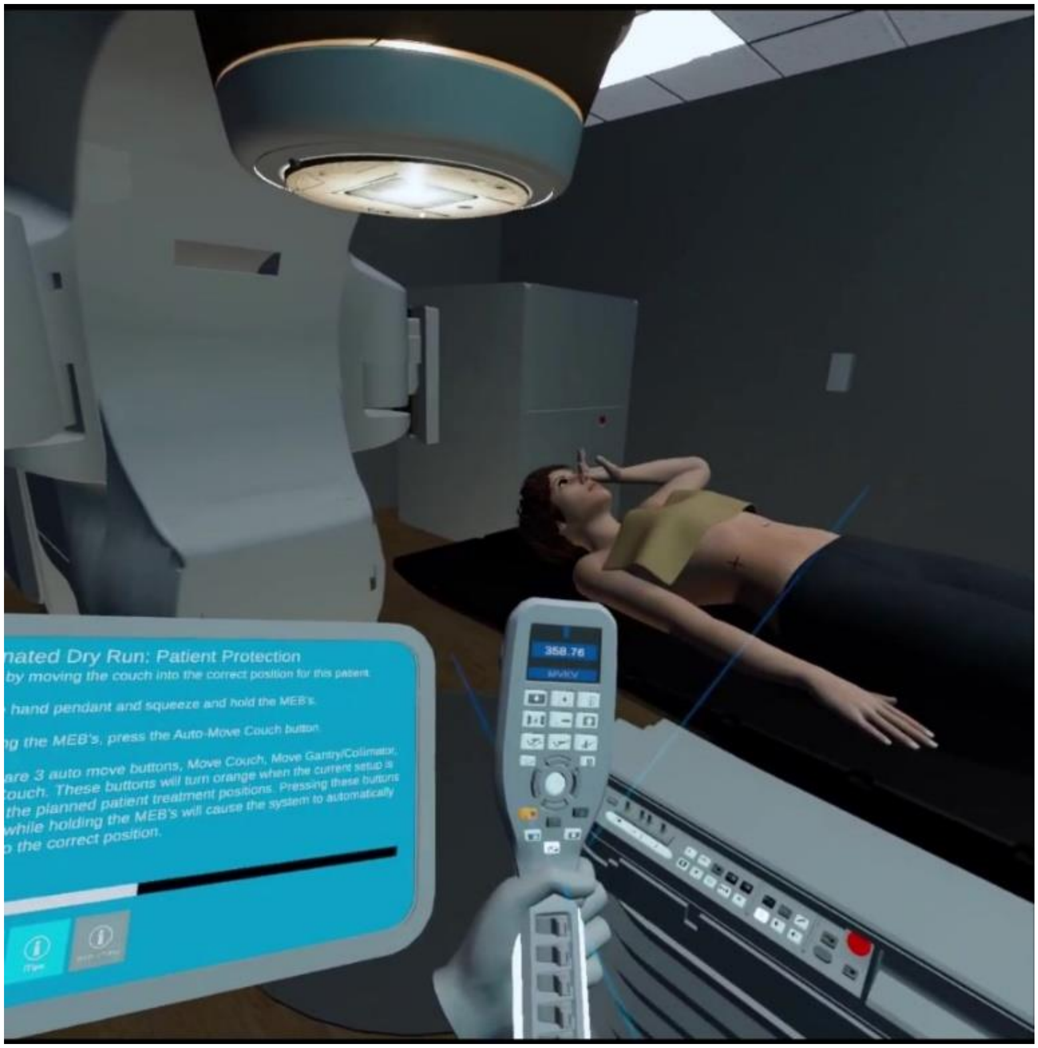

Figure 6: VR Controllers and the main application

Participants used an Oculus Quest 2 VR headset to complete the virtual training experience. The VR environment could be experienced while standing in a fixed position or by establishing a Guardian Boundary within the available physical space, allowing participants to move safely within the simulated environment. Participants used handheld VR controllers to interact with virtual objects, equipment, and user interface elements throughout the training.

The directed training modules were structured as a sequence of information steps and action steps. Information steps were designed to introduce participants to relevant system components, procedural concepts, or workflow processes. During these steps, participants were guided to observe specific equipment or areas within the virtual environment and were provided with explanatory content regarding their function. Action steps required participants to actively engage with the simulation by performing task-based interactions, such as selecting interface options, manipulating virtual objects, or completing procedural actions within the VR environment.

Study Protocol and Use Cases

Figure 7: Main Use Cases on the VR Simulator

Home

Participants accessed the VR simulator through Explore Mode, which provided hands-on practice with LINAC operation using the couch side panels and handheld pendants. Within this mode, participants practiced multiple procedural scenarios, including Manual Dry Run, Automated Dry Run, Machine Protection, and Patient Protection as shown in Figure 7. These scenarios were designed to allow participants to rehearse dry-run workflows with a simulated patient and to become familiar with the LINAC motion safety system. Additional procedural guidance was available through the simulator's information icon as shown in Figure 8.

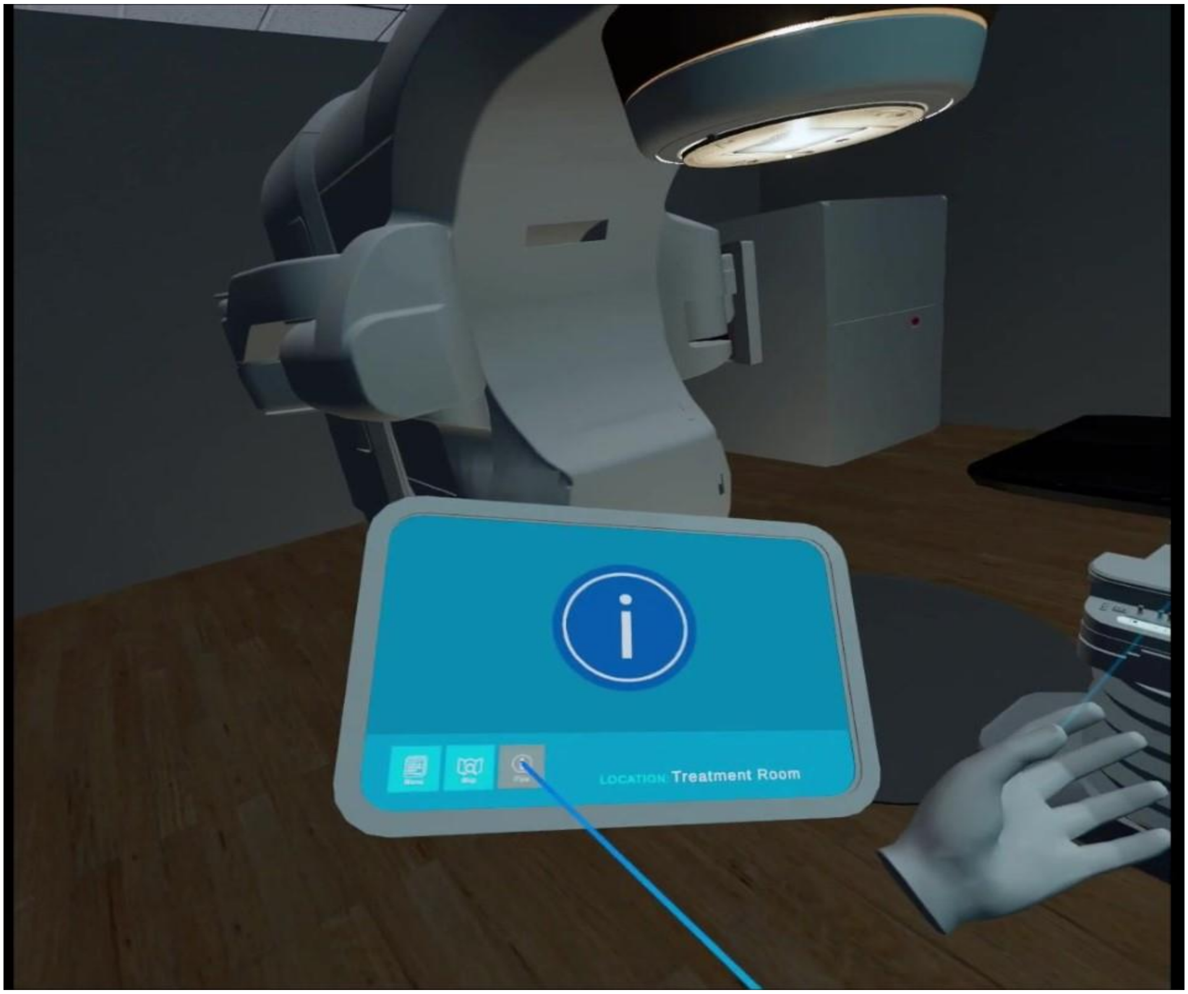

Figure 8: VR Simulator Information Tab

Instructions

Participants were instructed to navigate the virtual environment and use the VR controllers to interact with the simulated LINAC system and associated equipment as shown in Figure 9. To support additional learning, participants could access Explore Mode and activate tooltips by selecting the X icon, which provided supplementary information about system components and their functions. Participants were encouraged to become familiar with the couch controls and hand pendant before completing the four dry-run scenarios in sequence.

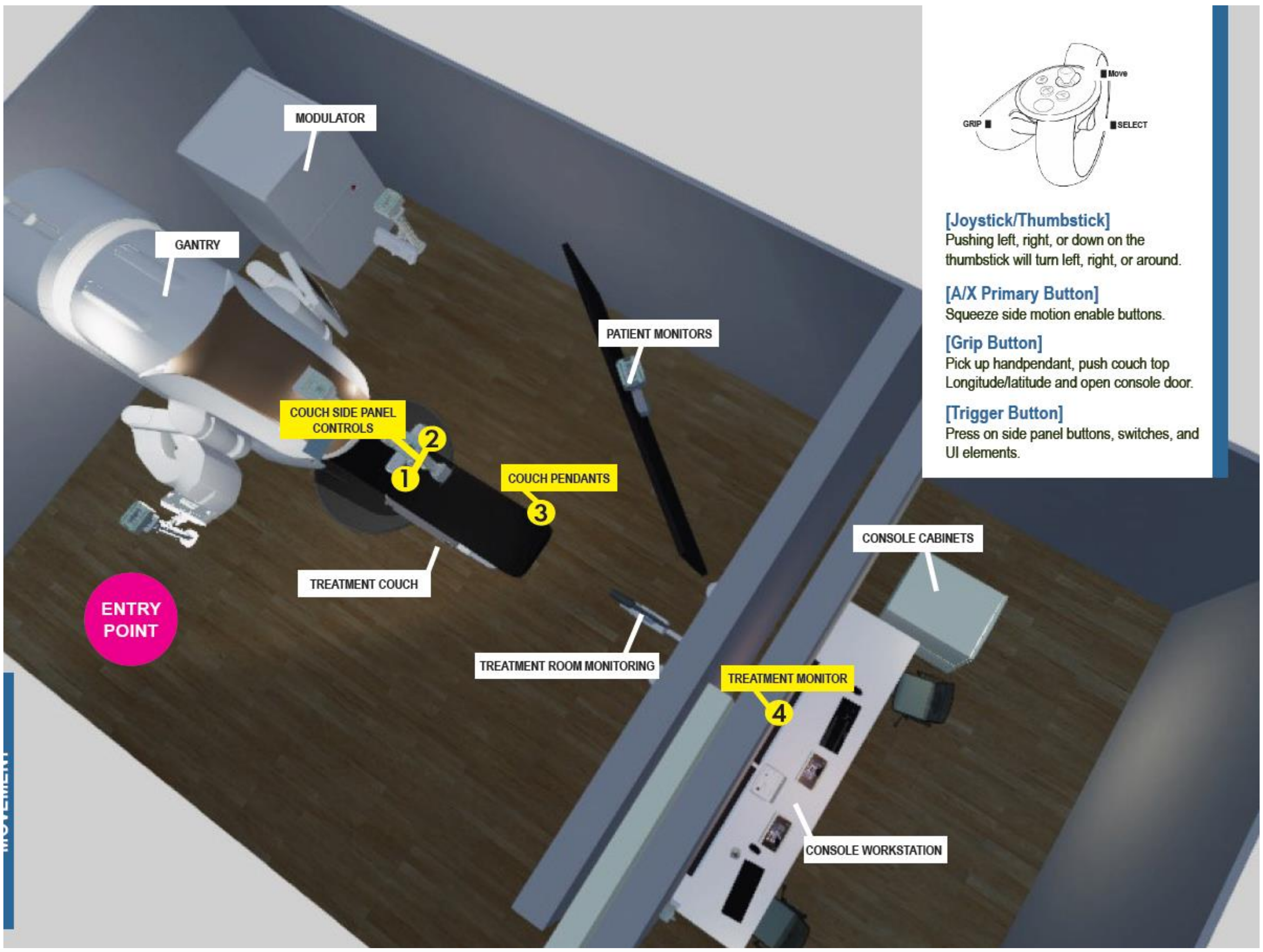

Figure 9: VR Simulator Experience Layout

Explore Mode with Tool Tips On/Off

In Explore Mode, participants were not required to complete predefined objectives. Instead, they were given time as part of the 30-minute experiment to independently explore the virtual environment and observe how the simulated LINAC system functioned. Participants practiced manipulating the gantry and moving the treatment couch using both the couch side panel controls and the handheld pendant. When additional guidance was needed, tooltips could be toggled on or off by selecting the X icon, allowing participants to access supplementary information about the system and its functions.

Manual Dry Run

Participants practiced performing a manual dry run with a simulated patient positioned on the treatment couch. During this activity, they observed the gantry as it rotated through different treatment plan positions and assessed whether the gantry could move safely without colliding with the patient or surrounding equipment. The activity also introduced participants to the procedure for stopping and resuming the manual dry run, reinforcing their understanding of motion monitoring and collision prevention during LINAC operation.

Automated Dry Run

Participants practiced performing an automated dry run with a simulated patient positioned on the treatment couch. During this activity, they observed the gantry as it automatically rotated through the planned treatment positions and assessed whether the motion path remained clear of the patient and surrounding equipment. This scenario supported participants' understanding of automated motion execution, spatial awareness, and collision avoidance during LINAC operation.

Machine Protection (Automated Dry Run - Machine Protection On)

Participants learned how the motion safety system operated while performing a dry run with a simulated patient positioned on the treatment couch. This scenario allowed participants to observe how the system identified and managed potential collision risks during gantry movement. Participants also practiced using the override function to manually rotate the gantry through a machine protection collision zone, reinforcing their understanding of controlled motion management, safety boundaries, and collision prevention during LINAC operation.

Patient Protection (Automated Dry Run - Patient Protection On)

Participants learned how the motion safety system operated while performing a dry run with a simulated patient positioned on the treatment couch. This scenario enabled participants to observe how the system detected and managed potential collision risks involving the patient protection zone during gantry movement. Participants also practiced using the override function to manually rotate the gantry through a patient protection collision zone, reinforcing their understanding of patient-specific safety boundaries, controlled motion management, and collision avoidance during LINAC operation.

Manual Dry Run

Introduction

This section introduced participants to the process of performing a manual dry run with a simulated patient. The purpose of the manual dry run was to allow participants to visually monitor gantry movement as it rotated through the planned patient treatment positions and to verify that the gantry would not collide with the patient or surrounding equipment. This visual confirmation was intended to support participant confidence in safely proceeding with the treatment plan.

At the beginning of the module, the simulated room was configured with the room lights on, the couch and gantry positioned at 0 degrees, and the patient positioned on the treatment couch. Participants began in the control room in front of the console workstation and initiated the activity by selecting continue. During the dry run, participants were instructed to closely observe the gantry motion. If the gantry appeared to approach the patient or nearby equipment, participants were instructed to release the motion enable bars to stop all motion. If further inspection indicated that a collision would occur, participants were expected to adjust the patient, equipment, or plan positions as appropriate and repeat the dry run. If no collision risk was identified, participants could resume and complete the dry run. Participants also had the option to reset the room settings and gantry or couch positions at any time by reopening the Manual Dry Run module from the menu.

Manual Dry Run

At the start of the activity, a simulated patient case had already been loaded into the treatment queue. Participants were first required to select the appropriate treatment plan from the Treatment screen as shown in Figure 10. Specifically, participants selected the AP/PA Lung plan by checking the box next to the corresponding APPA Lung entry in the plan list.

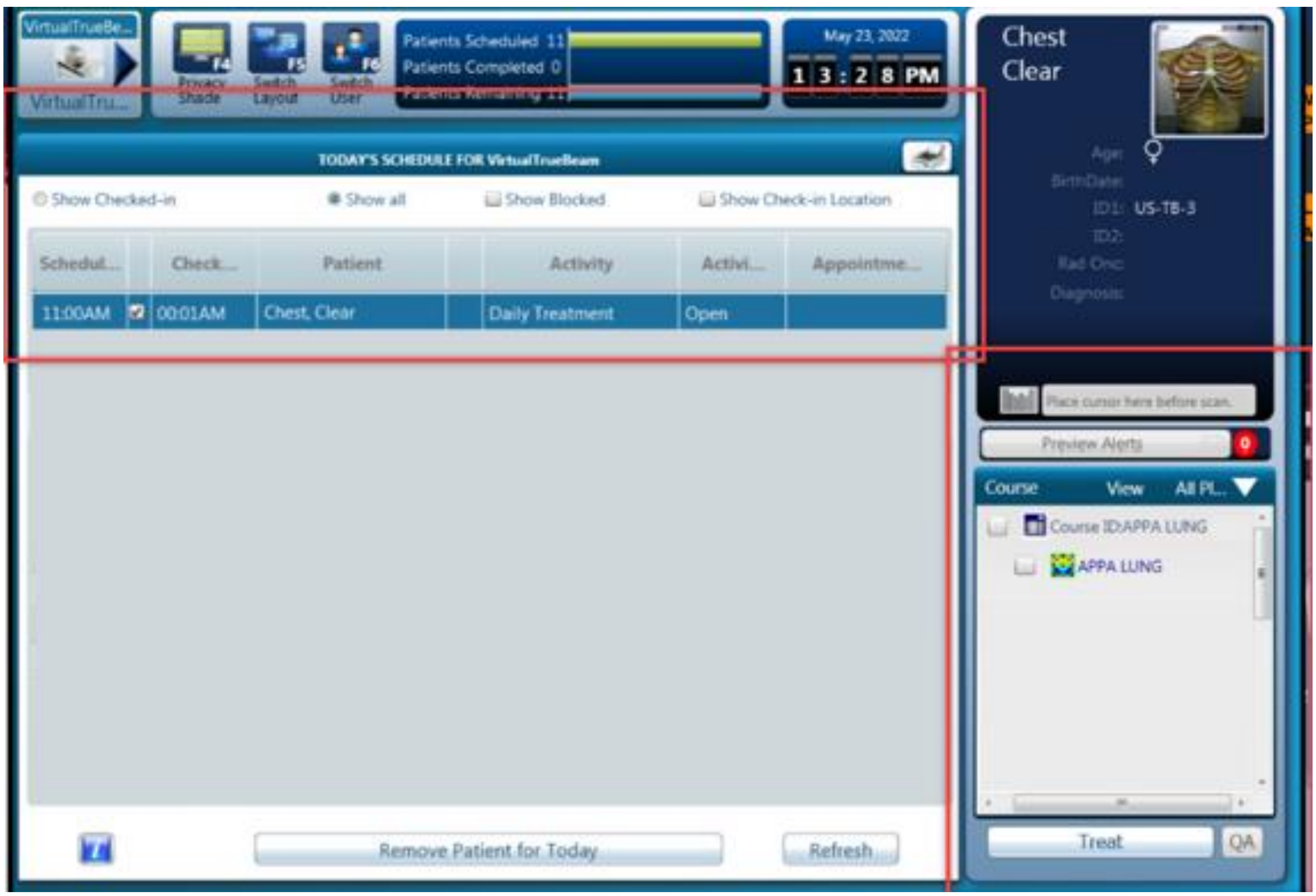

Figure 10: Treatment Plan Selection

After selecting the AP/PA Lung plan from the treatment queue, participants proceeded by selecting Treat. This action initiated the next step in the simulated treatment workflow and advanced the participant into the manual dry-run sequence as shown in Figure 11.

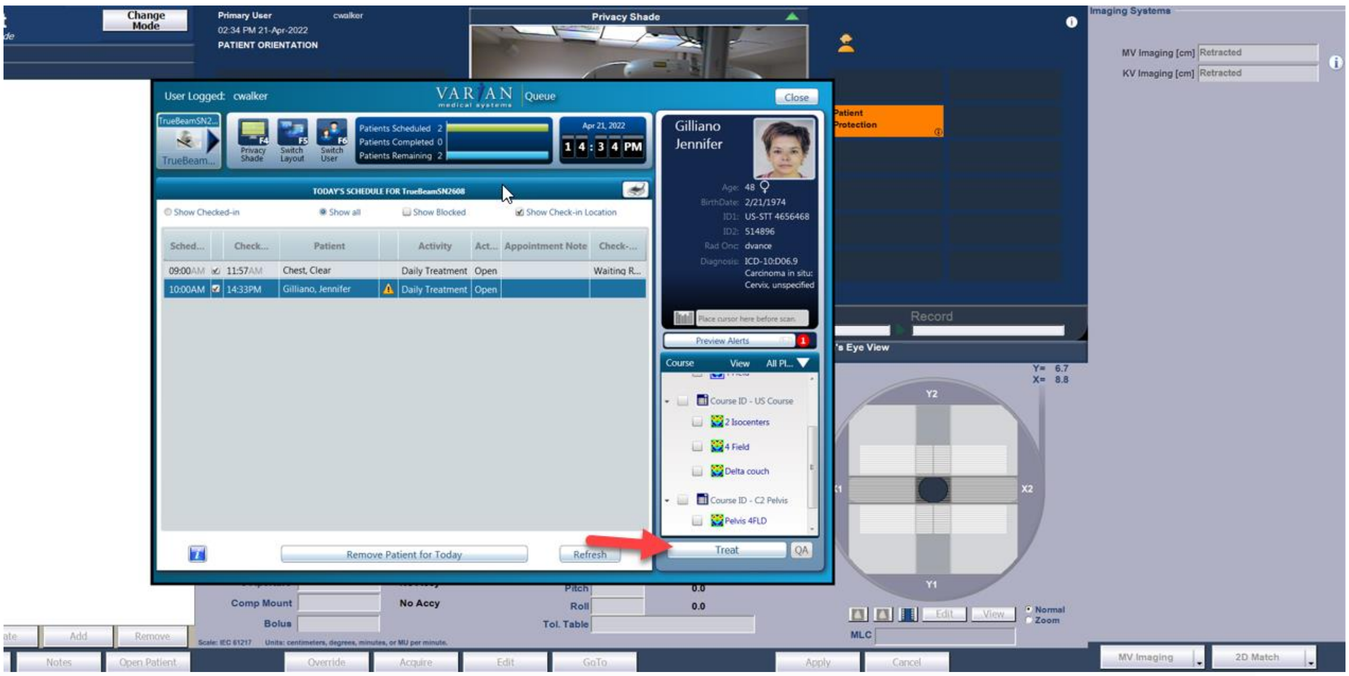

Figure 11: Treatment Workflow

Participants were then instructed to enter the treatment room and verify that the simulated patient was positioned on the couch and ready for the dry-run procedure. To advance in the module, participants were required to walk into the treatment room and approach the treatment couch. Once the participant reached the couch area, the simulator advanced to the next instructional screen as shown below in Figure 12.

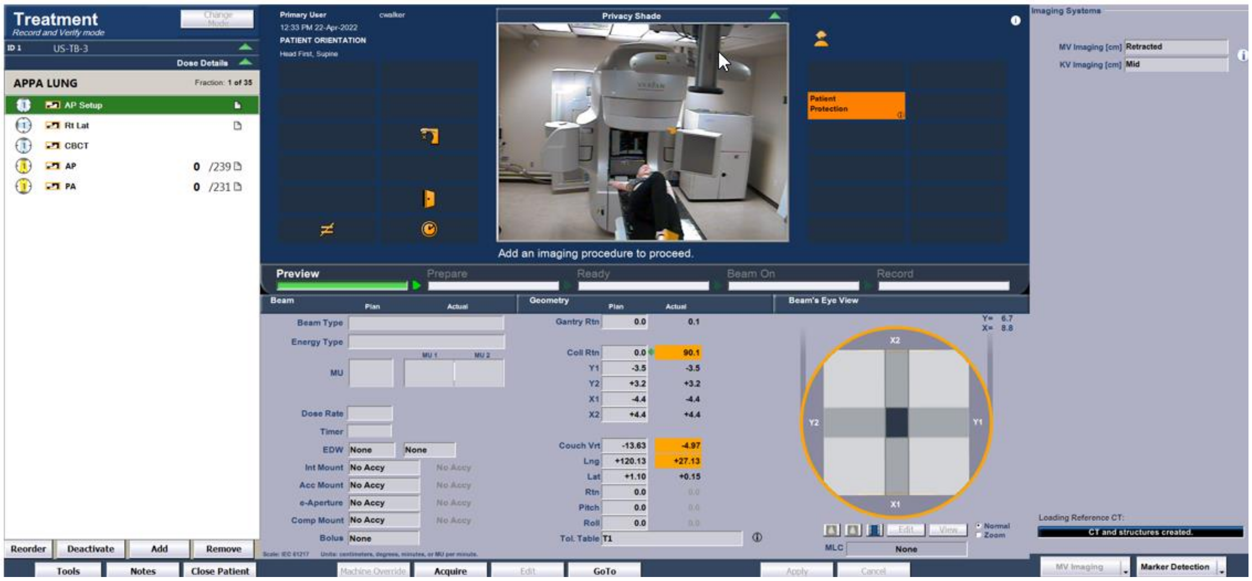

Figure 12: Control Room Workflow

Participants confirmed that the simulated patient was positioned appropriately on the treatment couch. They were then instructed to review the in-room machine monitor to assess whether the couch and gantry parameters matched the planned treatment positions. Values that were outside the planned position were highlighted in orange as shown in Figure 13. Green arrows next to a value indicated that the participant could use the auto-move controls to adjust the couch or gantry into the planned position. Participants then selected Continue to proceed to the next step of the module.

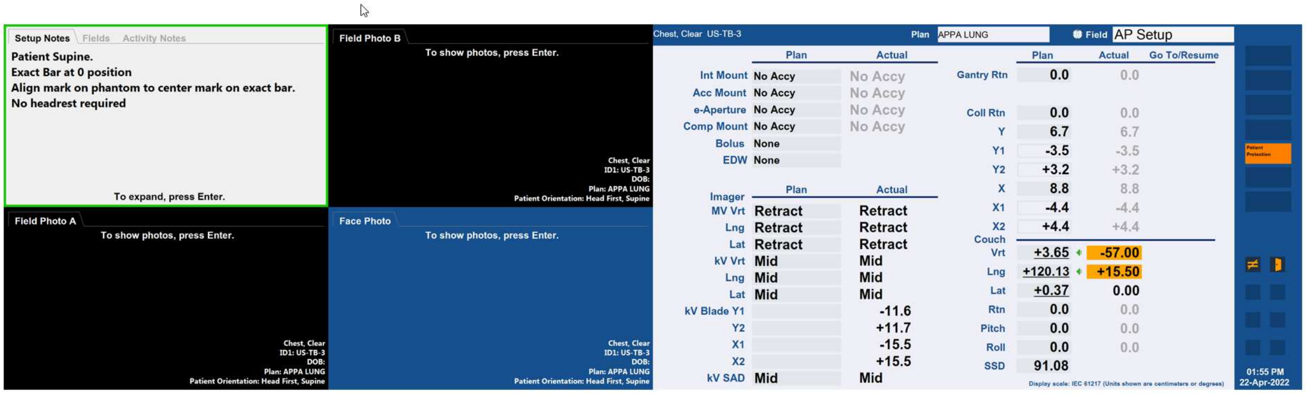

Figure 13: In-Room Monitor Setup Notes

Participants were instructed to begin by moving the treatment couch into the planned position for the simulated patient as shown in Figure 14. To complete this step, participants picked up the hand pendant, squeezed and held the motion enable bars, and selected the Auto-Move Couch button as shown in Figure 15. The Auto-Move Couch button appeared orange when the current couch position did not match the planned treatment position as shown in Figure 16.

The module also introduced participants to the three auto-move functions available through the hand pendant: Move Couch, Move Gantry/Collimator, and Rotate Couch. These controls appeared orange when the current setup differed from the planned patient treatment position. When participants pressed an orange auto-move button while holding the motion enable bars, the system automatically moved the corresponding component into the planned position. If the participant released the motion enable bars at any point, system motion stopped immediately. In this step, activation of the Auto-Move Couch function moved the couch into its final planned position.

Figure 14: Hand Pendant Controls

Figure 15: Lateral Couch Movement

Figure 16: Additional Pendant Controls

After the Auto-Move Couch function was completed, participants verified that the treatment couch had reached the planned position. Participants were instructed to review the in-room machine monitor and confirm that the couch-related values were no longer highlighted in orange. The absence of orange highlights and green arrows indicated that the couch position matched the planned treatment parameters as shown in Figure 17. Participants then selected Continue to proceed to the next step of the module.

Figure 17: In Room Monitor Couch Values

Participants then activated the room lasers to confirm patient positioning. To complete this step, participants pressed the laser button as shown in Figure 18, which turned on the positioning lasers within the simulated treatment room as shown in Figure 19. In radiation therapy, patient markers refer to visible or reference alignment marks placed on the patient's skin, immobilization device, or simulation setup to help reproduce the planned treatment position accurately. These markers serve as external reference points that correspond to the treatment setup coordinates established during simulation and planning. The lasers were used to verify that the isocenter aligned with the patient markers and to confirm that the simulated patient was positioned correctly before proceeding with the dry-run workflow.

Figure 18: Laser Markers using Pendant

Participants confirmed that the isocenter aligned with the patient marks before proceeding. In the simulation, the green laser was used as a visual positioning reference and was expected to align with the marked X indicators on the simulated patient. These patient marks represented external setup references used to verify that the patient was correctly positioned relative to the planned treatment isocenter as shown in Figure 20. After confirming appropriate laser alignment with the patient marks, participants selected Continue to advance to the next step of the manual dry-run workflow.

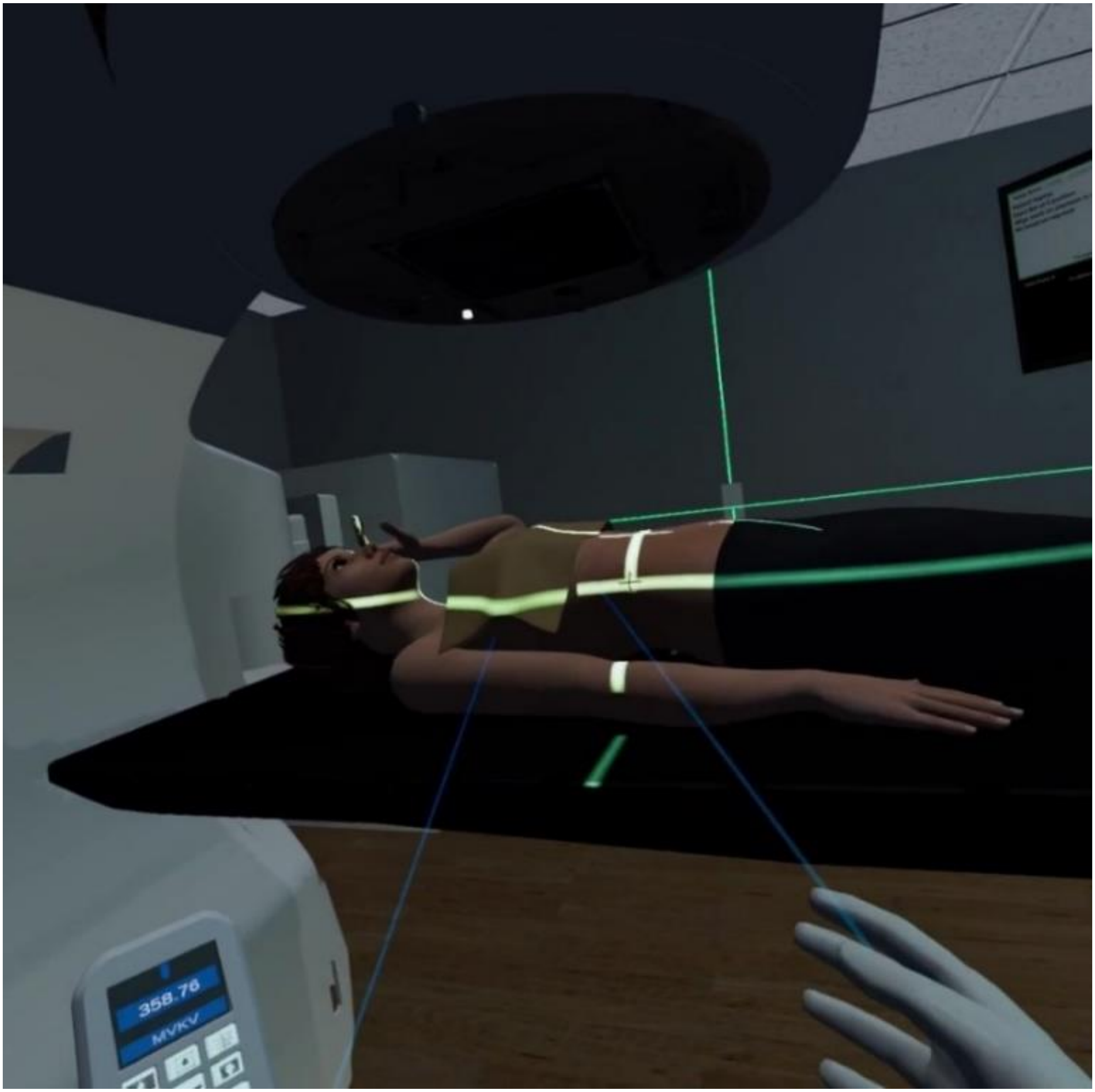

Figure 19: Matching Isocenter position

Figure 20: Pendant Controls for laser Markings

Participants were then instructed to review the patient monitor within the treatment room. Using the navigation buttons on the hand pendant, participants moved from the Setup Notes tab to the Fields tab by pressing the right directional button. This action updated the left in-room patient monitor and advanced the display from the setup information to the treatment field information needed for the next stage of the manual dry-run workflow. This workflow is captured visually in Figure 21, Figure 22,Figure 23.

Figure 21: Pendant Controls for Treatment Fields

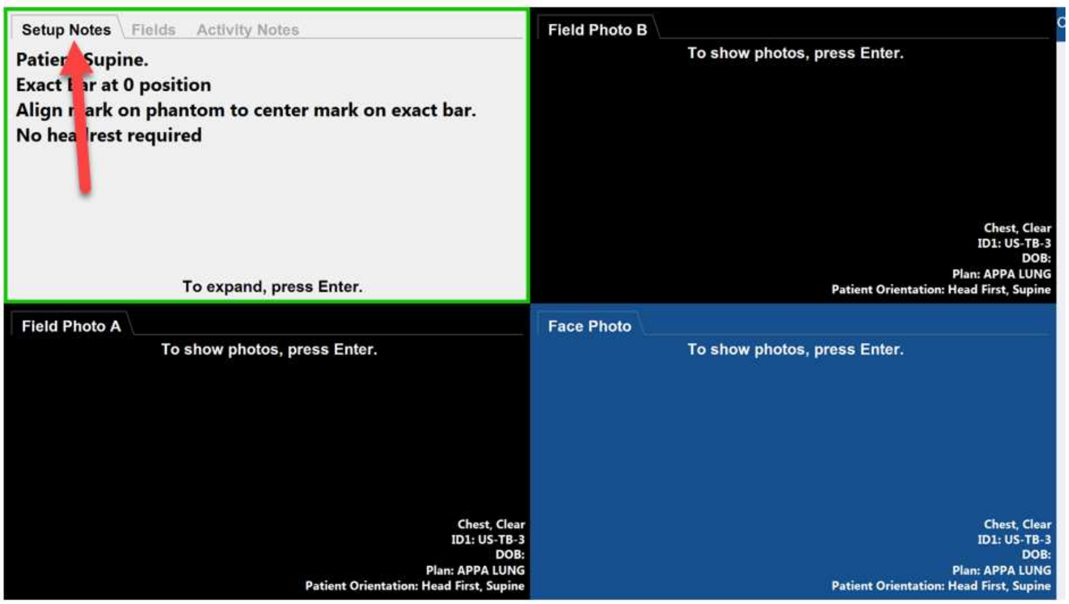

Figure 22: Setup Notes for Treatment Field

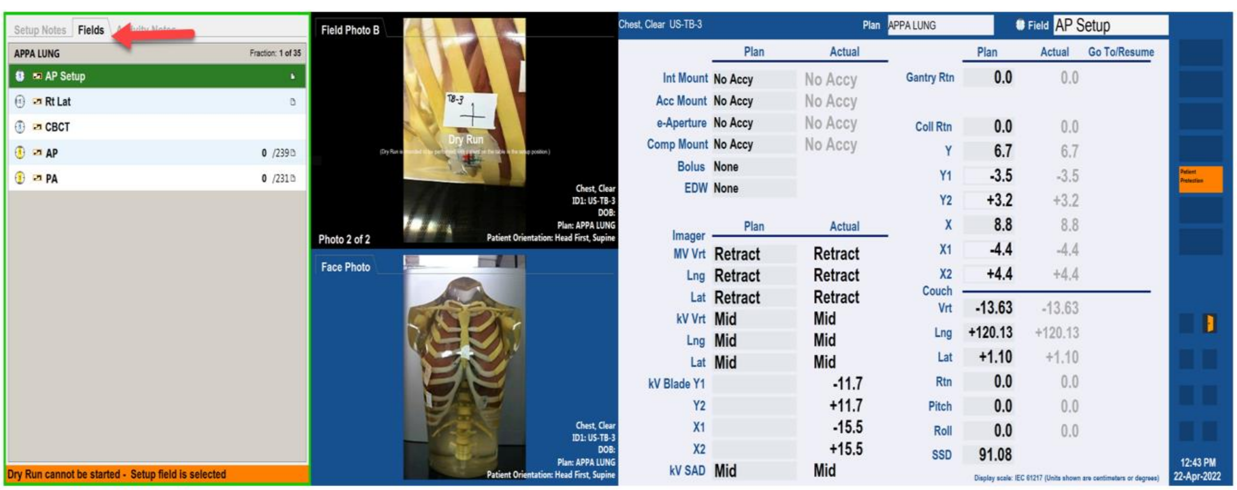

Figure 23: In-Room Monitor for Treatment Field

Participants used the hand pendant navigation controls to locate the first treatment field on the patient monitor. They were instructed to move past the setup fields, represented by blue icons, until reaching the first treatment field as shown in Figure 24, represented by the first yellow icon. In this step, participants pressed the down navigation button three times on the hand pendant to advance to the first yellow treatment field as shown in Figure 25.

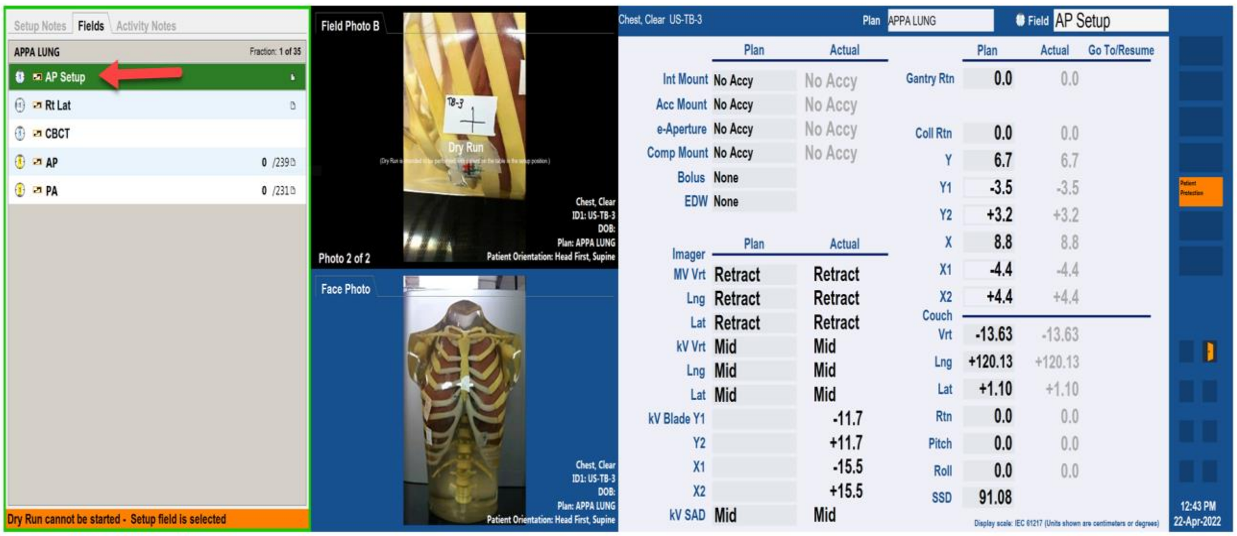

Figure 24: Treatment Field Workflow

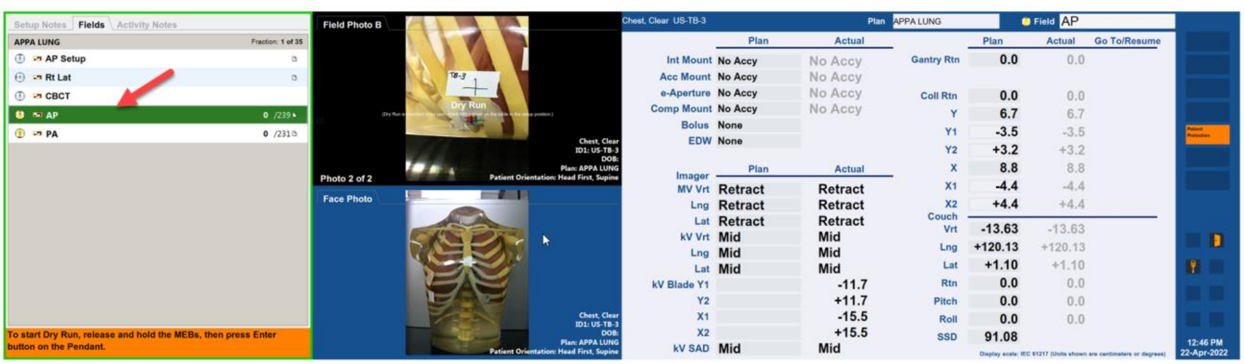

Figure 25: Treatment Field Programming

Participants then initiated the first treatment field using the hand pendant. After navigating to the first yellow treatment field, participants squeezed and held the motion enable bars and pressed the Enter button on the navigation controls. This action initiated the selected treatment field and advanced the manual dry-run workflow while maintaining the required motion safety control through continued engagement of the motion enable bars as shown in Figure 26 by squeezing both sides of the hand pendant.

Figure 26: Motion Enable Bars (MEBs)

In this step, the system did not initiate additional motion because the machine was already positioned for the first treatment field. Participants were instructed to review the patient monitor to confirm that the first treatment field had been completed. Once the field was completed, the system automatically advanced to the second treatment field on the patient monitor. This step demonstrated that, during the manual dry-run workflow, completed treatment fields were sequentially advanced by the system when no further motion was required for the selected field as shown in Figure 27.

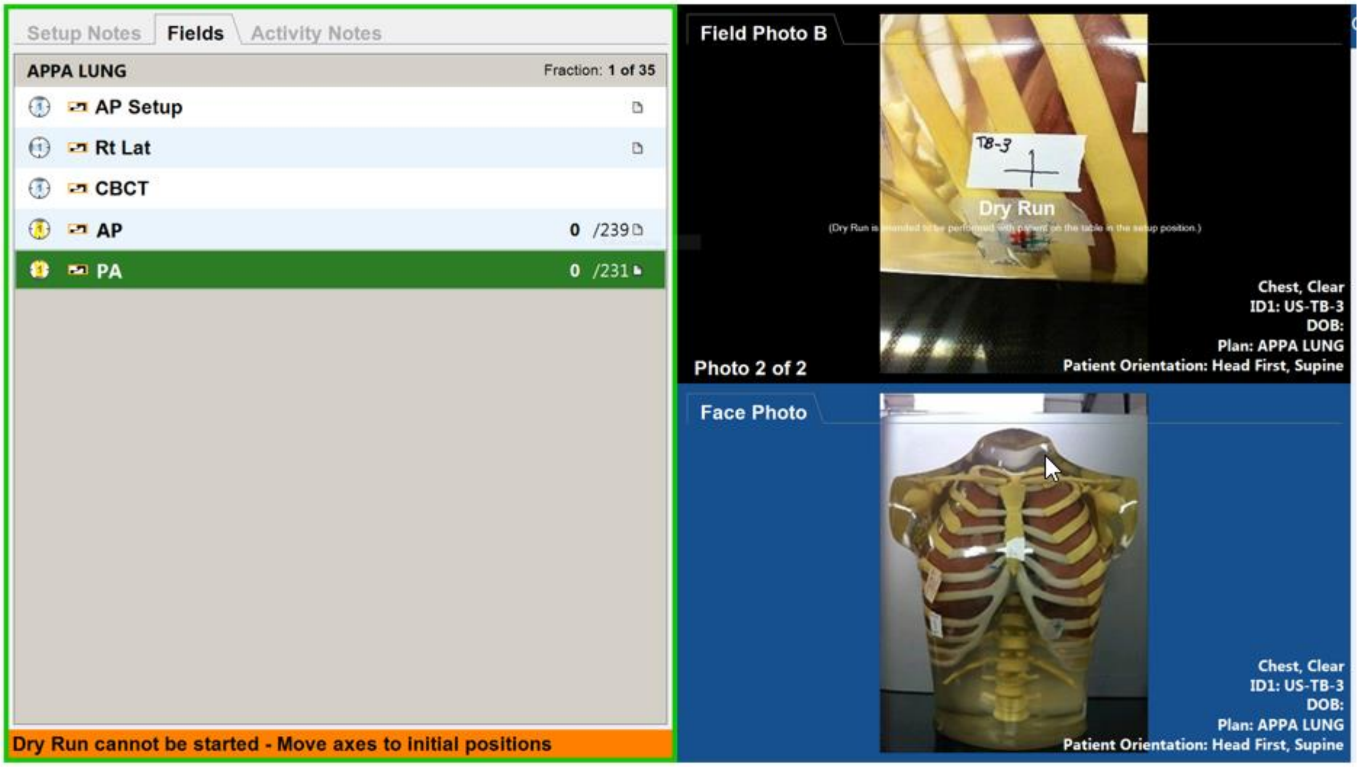

Figure 27: In-Room Treatment Field Status

Participants then advanced to the second and final treatment field. Before initiating motion, they were instructed to carefully observe the gantry as it rotated toward the next planned treatment position. Participants were advised to move to the right side of the treatment table, corresponding to the patient's left side, to better assess clearance as the gantry rotated clockwise. This reinforced the purpose of the dry run, which was to visually confirm that gantry motion could be completed safely without collision with the patient or surrounding equipment.

To initiate motion to the second treatment field, participants squeezed and held the motion enable bars and activated the Auto-Move Gantry control, which appeared orange to indicate that the gantry was not yet in the planned position as shown in Figure 28. Once activated, the gantry began rotating clockwise from 0 degrees toward 180 degrees.

Figure 28: Treatment Field Workflow on Pendant

The module then introduced a scenario in which participants needed to stop the dry run to assess a potential collision risk and subsequently resume the procedure. Participants were returned to the second treatment field to repeat the gantry motion sequence, this time with the specific objective of practicing interruption and resumption of motion.

Participants were instructed to squeeze and hold the motion enable bars and initiate motion to the second treatment field. While the gantry was rotating, participants released the motion enable bars to stop all motion. This step demonstrated the safety function of the motion enable bars, where releasing them immediately interrupted gantry movement. If participants did not release the motion enable bars during gantry rotation, the simulator prompted them to repeat the step and specifically instructed them to release the motion enable bars to stop the gantry motion. The gantry was then reset to 0 degrees so the participant could repeat the stopping procedure correctly.

The module required participants to practice stopping and resuming gantry motion during the manual dry-run sequence. Participants initiated gantry movement by holding the motion enable bars and selecting the Auto-Move Gantry control, which appeared orange to indicate that the gantry was not yet in the planned position. Once activated, the gantry began rotating clockwise from 0 degrees toward 180 degrees. Participants were instructed to release the motion enable bars during gantry rotation to stop motion and simulate a pause for collision assessment.

If participants did not release the motion enable bars before the gantry reached the end of its motion range, the simulator prompted them to repeat the step. The prompt informed participants that the motion enable bars needed to be released while the gantry was rotating in order to stop motion, and the gantry was reset to 0 degrees so the step could be repeated. Once participants successfully stopped the gantry mid-rotation, they were instructed to inspect the patient, equipment, and gantry clearance. If a collision risk was identified, participants were instructed to adjust the patient, equipment, or planned positions and repeat the dry run. If no collision risk was identified, participants could resume the dry run.

In this scenario, participants determined that no collision would occur. To resume the dry run, they held the motion enable bars and selected the Auto-Move Gantry control again. The gantry then continued rotating to the planned 180-degree position, completing the dry-run sequence. Participants were then instructed to exit the dry run. The simulation presented multiple exit options, including pressing Cancel on the hand pendant, returning to the console area and selecting Done as shown in Figure 29, or using the left directional button on the hand pendant to navigate back to the Setup Notes tab. For this workflow, participants returned to the console area and selected Done on the In-Room workstation.

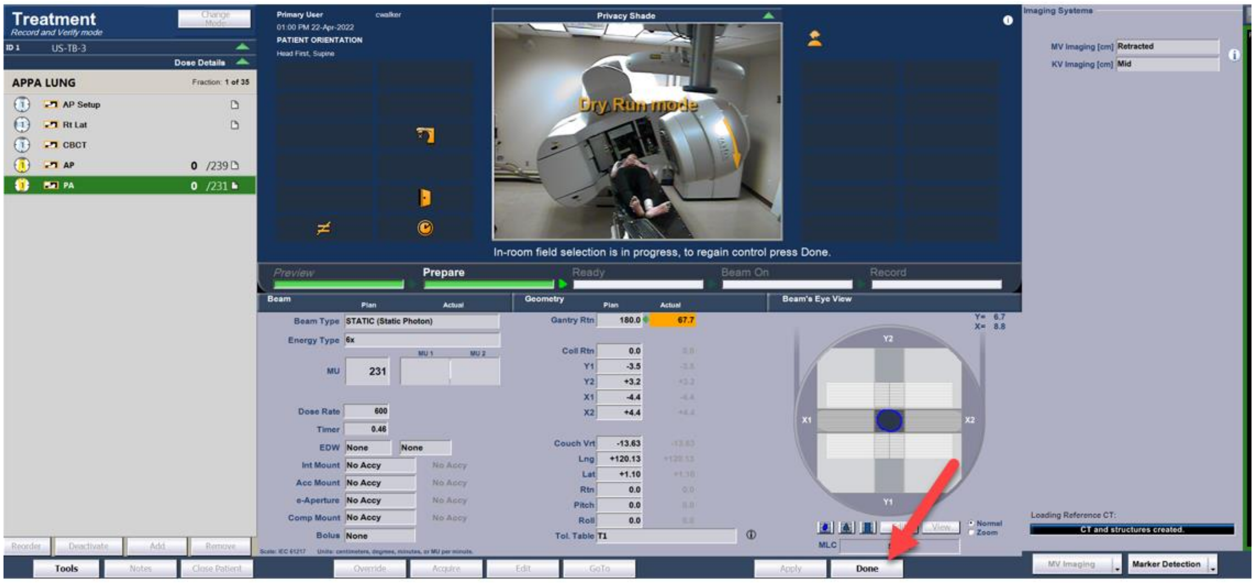

Figure 29: Console Room Treatment Field Status

Upon completion of the Manual Dry Run module, participants were directed to proceed to the Automated Dry Run module. This subsequent module was intended to introduce the automated dry-run functionality and provide participants with additional experience observing how automated system motion is executed and monitored within the simulated LINAC environment.

Automated Dry Run

This section introduced participants to the process of performing an automated dry run with a simulated patient. Similar to the manual dry-run workflow, the purpose of the automated dry run was to allow participants to visually monitor gantry movement as it rotated through the planned patient treatment positions and to verify that the gantry would not collide with the patient or surrounding equipment. This visual confirmation was intended to support confidence in safely proceeding with the patient treatment plan.

At the beginning of the module, the simulated treatment room was configured with the room lights on, the couch and gantry positioned at 0 degrees, and the patient positioned on the treatment couch. Participants began in the control room in front of the console workstation and initiated the activity by selecting Continue. Participants were instructed to observe the gantry closely throughout the dry run. If the gantry appeared to approach the patient or nearby equipment, participants were instructed to release the motion enable bars to stop all motion. If further inspection indicated that a collision would occur, participants were expected to adjust the patient, equipment, or planned positions as appropriate and repeat the dry run. If no collision risk was identified, participants could resume the run. Participants also had the option to reset the room settings and gantry or couch positions at any time by reopening the Automated Dry Run module from the menu.

At the start of the automated dry-run activity, a simulated patient case had already been loaded into the treatment queue as shown in Figure 10. Participants were first required to select the appropriate treatment plan from the Treatment screen. Specifically, participants selected the AP/PA Lung plan by checking the box next to the corresponding APPA Lung entry in the plan list as shown in Figure 11.

After selecting the AP/PA Lung plan from the treatment queue, participants selected Treat to proceed. This action initiated the automated dry-run workflow and advanced participants to the next step of the simulated treatment sequence as shown in Figure 11.

Participants then added automation to the selected patient plan. To complete this step, participants selected Add from the lower-left area of the Treatment screen. This action initiated the process of configuring automated functionality for the patient plan within the simulated treatment workflow as shown in Figure 30 below.

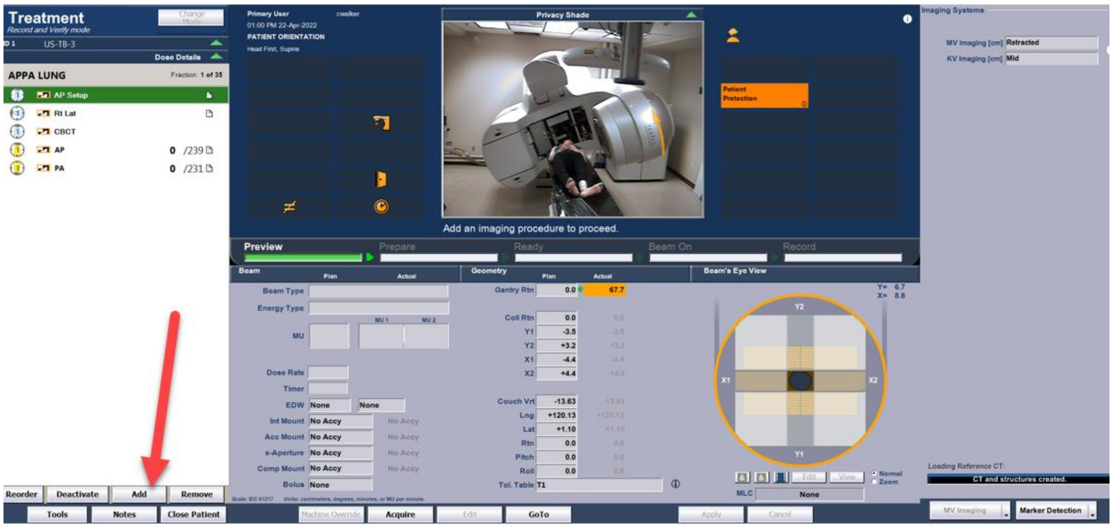

Figure 30: Automatic Dry Run Control Room Workflow

Participants then selected Add Automation from the drop-down menu as shown in Figure 31. This action applied the automation configuration pathway to the selected patient plan and advanced the participant to the next step of the automated dry-run workflow.

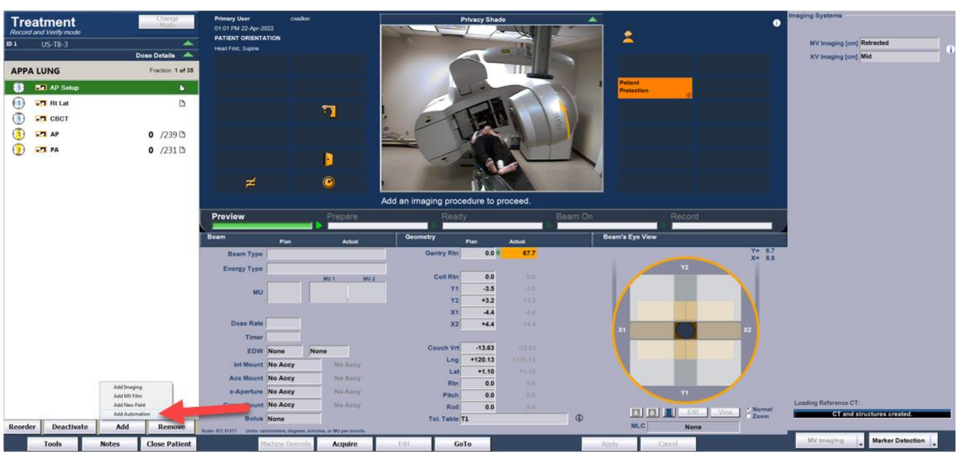

Figure 31: Automatic Dry Run Programming

After automation was added to the selected patient plan, participants verified that automation had been applied by observing the treatment field list. A green bar appeared next to the treatment fields, indicating that automated functionality was now enabled for those fields as shown in Figure 32.

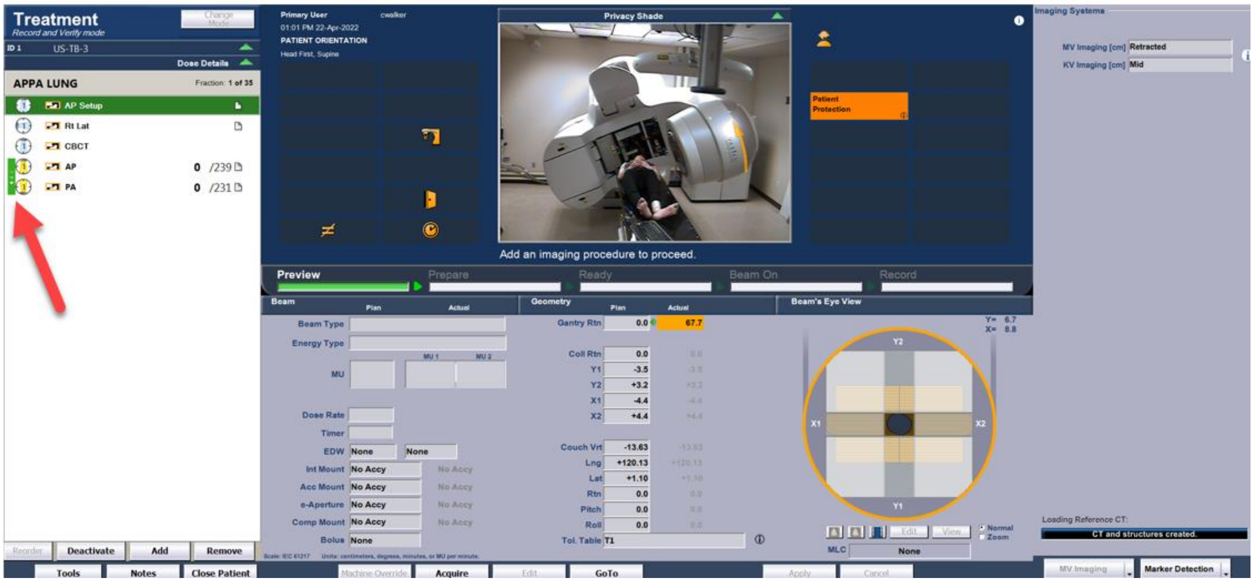

Figure 32: Automatic Dry Run adding plan workflow

Participants were then instructed to enter the treatment room and verify that the simulated patient was positioned on the couch and ready for the automated dry run. To advance in the module, participants walked into the treatment room and approached the treatment couch. Once the participant reached the couch area, the simulator advanced to the next instructional screen as shown in Figure 12.

Participants confirmed that the simulated patient was on the couch and in the appropriate position. They were then instructed to review the in-room machine monitor to assess whether the couch and gantry parameters matched the planned treatment positions. Values that were outside the planned position were highlighted in orange as shown in Figure 13. Green arrows next to a value indicated that the participant could use the auto-move controls to move the couch or gantry into the planned position. Participants then selected Continue to proceed to the next step of the automated dry-run workflow.

Participants began by moving the treatment couch into the planned position for the simulated patient as shown in Figure 14. To complete this step, participants picked up the hand pendant, squeezed and held the motion enable bars, and selected the Auto-Move Couch button as shown in Figure 15. The Auto-Move Couch control appeared orange when the current couch position did not match the planned treatment position as shown in Figure 16.

This step also reinforced the use of the three available auto-move functions on the hand pendant: Move Couch, Move Gantry/Collimator, and Rotate Couch. These controls appeared orange when the current machine setup did not correspond to the planned treatment parameters. When an orange auto-move control was selected while the motion enable bars were held, the system automatically moved the corresponding component into the correct planned position. If the participant released the motion enable bars at any point, all motion stopped immediately. In this step, activation of the Auto-Move Couch function moved the couch into its final planned position for the patient plan.

After the Auto-Move Couch function was completed, participants verified that the treatment couch had reached the planned position. Participants reviewed the in-room machine monitor and confirmed that the previously highlighted values were no longer displayed in orange. The disappearance of the orange highlights and green arrows indicated that the couch position matched the planned treatment parameters as shown in Figure 17. Participants then selected Continue to advance to the next step of the automated dry-run workflow.

Participants then activated the room lasers to confirm patient positioning before proceeding with the automated dry-run workflow. To complete this step, participants pressed the laser button, which turned on the positioning lasers in the simulated treatment room as shown in Figure 18. The lasers were used to verify that the isocenter aligned with the patient marks and to validate that the simulated patient was positioned correctly for the selected treatment plan as shown in Figure 19.

Participants confirmed that the treatment isocenter aligned with the patient marks before proceeding. In the simulation, the green positioning laser was expected to align with the marked X indicators on the simulated patient, confirming that the patient setup corresponded with the planned treatment position as shown in Figure 20. After verifying alignment, participants selected Continue to advance to the next step of the automated dry-run workflow.

Participants were then instructed to review the patient monitor within the treatment room. Using the navigation buttons on the hand pendant, participants moved from the Setup Notes tab to the Fields tab by pressing the right directional button. This action updated the left in-room patient monitor display from setup information to the treatment field information required for the automated dry-run workflow. This workflow is captured visually in Figure 21 to Figure 23.

Participants used the hand pendant navigation controls to identify the first treatment field on the patient monitor. They were instructed to move past the setup fields, represented by blue icons, until reaching the first treatment field as shown in Figure 24, represented by the first yellow icon. In this step, participants pressed the down navigation button three times on the hand pendant to navigate to the first yellow treatment field as shown in Figure 25.

Participants were instructed to observe that the treatment fields displayed a green bar, indicating that automation had been added to those fields as shown in Figure 33. The module then introduced the concept of automation within the dry-run workflow. In a manual dry run without automation, participants were required to initiate motion for each treatment field individually and move the equipment to each planned position one step at a time. In contrast, when automation was enabled, participants only needed to initiate the first treatment field. The system then automatically advanced from one treatment field to the next and moved the equipment through the planned positions as long as the participant continued holding the motion enable bars.

For example, if a plan included five treatment fields, the participant would select and initiate the first field, and the system would continue moving through each subsequent treatment field position until all fields were completed, provided the motion enable bars remained engaged as shown in Figure 26.

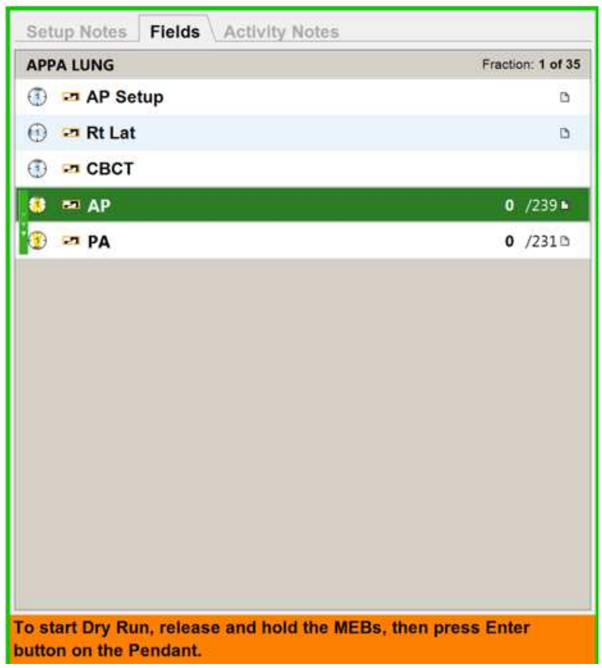

Figure 33: Automatic Dry Run Treatment Field Status

Participants were instructed to carefully observe the gantry as automated motion was initiated. To improve visibility of the clearance between the gantry, patient, and surrounding equipment, participants were advised to move to the right side of the treatment table, corresponding to the patient's left side, as the gantry rotated clockwise. This step reinforced the purpose of the dry run, which was to visually confirm that gantry motion could be completed safely without collision.

While positioned on the first treatment field, participants squeezed and held the motion enable bars and pressed Enter on the hand pendant navigation controls. This action initiated the automated dry-run sequence. Once activated, the gantry began rotating clockwise from 0 degrees toward 180 degrees while participants continued to monitor the motion path for potential collision risks.

Upon completion of the automated dry run, participants were instructed to exit the dry-run workflow. The simulation presented multiple options for exiting the module, including pressing Cancel on the hand pendant, returning to the console area and selecting Done, or using the left directional button on the hand pendant to navigate back to the Setup Notes tab. For this workflow, participants returned to the console area after the gantry reached 180 degrees and selected Done on the treatment workstation interface.

Patient Protection

The Patient Protection module introduced participants to another component of the LINAC Motion Safety System, specifically Patient Protection, also referred to as LaserGuard II. This feature was described as a safety mechanism designed to slow or stop motion under defined conditions to prevent potential collisions between machine components, the patient, or other objects within the treatment area.

In this module scenario, the simulated patient was positioned close enough to the gantry during treatment to activate the patient protection function. Specifically, the patient entered the LaserGuard II protection area and triggered the sensor. LaserGuard II was presented as an infrared laser system that scans just below the collimator face. When an object or patient enters the defined protection area, the system triggers a collision interlock. Participants were instructed to look toward the gantry beneath the collimator to observe a visual representation of the LaserGuard II beam within the simulation.

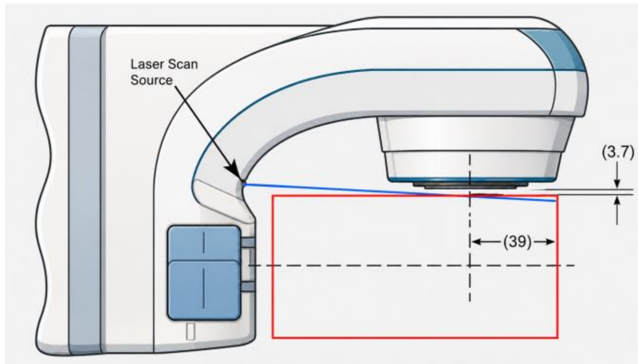

Figure 34: Patient Protection Mechanism

Participants were informed that, in some clinical scenarios, the gantry may come very close to the patient or another object without resulting in actual contact. In such cases, the collision reset feature may be used to continue the dry run under careful observation after the participant has determined that no imminent collision is present. This module guided participants through the process of using collision reset to manually move the gantry through a patient protection collision zone as shown in Figure 34.

Participants were also reminded that the room settings and gantry or couch positions could be reset at any time by reopening the Automated Dry Run: Patient Protection module from the menu. The module continued to display the LaserGuard II laser beneath the collimator so participants could observe the location of the protection area during the workflow.

At the start of the automated dry-run activity, a simulated patient case had already been loaded into the treatment queue. Participants were instructed to enter the control room and select the appropriate treatment plan from the Treatment screen. Specifically, participants selected the AP/PA Lung plan by checking the box next to the corresponding APPA Lung entry in the plan list as shown in Figure 10.

After selecting the AP/PA Lung plan from the treatment queue, participants selected Treat to proceed. This action initiated the Patient Protection workflow and advanced participants to the next step of the simulated automated dry-run sequence as shown in Figure 11.

Participants then added automation to the selected patient plan. To complete this step, participants selected Add from the lower-left area of the Treatment screen. This action initiated the automation configuration process and prepared the selected plan for the Patient Protection dry-run workflow as shown in Figure 10.

Participants then selected Add Automation from the drop-down menu. This action enabled automated functionality for the selected patient plan and advanced participants to the next step of the Patient Protection dry-run workflow as shown in Figure 31.

After automation was added to the selected patient plan, participants verified that automation had been enabled by observing the treatment field list. A green bar appeared next to the patient treatment fields, indicating that automated functionality had been applied to those fields for the Patient Protection dry-run workflow as shown in Figure 31.

Participants were instructed to enter the treatment room and verify that the simulated patient was positioned on the couch and ready for the Patient Protection dry-run scenario. To advance in the module, participants walked into the treatment room and approached the treatment couch. Once the participant reached the couch area, the simulator advanced to the next instructional screen as shown in Figure 12.

Participants confirmed that the simulated patient was on the couch and in position. They were then instructed to review the in-room machine monitor to determine whether the couch and gantry parameters matched the planned treatment positions. Values outside the planned position were highlighted in orange as shown in Figure 13. Green arrows next to a value indicated that the participant could use the auto-move controls to move the couch or gantry into the planned position. Participants then selected Continue to proceed to the next step of the Patient Protection workflow.

Participants began by moving the treatment couch into the planned position for the simulated patient as shown in Figure 14. To complete this step, participants picked up the hand pendant, squeezed and held the motion enable bars, and selected the Auto-Move Couch button as shown in Figure 15. The Auto-Move Couch control appeared orange when the current couch position did not match the planned treatment position as shown in Figure 16.

This step also reinforced the use of the three auto-move functions available through the hand pendant: Move Couch, Move Gantry/Collimator, and Rotate Couch. These controls appeared orange when the current machine setup did not match the planned treatment parameters. When an orange auto-move control was selected while the motion enable bars were held, the system automatically moved the corresponding component into the correct planned position. If the participant released the motion enable bars at any point, all motion stopped immediately. In this step, activation of the Auto-Move Couch function moved the couch into its final planned position for the Patient Protection scenario.

After the Auto-Move Couch function was completed, participants verified that the treatment couch had reached the planned position. Participants reviewed the in-room machine monitor and confirmed that the couch-related values were no longer highlighted in orange. The absence of orange highlights and green arrows indicated that the couch position matched the planned treatment parameters as shown in Figure 24. Participants then selected Continue to advance to the next step of the Patient Protection workflow.

Participants then activated the room lasers to verify patient positioning before proceeding with the Patient Protection dry-run workflow. To complete this step, participants pressed the laser button as shown in Figure 18, which turned on the positioning lasers within the simulated treatment room as shown in Figure 19. The lasers were used to confirm that the treatment isocenter aligned with the patient marks and to validate that the simulated patient was positioned correctly for the selected treatment plan.

Participants confirmed that the treatment isocenter aligned with the patient marks before proceeding. In the simulation, the green positioning laser aligned with the marked X indicators on the simulated patient, confirming that the patient setup corresponded with the planned treatment position as shown in Figure 20. After verifying alignment, participants selected Continue to advance to the next step of the Patient Protection workflow.

Participants were then instructed to review the patient monitor within the treatment room. Using the navigation buttons on the hand pendant, participants moved from the Setup Notes tab to the Fields tab by pressing the right directional button. This action updated the left in-room patient monitor display from setup information to the treatment field information required for the Patient Protection dry-run workflow as shown in Figure 21 to Figure 23.

Participants used the hand pendant navigation controls to locate the first treatment field on the patient monitor. They were instructed to move past the setup fields, represented by blue icons, until reaching the first treatment field as shown in Figure 24, represented by the first yellow icon. In this step, participants pressed the down navigation button three times on the hand pendant to navigate to the first yellow treatment field as shown in Figure 25.

Participants were instructed to carefully observe the gantry as motion was initiated during the Patient Protection dry-run workflow. To improve visibility of the clearance between the gantry, patient, treatment couch, and surrounding equipment, participants were advised to move to the right side of the treatment table, corresponding to the patient's left side, as the gantry rotated clockwise. This step reinforced the purpose of the dry run, which was to visually confirm that gantry motion could be completed safely without collision.

While positioned on the first treatment field, participants squeezed and held the motion enable bars and pressed Enter on the hand pendant navigation controls. This action initiated gantry motion from 0 degrees toward 180 degrees. As the gantry approached the defined patient protection area, the motion safety system reduced gantry speed and then stopped motion, indicating activation of the Patient Protection response.

The gantry stopped because the patient protection function of the Motion Safety System was activated. In this scenario, the simulated patient's elbow entered the LaserGuard II protection area, which triggered the sensor and caused gantry motion to stop. Participants were instructed to note the collision alert icon displayed on the machine monitor, which indicated that a patient protection alert had been activated.

Before continuing, participants were required to acknowledge the alert displayed on the screen as shown in Figure 36. To complete this step, participants pressed Enter on the hand pendant, acknowledging the fault and allowing the workflow to proceed to the next stage of the Patient Protection dry-run module as shown in Figure 35.

Figure 35: Patient Protection Collision Alert

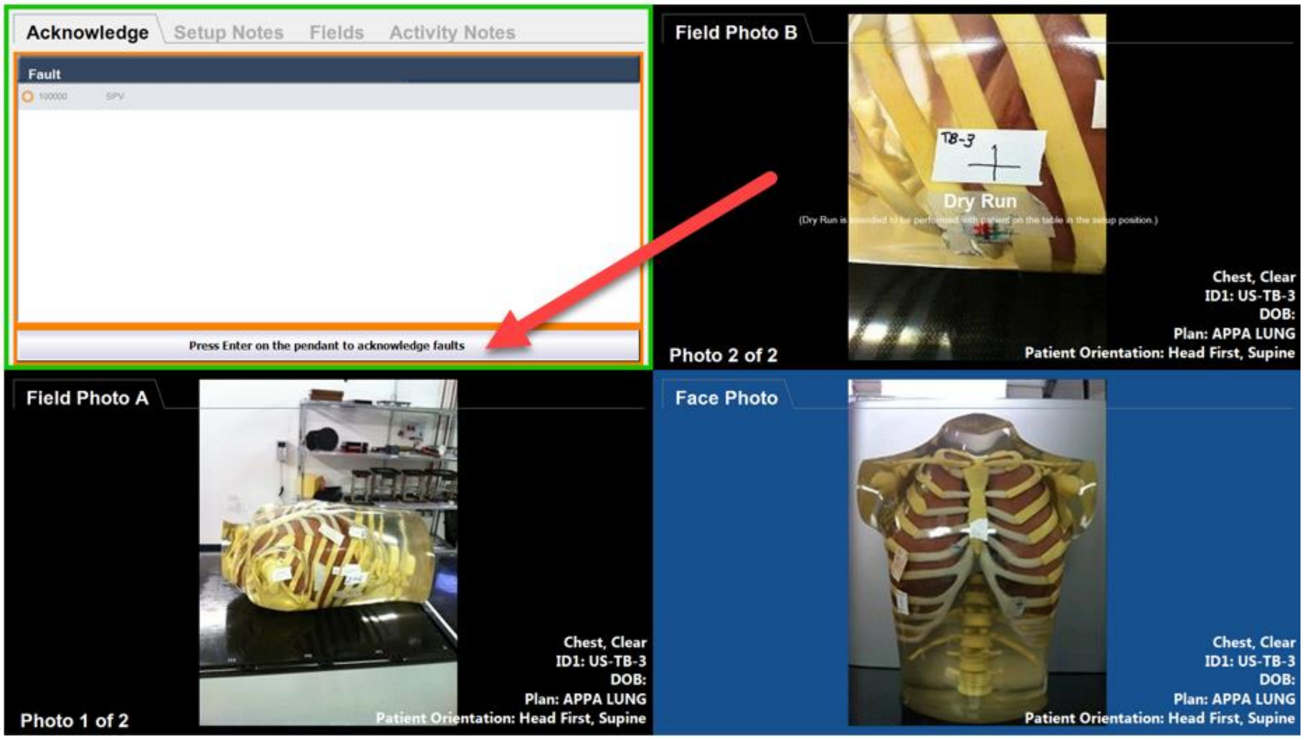

Figure 36: Patient Protection IRM Treatment Field Status

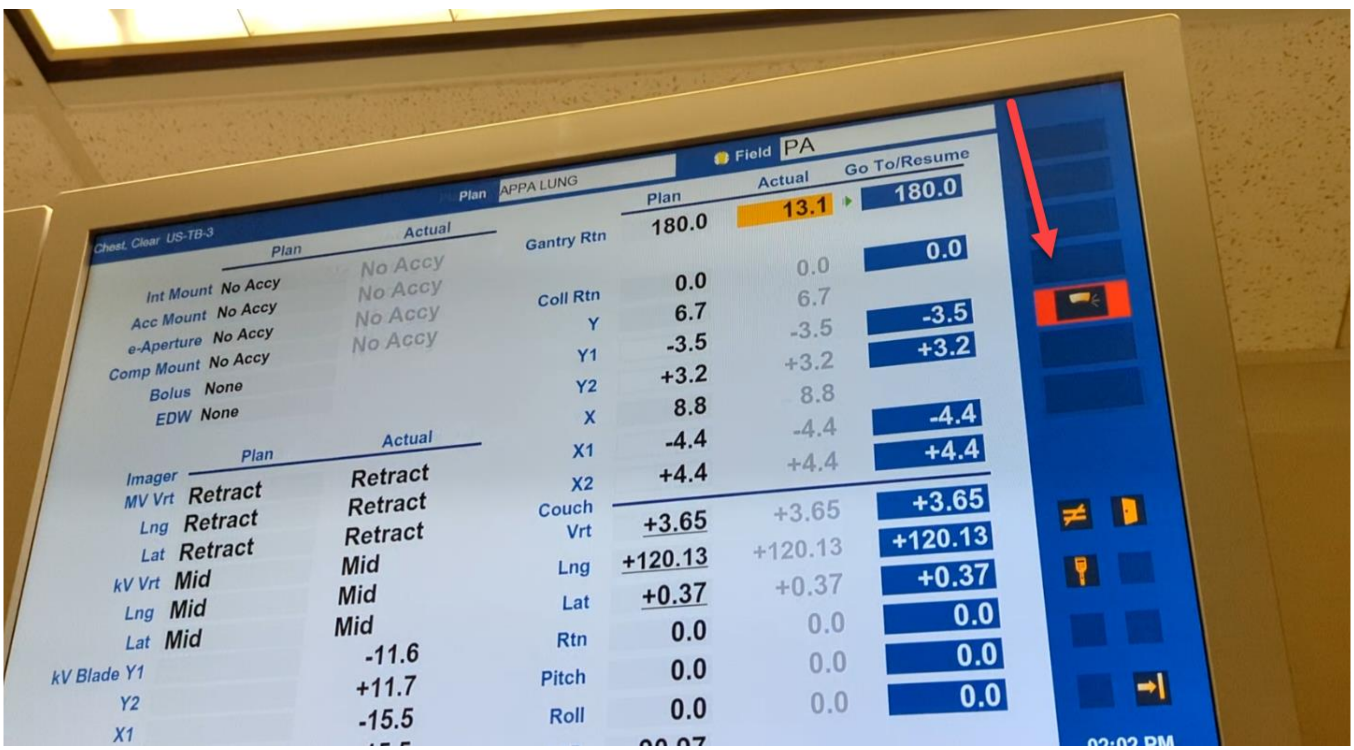

Figure 37: Patient Protection Interlock Alert

Participants were instructed to examine the clearance between the gantry and the simulated patient after the patient protection stop occurred. In this scenario, the gantry was positioned close to the patient's elbow; however, the participant determined that no imminent collision would occur. Based on this assessment, participants were introduced to the collision reset feature as a method for continuing the dry run under careful visual observation as shown in Figure 37.

Participants were directed to identify the collision reset button on the couch side panel, which appeared red after the patient protection alert was triggered. To activate collision reset, participants were required to perform three actions simultaneously: squeeze and hold the motion enable bars, press and hold the collision reset button, and use the controller or hand pendant control to manually rotate the gantry through the collision area. During this process, the gantry initially moved slowly while passing through the patient protection collision zone. An audible signal indicated when the gantry cleared the collision area, after which gantry motion resumed at normal speed and continued to the planned 180-degree position.

After completing the dry run and successfully using the collision reset function, participants were instructed to exit the dry-run workflow. The simulation presented several exit options, including pressing Cancel on the hand pendant, returning to the console area and selecting Done, or using the left directional button on the hand pendant to navigate back to the Setup Notes tab. In this workflow, participants returned to the control room after the gantry reached 180 degrees and selected Done on the treatment workstation interface.

After completing the Patient Protection Dry Run module, participants concluded the final guided dry-run scenario within the VR training sequence. This module reinforced participants' understanding of the LINAC Motion Safety System, including how patient protection alerts are triggered, how collision risk is assessed through visual inspection, and how the collision reset function can be used to continue gantry motion when no imminent collision is identified.

Data Collection and Analysis

Data collection for the study was designed to capture multiple dimensions of training effectiveness, including knowledge acquisition, learner perception, procedural performance, clinical readiness, efficiency, error patterns, and qualitative learner feedback. Fifteen multiple-choice questions were used for the pre-training, post-training, and retention assessments. These questions were designed to evaluate participants' understanding of the core concepts, procedural steps, and safety-related knowledge associated with the training scenario. To reduce test-order effects and minimize memorization bias, both the questions and answer options were randomized across assessment administrations. This approach helped ensure that changes in assessment scores more accurately reflected learning and retention rather than simple recall of question order.

In addition to the knowledge assessments, forty learning effectiveness questions were administered using a five-point Likert scale. These questions were used to capture the learner's perspective on the training experience, including perceived usefulness, confidence, usability, engagement, clarity of instruction, and preparedness for clinical workflow execution. The Likert-scale structure allowed participants to provide standardized responses that could be analyzed quantitatively while still reflecting subjective learner experience. This was particularly important for comparing how participants perceived the value of different training modalities and for understanding whether the training supported confidence and readiness in addition to knowledge gain.

Procedural performance was assessed using a binary performance checklist, which documented whether participants completed each required workflow step correctly or incorrectly. This checklist provided an objective measure of task execution and allowed the study to evaluate whether learners could translate training into observable procedural performance. In parallel, an expert rating rubric was used to assess broader dimensions of clinical performance, including technical accuracy, workflow fluency, error recognition, clinical judgment, and overall competence. Time to completion and error rates were also recorded to provide additional quantitative indicators of efficiency, workflow control, and performance reliability during the simulated clinical task.

The study also included three open-ended questions focused on participants' VR experiences, perceived strengths of the training system, barriers or limitations encountered, and suggestions for future improvement. These qualitative responses allowed participants to describe aspects of the training experience that may not have been fully captured through structured survey items. In particular, the open-ended questions provided insight into usability challenges, comfort issues, perceived realism, workflow clarity, and opportunities to improve future versions of the VR training platform.

During data preparation, all collected data were reviewed for validity, completeness, and consistency prior to analysis. Responses were checked to identify missing values, duplicate entries, incomplete submissions, and any inconsistencies across assessment records. The dataset was then structured and formatted to support analysis using tools such as Python and R scripts. This preparation step ensured that the quantitative and qualitative data could be organized systematically, cleaned appropriately, and analyzed in a reproducible manner.

Data analysis involved triangulating findings across multiple data sources to generate a comprehensive understanding of training effectiveness. Descriptive statistics were first calculated for all quantitative variables, including means, standard deviations, medians, ranges, frequencies, and percentages as appropriate. Knowledge assessment scores from the pre-test, post-test, and retention test were analyzed to evaluate learning gains and durability of knowledge over time. Between-group comparisons of knowledge scores for the VR and Traditional 2D cohorts were conducted using independent-samples *t*-tests or Welch's *t*-tests when group variances were unequal. Within-group changes from pre-test to post-test and from post-test to retention were analyzed using paired-samples *t*-tests. Effect sizes were calculated using Cohen's *d* or Hedges' *g* to estimate the magnitude of observed differences.

Likert-scale survey responses were analyzed using descriptive statistics, including item-level means, standard deviations, and response distributions. Because Likert-scale data are ordinal, group differences between the VR and Traditional 2D cohorts were evaluated using nonparametric Mann-Whitney *U* tests when comparing individual Likert items. Where multiple items were combined into composite constructs, such as confidence, preparedness, usability, or perceived learning effectiveness, internal consistency was assessed using Cronbach's alpha, and composite mean scores were compared between groups using independent-samples *t*-tests or Welch's *t*-tests, depending on variance assumptions.

Procedural performance checklist scores were analyzed as both total scores and item-level completion rates. Total checklist scores were treated as continuous performance outcomes and compared between the VR and Traditional 2D cohorts using Welch's *t*-tests, with effect sizes calculated to quantify the magnitude of group differences. Individual checklist items were binary scored as correct or incorrect; therefore, item-level completion rates were summarized as frequencies and percentages. Between-group differences for individual checklist items were examined using chi-square tests of independence or Fisher's exact tests when expected cell counts were small.

Expert rating rubric scores were analyzed at both the domain level and overall score level. Each expert rating domain, including technical accuracy, workflow fluency, error recognition, clinical judgment, and overall competence, was summarized using means and standard deviations. Between-group comparisons of domain scores, expert total scores, and expert mean scores were conducted using Welch's *t*-tests because the VR and Traditional 2D cohorts had unequal sample sizes and potentially unequal variances. Effect sizes were reported using Hedges' *g* to account for sample-size differences. Completion time and objective error counts were also analyzed using descriptive statistics and compared between cohorts using Welch's *t*-tests. When error count distributions were skewed, nonparametric sensitivity analyses using Mann-Whitney *U* tests were considered to confirm the robustness of group comparisons.

Associations among key outcomes were examined using correlation analyses. Pearson correlation coefficients were used when variables were approximately continuous and normally distributed, such as confidence composite scores and expert mean ratings. Spearman rank-order correlations were used when variables were ordinal, skewed, or count-based, such as Likert-scale confidence scores and objective error counts. These analyses were used to examine whether self-reported confidence and preparedness were aligned with objective indicators of performance, including error count, completion time, checklist score, and expert-rated competence.

Open-ended responses were analyzed using thematic analysis. Responses were reviewed, coded, and grouped into recurring themes related to perceived benefits, barriers, usability, learning value, and recommendations for future improvement. Frequencies were calculated for each theme to describe how often major concepts appeared across participant responses. Qualitative findings were then used to contextualize and interpret the quantitative results, particularly in relation to learner experience, usability barriers, perceived realism, confidence development, and transfer of training.

All statistical tests were interpreted using a significance threshold of $p < .05$. Where appropriate, 95% confidence intervals were reported alongside *p*-values and effect sizes to support interpretation of both statistical significance and practical significance. By integrating knowledge scores, Likert-scale perceptions, procedural checklist outcomes, expert ratings, completion time, error rates, and open-ended responses, the analysis examined what learners knew, what they could do, how well they performed clinically, and how they experienced the training intervention.

CHAPTER 3: RESULTS

Pilot Study

Results

The results indicated in Table 4 that the VR-based radiation oncology education module was associated with meaningful improvement in participant knowledge. A total of 32 participants completed both the pre-assessment and post-assessment. The average pre-assessment score was 12.38 out of 25, while the average post-assessment score increased to 18.84 out of 25. This represented an average improvement of 6.43 points. The improvement suggests that participants gained knowledge after engaging with the VR learning environment.

Table 4: Summary of Assessment Scores

Statistics	Pre-Assessment Score	Post-Assessment Score	Improvement
Count	32	32	32
Mean	12.38	18.84	6.43
Standard Deviation	2.74	2.38	3.66
Minimum	8	13	0
25th Percentile	10.75	18	3
Median	12	19	7
75th Percentile	14	21	9
Maximum	19	23	13

The distribution of scores also supported the finding of improved learning. The standard deviation for the pre-assessment was 2.74, while the standard deviation for the post-assessment was 2.38. This indicates that post-assessment scores were not only higher on average but also slightly more consistent across participants. The minimum pre-assessment score was 8, compared with a minimum post-assessment score of 13. The maximum score increased from 19 on the pre-assessment to 23 on the post-assessment. The median score rose from 12 before the VR intervention to 19 after the intervention. The 25th percentile increased from 10.75 to 18, and the 75th percentile increased from 14 to 21. These changes show that improvement occurred across the score distribution, not only among a few high-performing participants.

The box-and-whisker plot shown in Figure 38 visually confirmed this improvement. The post-assessment scores showed a higher median and an upward shift in the quartiles compared with the pre-assessment scores. This supported the quantitative conclusion that the VR module improved participants' understanding of radiation oncology topics.

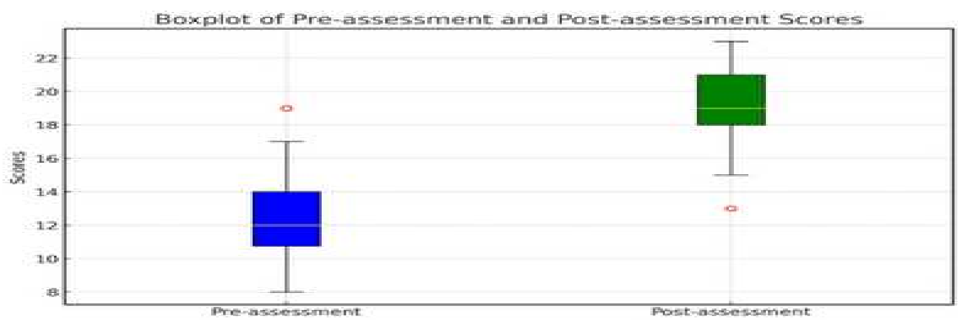

Figure 38: Pre and Post assessment scores

The study also examined the number of attempts required for participants to achieve mastery as shown in Figure 39. Although the attempt-analysis table included only a subset of participants, the results suggested that several participants reached the mastery threshold with very few attempts. Some participants achieved mastery in one attempt, while others required two or three attempts. This finding was interpreted as evidence that the VR module may support rapid learning and efficient knowledge acquisition. The histogram of attempts further illustrated that many participants were able to grasp the material with relatively few attempts, reinforcing the idea that VR can be an effective educational format.

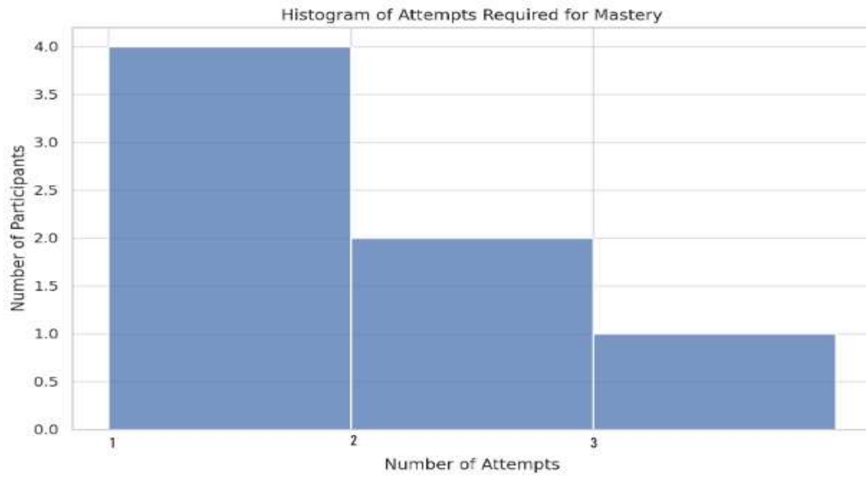

Figure 39: Histogram of attempts for mastery

Qualitative feedback was generally positive. Participants described the VR learning experience using favorable terms such as “great” and “very positive.” Many participants appreciated the clarity and quality of the content, noting that it was thorough enough to communicate the necessary information without being overly long. This suggests that the module’s pacing and content depth were appropriate for introductory radiation oncology education.

Participants also identified areas for improvement. Some recommended making the visual environment more closely resemble a hospital or clinical radiation therapy setting to improve realism. Others suggested adding a glossary or acronym reference to help learners understand technical terminology. Usability feedback included difficulty angling the camera or reading signs, which indicates that the VR interface could be refined to improve navigation and accessibility.

Overall VR experience ratings ranged from 3 to 5, with many participants giving the highest rating of 5. Participants also reported a strong likelihood of using VR for education in the future, with responses overwhelmingly at the highest level. These findings suggest high learner acceptance and perceived value of VR as an educational tool. Please see Figure 40 for more details.

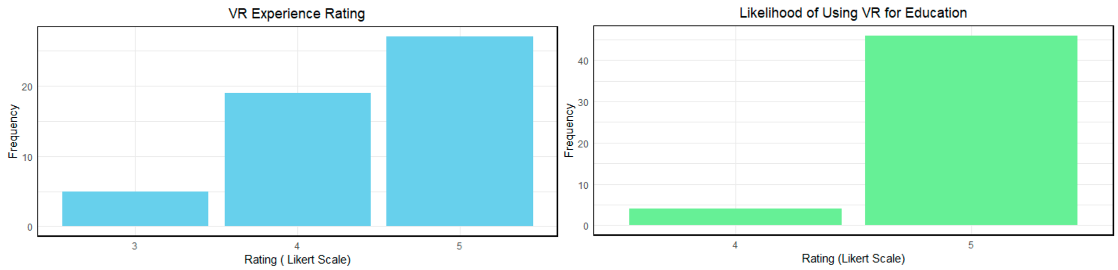

Figure 40: Participants' Feedback Scores

In summary, the results showed that the VR space improved knowledge scores, supported rapid mastery for several participants, and was generally well received by users. The pilot study provides preliminary evidence that VR can be a useful, accessible, and engaging educational method for radiation oncology training. However, the findings are based on a relatively small sample and short-term assessment, so larger comparative studies would be needed to confirm long-term effectiveness and compare VR directly with traditional training methods.

This pilot study was significant because it established the initial feasibility, educational value, and learner acceptability of using a virtual reality environment for radiation oncology training before advancing to a more rigorous comparative study. By demonstrating measurable improvement between pre-assessment and post-assessment scores, the pilot provided preliminary evidence that VR-based instruction could support knowledge acquisition in radiation oncology concepts, LINAC familiarity, patient setup, treatment workflow, and treatment delivery principles. Equally important, participant feedback suggested that the VR environment was engaging, usable, and perceived as a valuable educational tool, while also identifying areas for refinement, including environmental realism, navigation, terminology support, and interface usability. These findings helped validate the VR platform as a credible training modality and informed the design of the subsequent comparative 2D versus VR study. Specifically, the pilot clarified which learning objectives, assessment items, usability factors, and performance indicators should be retained or strengthened in the main thesis. As a result, the pilot study served as a foundational step that transformed the research from an exploratory proof-of-concept into a structured comparative investigation, enabling the main study to evaluate whether immersive 3D VR training offers measurable advantages over traditional 2D instructional methods in skill acquisition, confidence, usability, knowledge retention, and procedural preparedness.

Main Study

A total of sixty-six participants completed the study. Forty were assigned to the immersive 3D VR cohort and twenty-six to the traditional 2D cohort. Demographic distributions were broadly balanced across gender and training condition, as shown in Table 5. Participants received a standardized orientation before beginning any training activity. Randomization assigned each participant to one cohort only, ensuring that performance could be attributed to the training modality rather than repeated exposure to both methods.

Table 5: Participant demographics by training modality

Training Type	Female, n (%)	Male, n (%)	Total, n (%)
3D VR	17 (42.5%)	23 (57.5%)	40 (60.6%)
Traditional 2D	14 (53.8%)	12 (46.2%)	26 (39.4%)
Total	31 (47.0%)	35 (53.0%)	66 (100%)

The results are presented in three aligned subsections corresponding to the research questions. Although each subsection emphasizes a different conceptual domain, the findings should be interpreted together because the same pattern recurs across cognitive, procedural, psychological, and usability-related measures. In brief, immersive VR consistently outperformed traditional 2D instruction on the metrics most relevant to clinical readiness: larger knowledge gains, better retention, stronger procedural execution, higher expert ratings, lower error frequency, faster task completion, and more positive but also more performance-calibrated trainee perceptions. Figure 41 shows a VR training session in progress.

Figure 41: Active VR Experience

RQ 1: Skill acquisition and competency development

Research Question 1 investigated whether immersive VR enhances skill acquisition and competency development compared to traditional 2D training. The answer was consistently affirmative across all objective indicators. Baseline knowledge scores were comparable between the two cohorts, indicating that participants entered the study with similar starting competency. Following training, however, the VR cohort demonstrated much larger gains in knowledge assessment performance than the traditional cohort. The average post-minus-pre gain was 5.98 points in the VR group versus 2.15 points in the 2D group. Importantly, this advantage was largely preserved at the retention interval, where the VR group maintained a mean gain of 5.73 points compared with 2.00 points in the 2D group.

The triangulated competency outcomes are summarized in Table 6. The pattern suggests that immersive VR supports a more integrated form of learning in which conceptual understanding, procedural memory, and situated execution reinforce one another rather than remaining disconnected. This is exactly the type of educational outcome expected when learners can repeatedly enact workflows in context instead of trying to infer three-dimensional action from static instructional materials.

Table 6: Triangulated competency outcomes by training type

Outcome	3D VR (n=40) M (SD)	Traditional 2D (n=26) M (SD)	Welch t(df)	p-value	Cohen's d
SC0 Gain (Post–Pre)	5.98 (2.84)	2.15 (2.54)	5.70 (57.72)	< .001	1.40
SC0 Gain (Ret–Pre)	5.73 (3.10)	2.00 (2.50)	5.38 (60.92)	< .001	1.29
Checklist Total (0–10)	8.85 (1.25)	6.88 (1.53)	5.46 (45.87)	< .001	1.44

Outcome	3D VR (n=40) M (SD)	Traditional 2D (n=26) M (SD)	Welch t(df)	p-value	Cohen's d
Expert Mean (1–5)	4.24 (0.19)	3.32 (0.25)	16.24 (43.30)	< .001	4.34
Time to Complete (min)	17.43 (2.83)	26.22 (3.85)	−10.02 (42.31)	< .001	−2.69
Error Count	0.88 (0.91)	3.00 (1.33)	−7.15 (40.25)	< .001	−1.95

A particularly important aspect of RQ1 is that the gains were broad rather than narrow. The simplified comparative synthesis in Table 7 shows that VR outperformed the conventional condition on immediate learning, retained learning, procedural completion, expert competence, efficiency, and error reduction. This breadth reduces the likelihood that the results are an artifact of one favorable metric. Instead, the evidence suggests that immersive VR accelerates the transition from declarative understanding to applied competency.

Table 7: Comparative analysis of instructional modalities

Outcome Measure	VR 3D	Traditional 2D	Direction of Effect	Evidence Interpretation
Pre → Post Knowledge Gain	Higher mean gain	Lower mean gain	VR > 2D	VR training produced greater immediate learning gains
Retention Score	Higher	Lower	VR > 2D	VR-supported learning was retained over time
Procedural Checklist Completion	Higher % tasks completed	Lower %	VR > 2D	VR trainees demonstrated superior procedural competence

Outcome Measure	VR 3D	Traditional 2D	Direction of Effect	Evidence Interpretation
Expert Global Rating	Higher mean score	Lower mean score	VR > 2D	Experts rated VR trainees as more clinically competent
Time to Complete Tasks	Shorter	Longer	VR < 2D	VR training improved procedural efficiency
Error Rate	Lower	Higher	VR < 2D	VR training reduced procedural errors

The visual evidence in Figure 42 through Figure 46 deepens this interpretation. Figure 42 shows the knowledge journey over time. Both groups begin at approximately the same baseline, but the VR cohort rises more sharply and retains much more of that gain at follow-up. Figure 43 focuses on one of the mechanisms that likely underlies this advantage: spatial understanding. Participants trained in VR overwhelmingly agreed that the training helped them understand spatial relationships in the treatment area, whereas the 2D group showed much more disagreement. Figure 44 shows that experts rated VR trainees substantially higher across competency domains. Figure 46 further indicates that procedural execution in the VR group was not only better on average but also more consistent across participants, with a tighter distribution of checklist scores.

Figure 42 serves as the longitudinal evidence of cognitive encoding and memory durability. Utilizing a randomized 15-point assessment, this metric evaluates participants across three critical phases: baseline (Pre-test), immediate acquisition (Post-test), and the longitudinal decay phase (4-week Retention). While both cohorts exhibited statistically equivalent baseline knowledge scores, with the 3D VR group scoring 6.93 and the Traditional 2D group scoring 6.88 on the pre-test, the 3D VR group demonstrated substantially greater immediate knowledge gains after training. Specifically, the VR cohort increased from 6.93 at baseline to 12.88 on the post-test, representing an absolute gain of 5.95 points. In contrast, the Traditional 2D cohort increased from 6.88 to 9.04, representing a smaller gain of 2.16 points. More importantly, the VR cohort sustained most of this improvement at delayed retention, with a retention score of 12.63, corresponding to a retained gain of 5.70 points above baseline and only a 0.25-point decrease from the post-test score. The Traditional 2D cohort showed a retention score of 8.88, corresponding to a retained gain of 2.00 points above baseline and a 0.16-point decrease from the post-test score. Although both groups showed relatively small declines from post-test to retention, the VR cohort maintained a substantially higher level of retained knowledge overall, with a retention advantage of 3.75 points over the Traditional 2D cohort. These findings suggest that the immersive spatial mapping and active procedural rehearsal inherent in VR may support deeper encoding and more durable knowledge retention than static didactic instruction, thereby reducing the common pedagogical challenge of limited transfer from short-term learning to sustained clinical understanding.

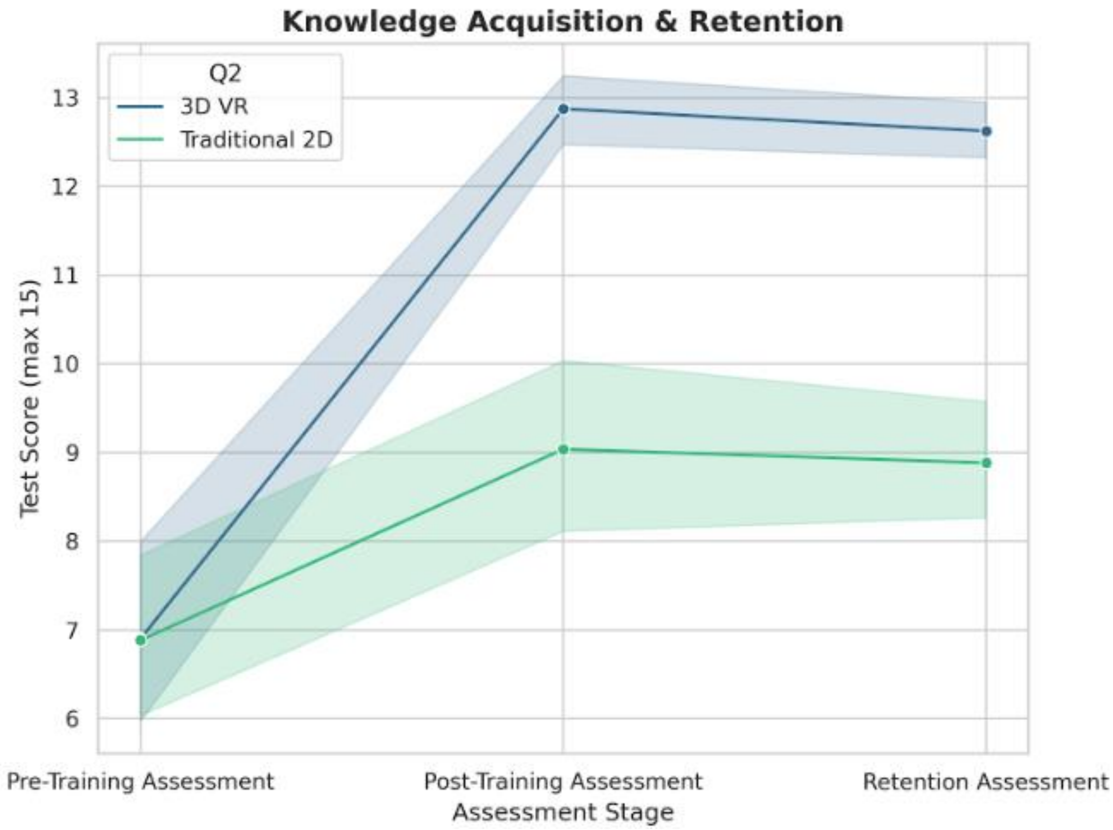

Figure 42: Knowledge journey analysis by training modality

From an educational standpoint, the RQ1 findings indicate that immersive VR is particularly effective because it supports mental model formation in a way that conventional instruction struggles to match. Learners can connect what they see, where they stand, what the machine does, and what action should come next. This reduces abstraction at the moment of encoding and likely helps explain the stronger retention trajectory. By the time trainees confront the physical LINAC, they are not encountering the workflow as an unfamiliar real-world translation problem; they are recognizing a sequence they have already enacted in context.

Figure 43 illustrates clear differences between the 3D VR and Traditional 2D training cohorts in perceived understanding of spatial relationships within the treatment area. A strong majority of participants in the VR cohort reported positive agreement, with 46.2% selecting

Agree and 53.8% selecting Strongly Agree, indicating near-unanimous endorsement of VR's effectiveness for spatial understanding. Notably, no VR participants expressed disagreement, suggesting a consistently positive learning experience. In contrast, responses in the Traditional 2D cohort were substantially more polarized. While some participants reported agreement (20.8%) or strong agreement (16.7%), a majority expressed disagreement, with 58.3% selecting Disagree and an additional 4.2% selecting Strongly Disagree. These findings suggest that VR training is markedly more effective than Traditional 2D instruction in supporting trainees' comprehension of three-dimensional spatial relationships critical to radiation therapy workflows. The results align with the immersive and embodied nature of VR, which enables learners to visualize and interact with spatial structures in ways that are difficult to replicate using two-dimensional training materials.

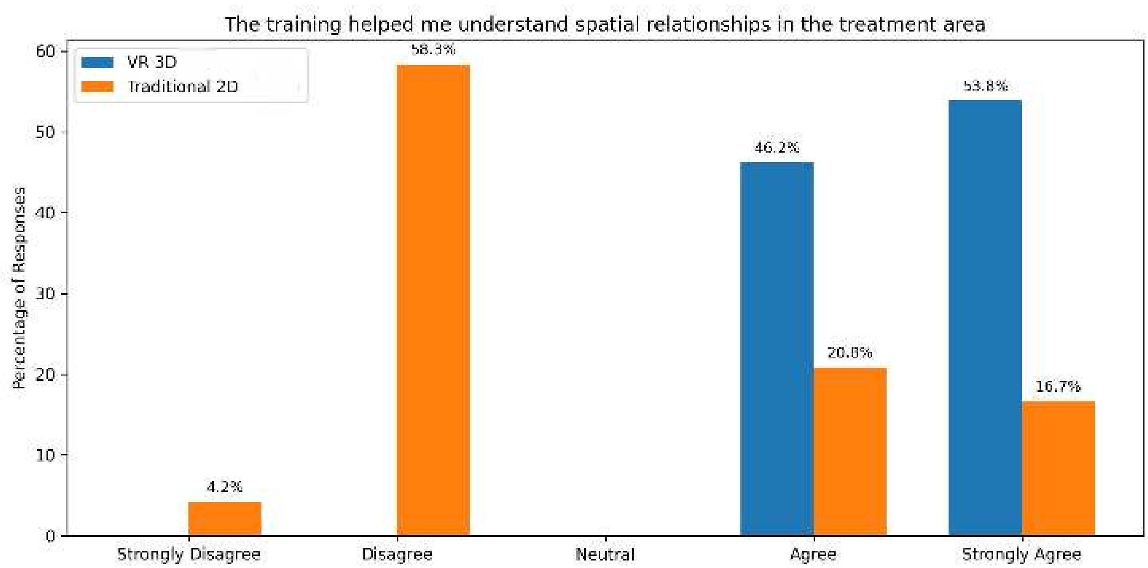

Figure 43: Perceived impact of training modality on spatial understanding

Across the full set of RQ1 outcomes, the most defensible conclusion is that immersive VR substantially improves radiation therapy skill acquisition and competency development relative to the traditional 2D didactic approach used in this study.

The results in Figure 44 demonstrate a statistically significant difference in expert-rated clinical competency between the 3D VR and Traditional 2D cohorts. The 3D VR group achieved a higher overall expert mean rating than the Traditional 2D group, with scores of 4.24 versus 3.32 on the 5-point rubric, respectively. This 0.92-point mean difference was tested using Welch's independent-samples *t*-test because the groups had unequal sample sizes and potentially unequal variances. The difference was statistically significant, $t(45.87) = 16.32$, $p < .001$, 95% CI [0.81, 1.03], with a very large effect size, Hedges' $g = 4.34$. Domain-level results also favored the VR cohort, particularly for Workflow Fluency, where the VR group scored 4.30 compared with 3.04 for the Traditional 2D group, and Clinical Judgment, where the VR group scored 4.30 compared with 3.23. These findings support the conclusion that VR training did more than improve basic technical knowledge; it was associated with stronger clinical execution, smoother workflow progression, and improved judgment during safety-critical task performance. Therefore, the observed "competency signature" reflects statistically supported differences in expert-rated performance rather than a purely descriptive interpretation of the figure.

Figure 44: Expert competence rating by training type

Figure 45 illustrates the distribution of total procedural checklist scores for participants trained using 3D VR compared with Traditional 2D instruction. The VR cohort demonstrated consistently higher performance, with median scores clustered near the upper end of the scale and a narrower interquartile range, indicating both stronger procedural competency and reduced variability across trainees. In contrast, the Traditional 2D cohort exhibited lower median scores and greater dispersion, including lower minimum values, suggesting less consistent mastery of required procedural steps. The presence of fewer low-performing outliers in the VR group further indicates that immersive training supported more uniform procedural readiness, reinforcing the finding that VR enhances reliable execution of clinical workflows

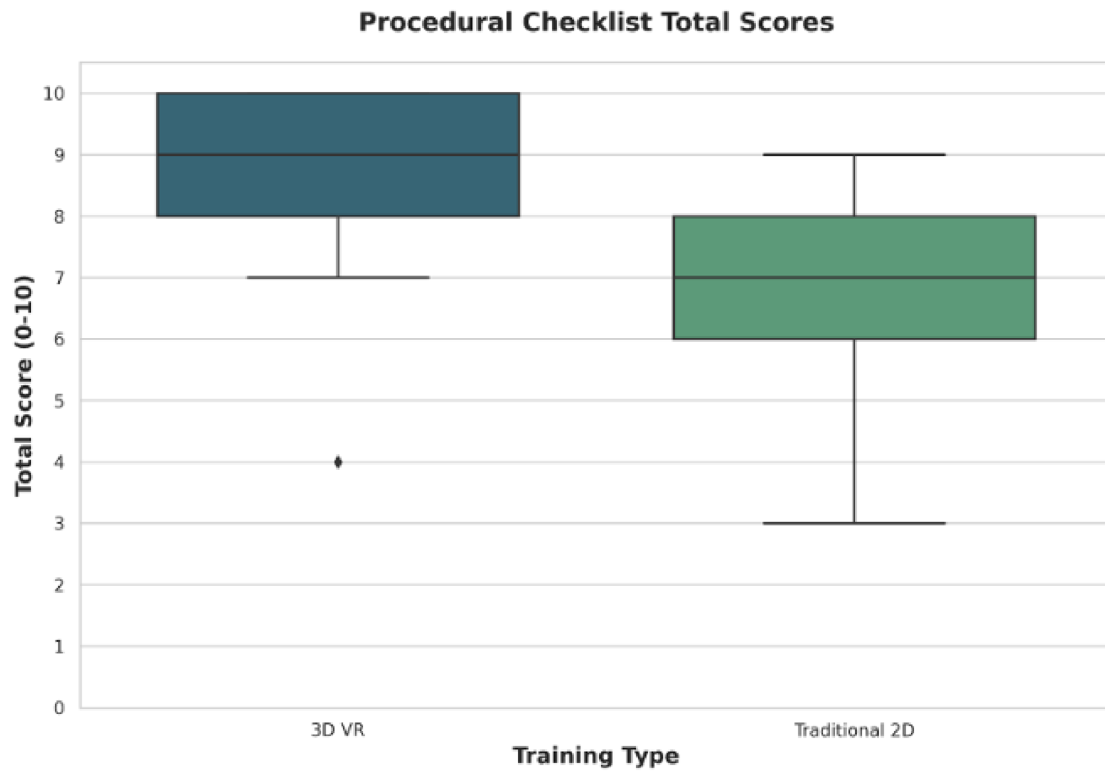

Figure 45: Distribution of procedural checklist scores by training modality

RQ 2: Confidence and preparedness for clinical practice

Research Question 2 examined whether immersive VR enhances confidence and preparedness for real-world clinical scenarios. Again, the results strongly favored the immersive modality. The confidence question is important because readiness in radiation therapy is not purely technical. Trainees must enter the treatment environment with enough assurance to act decisively and safely, but that assurance must be grounded in actual competence rather than unsupported optimism.

The subjective training-effectiveness results in Table 8 indicate that the 3D VR cohort reported significantly stronger psychological readiness across all measured domains compared with the Traditional 2D cohort. Perceived Preparedness showed the largest practical separation, with the VR group reporting a mean score of 4.62 (SD = 0.40) compared with 3.22 (SD = 0.65) in the Traditional 2D group. This 1.40-point difference on a 5-point scale was statistically significant, Welch's $t = 9.85$, $p < .001$, with a very large effect size, Cohen's $d = 2.58$. This finding suggests that participants who trained in VR left the intervention feeling substantially more prepared to perform the clinical workflow than those trained using static 2D materials.

Instructional Effectiveness followed a similar pattern. The VR cohort reported a mean score of 4.75 (SD = 0.38), compared with 3.45 (SD = 0.82) in the Traditional 2D cohort. The between-group difference was statistically significant, Welch's $t = 7.92$, $p < .001$, with a large effect size, Cohen's $d = 2.05$. This indicates that learners perceived VR as a more effective instructional modality, likely because it provided a more interactive, spatially realistic, and procedurally contextualized training experience.

Ease of Use was also significantly higher in the VR group, although the magnitude of the difference was smaller than for preparedness and instructional effectiveness. VR participants reported a mean score of 4.48 (SD = 0.52), while Traditional 2D participants reported a mean score of 3.88 (SD = 0.74). This difference was statistically significant, Welch's $t = 3.64$, $p < .001$, with a moderate-to-large effect size, Cohen's $d = 0.94$. Although VR systems can introduce usability challenges such as headset comfort and controller familiarity, these results suggest that participants still found the VR training environment easier to use or more supportive of learning than the Traditional 2D format.

Cognitive Comfort showed another large and statistically significant difference. The VR cohort reported a mean score of 4.55 (SD = 0.50), compared with 2.95 (SD = 0.88) in the Traditional 2D cohort. This 1.60-point difference was statistically significant, Welch's $t = 8.65$, $p < .001$, with a very large effect size, Cohen's $d = 2.24$. This result is particularly important because cognitive comfort reflects the extent to which learners felt mentally supported rather than overwhelmed during the transition from instruction to task execution. The higher VR score suggests that immersive, spatially organized simulation may have reduced cognitive fragmentation by allowing learners to connect procedural steps directly with the treatment-room environment and LINAC workflow.

Across all four metrics, the p-values were less than .001, indicating that the probability of observing differences of this magnitude by chance, assuming no true difference between groups, was very low. Therefore, the results provide strong statistical evidence that the VR training intervention produced higher self-reported preparedness, perceived instructional effectiveness, ease of use, and cognitive comfort than Traditional 2D instruction. The accompanying Cohen's d values further indicate that these were not only statistically significant differences, but also educationally meaningful effects, particularly for preparedness, instructional effectiveness, and cognitive comfort.

Table 8: Training effectiveness survey results across key psychological domains

Metric	3D VR Mean (SD)	2D Mean (SD)	Welch's t	P-value	Cohen's d
Perceived Preparedness	4.62 (0.40)	3.22 (0.65)	9.85	< .001	2.58
Instructional Effectiveness	4.75 (0.38)	3.45 (0.82)	7.92	< .001	2.05
Ease of Use	4.48 (0.52)	3.88 (0.74)	3.64	< .001	0.94
Cognitive Comfort	4.55 (0.50)	2.95 (0.88)	8.65	< .001	2.24

Those subjective gains aligned with objective performance markers. As shown in Table 9, participants trained in VR achieved higher expert ratings, faster task completion, and fewer observable errors. In other words, they not only felt more prepared, but also behaved in ways consistent with greater preparedness. This alignment matters because self-reported confidence can be misleading when separated from performance evidence. In the present study, however, the confidence gains appear to have been earned.

Table 9: Objective performance indicators of confidence and preparedness

Outcome	3D VR (n=40) M (SD)	2D (n=26) M (SD)	Welch t(df)	P-value	Cohen's d
Expert Mean Rating (1–5)	4.24 (0.19)	3.32 (0.25)	16.24 (43.30)	< .001	4.34
Time to Complete (min)	17.43 (2.83)	26.22 (3.85)	−10.02 (42.31)	< .001	−2.69
Error Count	0.88 (0.91)	3.00 (1.33)	−7.15 (40.25)	< .001	−1.95

The relationship between subjective confidence and observed safety provides a particularly important insight. Correlation analysis revealed a moderate negative association between self-confidence and objective error count, meaning that higher confidence was associated with fewer errors rather than more. This is shown in Figure 48 and supports the interpretation that immersive VR fostered calibrated self-efficacy. Rather than inflating self-perception in the absence of skill, the training helped participants develop a realistic sense of readiness grounded in successful execution.

Figure 46, Figure 47, and Figure 49 show complementary aspects of this psychological advantage. Figure 46 demonstrates that overall trainee perception and confidence were markedly higher in the VR cohort than in the traditional cohort. Figure 47 shows stronger and more consistent self-reported ratings across confidence, preparedness, and effectiveness constructs for

VR. Figure 48 reinforces that even when confidence is measured subjectively, its distribution looks less variable and less fragile in the immersive group. This suggests that VR may reduce the number of learners who leave training still uncertain about their ability to function in the treatment room.

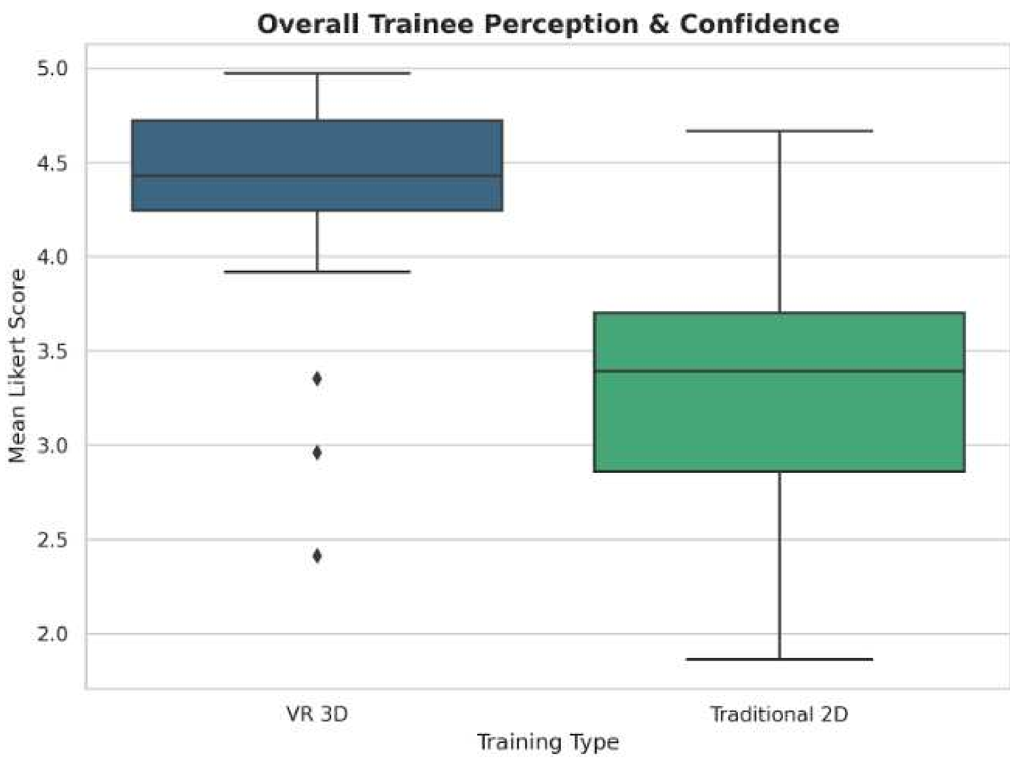

Figure 46: Overall trainee perception and confidence by training modality

The open-ended feedback deepens this interpretation. Participants did not always explicitly say "I am more confident," but they repeatedly used terms such as familiarity, comfort, recognition, realism, and workflow clarity. These are functionally important expressions of confidence because they indicate reduced uncertainty during execution. A trainee who recognizes the bunker layout, understands where to stand, and remembers what should happen next is likely to behave with greater decisional fluency and lower hesitation.

Figure 47: Self-reported perception across confidence, preparedness, and effectiveness

From a clinical education perspective, confidence and preparedness are especially valuable when they shorten the gap between initial instruction and supervised contribution in the real setting. The RQ2 findings imply that immersive VR may help trainees enter physical practice with stronger mental rehearsal, clearer orientation, and a more stable belief that they can execute required tasks safely. Because the psychological outcomes align with expert evaluation, time efficiency, and error reduction, the study supports the conclusion that VR enhances real-world preparedness rather than merely perceived preparedness.

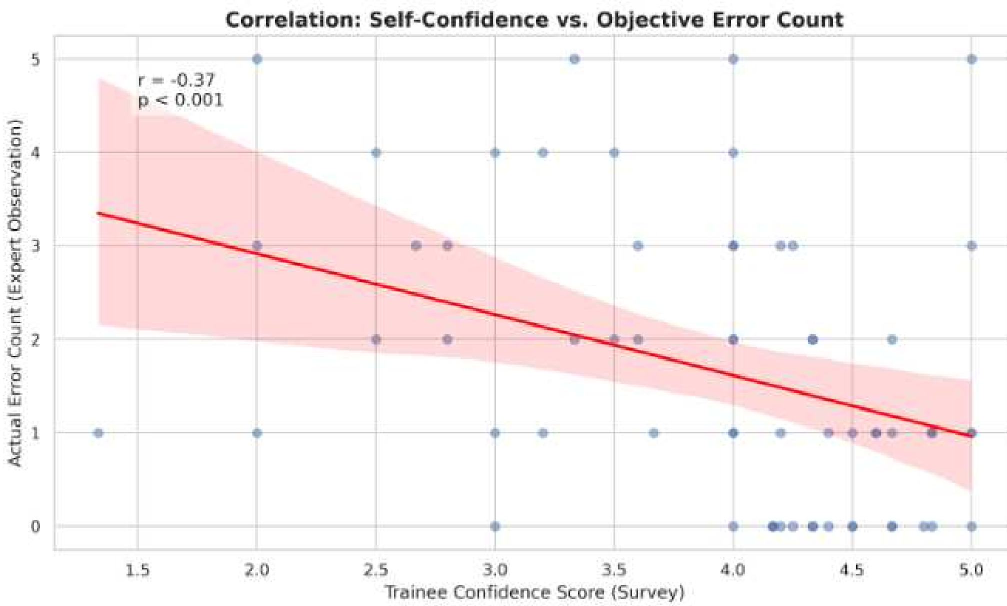

Figure 48: Correlation between self-confidence and objective error count

RQ 3: Translation to clinical performance, usability, and delayed stability

Research Question 3 moved beyond immediate learning and preparedness to ask whether immersive VR translates into precise and reliable clinical performance during hands-on execution, and how usability factors support or constrain that translation. This question is critical because a training method may increase understanding without yielding dependable performance on actual equipment. The present findings suggest that immersive VR does translate effectively, particularly for spatially complex and safety-critical procedural steps.

As supporting evidence, the longitudinal knowledge pattern remained stronger for the VR cohort at delayed assessment. Table 10 shows the qualitative summary of knowledge retention across time points, and Figure 48 shows the corresponding trajectory visually. The VR group demonstrated a larger immediate post-training increase and only minimal decline at follow-up, whereas the 2D group showed a shallower increase and more evident regression. This pattern indicates that the immersive modality supported more durable encoding of the workflow and its underlying concepts.

Table 10: Knowledge retention across time

Assessment Time Point	3D VR	Traditional 2D
Pre-training	Comparable baseline	Comparable baseline
Post-training	Higher than 2D	Lower than VR
Retention (2–4 weeks)	Stable with minimal decay	Decline with greater variability

More importantly, delayed practical performance remained stronger in the immersive group. Table 11 summarizes retained procedural performance and efficiency at delayed assessment, showing that VR-trained participants continued to achieve higher expert-rated competence, shorter completion time, and lower error count. The p-values in Table 11 represent the probability of observing between-group differences of this magnitude, or larger, if there were truly no difference between the 3D VR and Traditional 2D cohorts. Across all three retained performance outcomes, the p-values were less than .001, indicating that the observed differences were statistically significant and highly unlikely to be due to random sampling variation alone.

Specifically, the VR cohort achieved a higher expert global rating than the Traditional 2D cohort, with mean scores of 4.24 versus 3.32, respectively, and this difference was statistically significant, $p < .001$. VR-trained participants also completed the task more efficiently, requiring an average of 17.43 minutes compared with 26.22 minutes in the Traditional 2D cohort, $p < .001$. Finally, the VR cohort demonstrated fewer objective errors, with an average error count of 0.88 compared with 3.00 in the Traditional 2D cohort, $p < .001$. These results indicate that the retained advantage of VR training was not limited to one performance dimension; rather, it was consistently observed across clinical competence, workflow efficiency, and safety-related performance.

Figure 49 visually reinforces these retained differences. The persistence of statistically significant differences at delayed assessment weakens the argument that the observed effect was merely a novelty response to new technology. Instead, the findings suggest that immersive VR training supported more durable procedural performance and more reliable translation of training into hands-on clinical execution.

Table 11: Retained procedural performance and efficiency at delayed assessment

Outcome Measure	3D VR Mean (SD)	Traditional 2D Mean (SD)	P-value
Expert global rating	4.24 (0.19)	3.32 (0.25)	< .001
Task completion time (minutes)	17.43 (2.83)	26.22 (3.85)	< .001
Error count	0.88 (0.91)	3.00 (1.33)	< .001

Usability findings help explain why the immersive system was effective while also pointing to practical design refinements. Open-ended feedback, summarized in Figure 51, showed that realism/immersion, pace and time efficiency, workflow clarity, and the desire for additional scenarios were among the most commonly discussed themes. Participants valued the ability to experience the room as if they were there, to understand sequence through action rather than abstract description, and to feel continuity between training and physical execution. These usability-related benefits are not superficial. They are directly tied to how learners convert instruction into action.

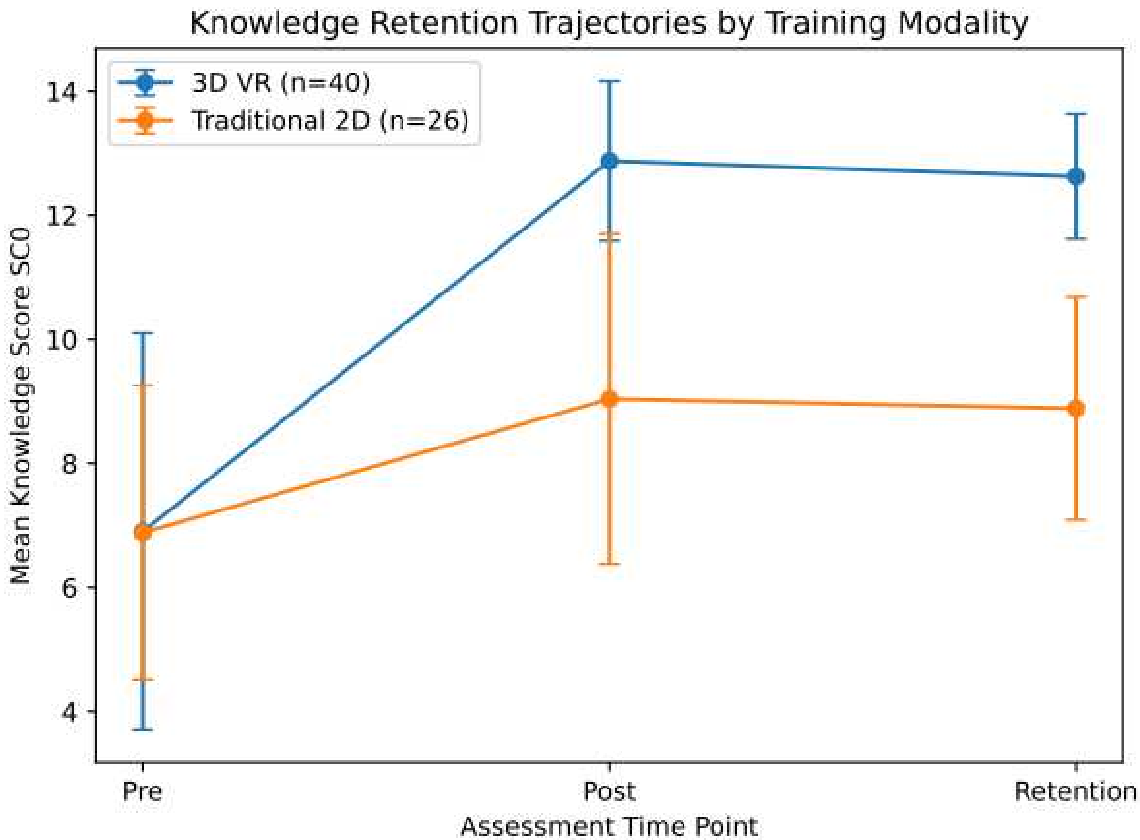

Figure 49: Knowledge retention trajectories by training modality

The step-level precision evidence is especially revealing. Figure 50 presents a heatmap of procedural failure rates by step, comparing VR-trained and traditionally trained participants. The largest between-group gaps occurred in steps such as isocenter setup, collision reset, gantry motion, navigate field, and protective stop handling. These are precisely the sorts of tasks in which spatial understanding, bodily positioning, and dynamic anticipation matter. By contrast, tasks that are more rule-based and less spatially demanding showed smaller differences. This pattern strongly supports the interpretation that immersive VR provides its greatest advantage where conventional 2D explanation leaves learners to perform too much mental reconstruction.

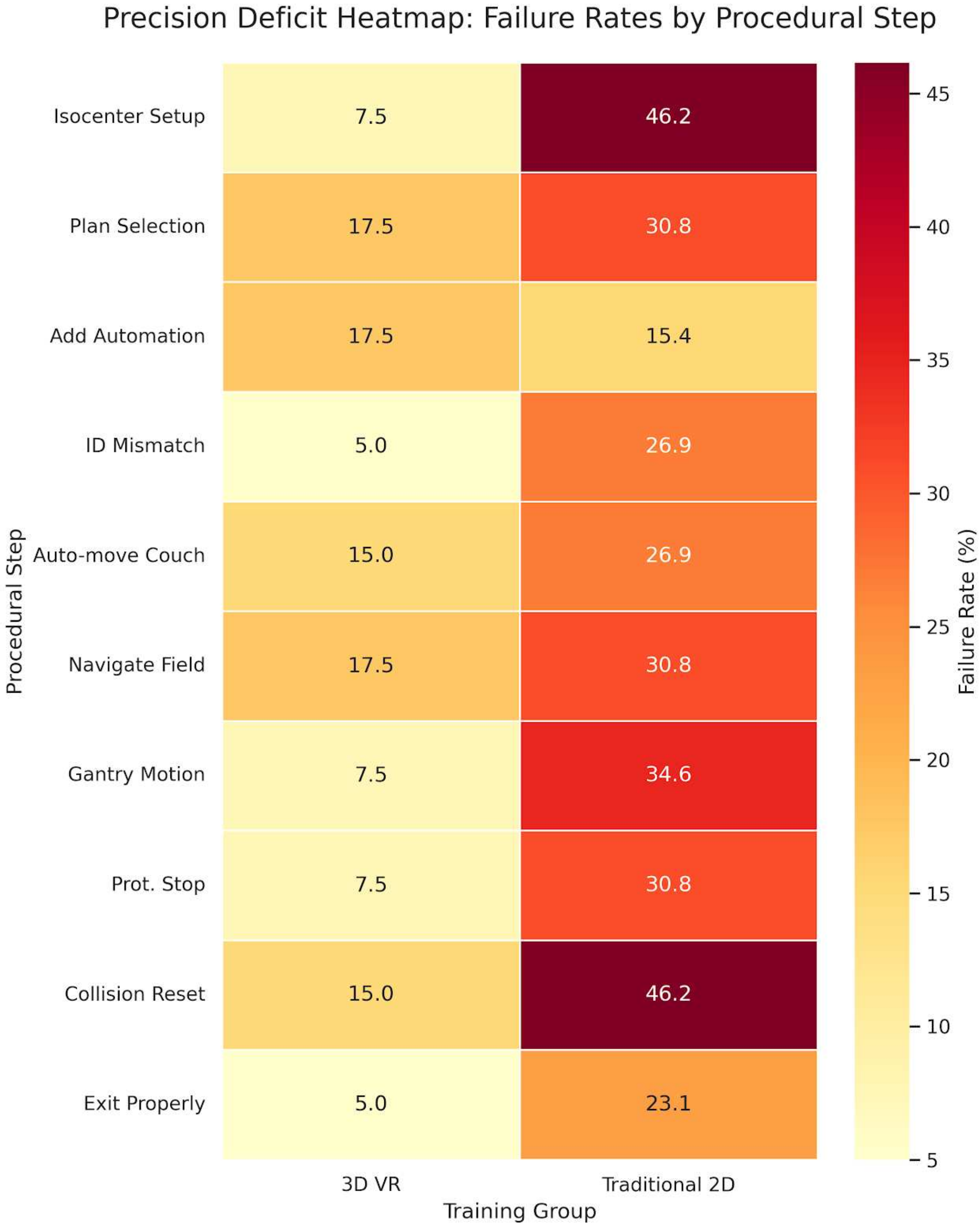

Figure 50: Precision deficit heatmap: failure rates by procedural step

At the same time, VR participants noted several practical barriers as shown in Figure 51. The most common involved headset weight and physical comfort during longer sessions, occasional Wi-Fi or system interruptions, and a short learning curve associated with controller interaction. Importantly, respondents generally described these as transitional or ergonomic constraints rather than fundamental flaws in the instructional design. Many noted that the controller barrier faded quickly with practice, suggesting that modest onboarding improvements could further strengthen the training experience without changing the core simulation. Study did not asked open-ended questions because these are not applicable to 2D cohort.

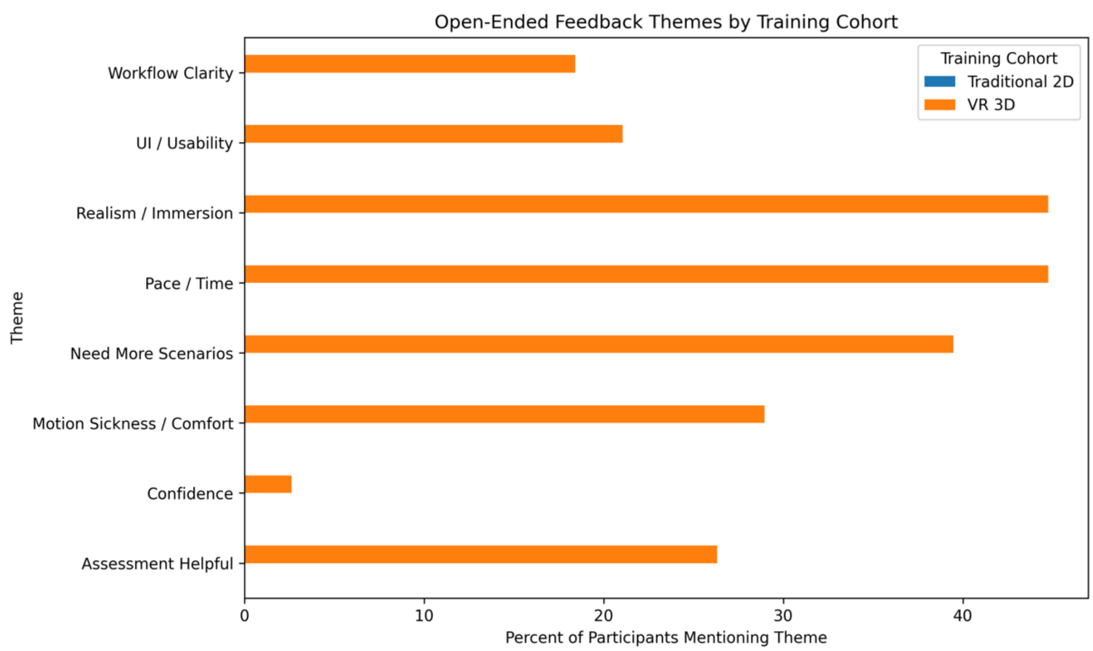

Figure 51: Open-ended feedback themes by training cohort

The RQ3 findings therefore support a nuanced conclusion. Immersive VR translated effectively into better real-world execution, and the most important usability characteristics were those that supported presence, recognition, and continuity between learning and acting as shown in Figure 52. The main design limitations identified by users were practical implementation issues that did not negate the instructional benefit of the platform. In a systems engineering sense, this is encouraging: the underlying educational mechanism appears sound, while the remaining barriers are refinements rather than failures.

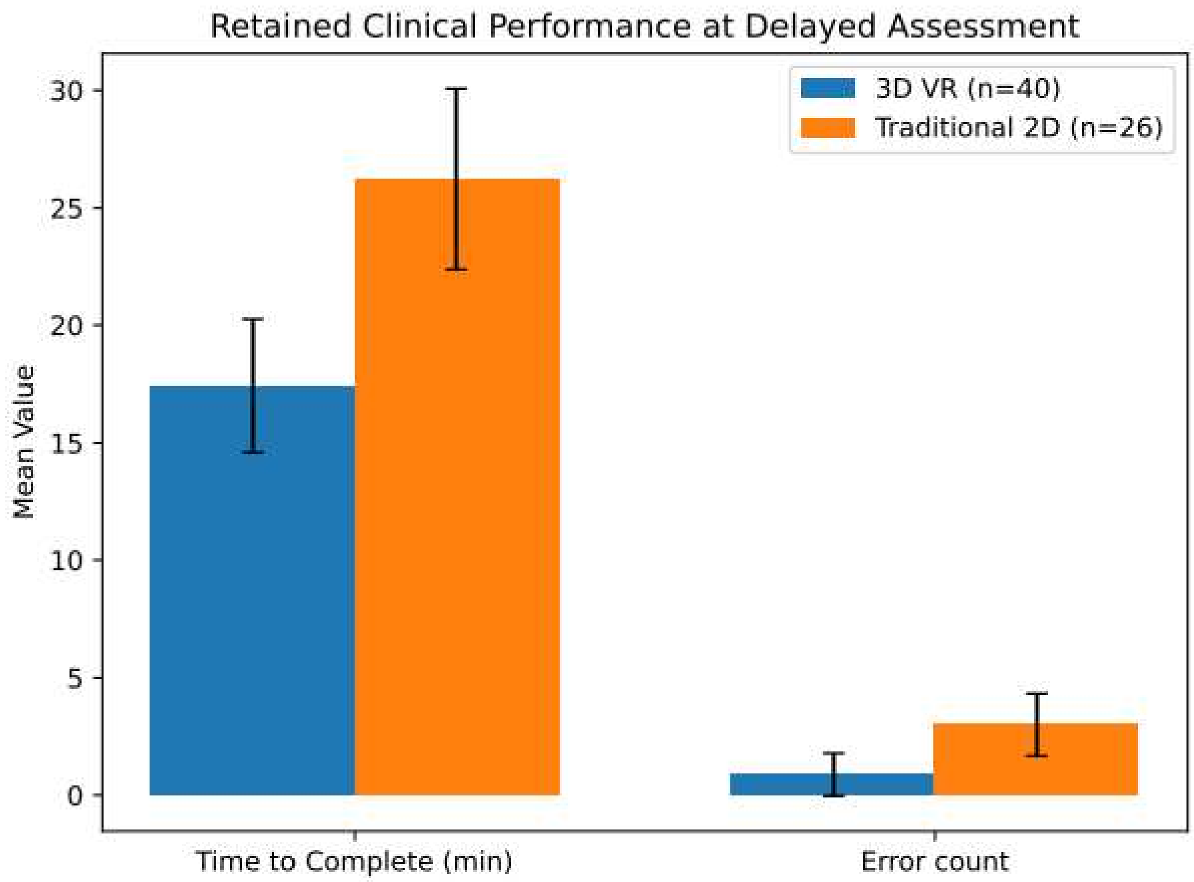

Figure 52: Retained clinical performance at delayed assessment

Taken together, the delayed performance evidence, precision analysis, and usability feedback position immersive VR as a modality that not only teaches but transfers. The simulation helped learners arrive at the physical LINAC with more stable schemas, more reliable execution patterns, and fewer step-level deficits in the very tasks most closely linked to safe clinical performance.

Summary of Procedural Performance Checklist Results

Procedural performance was assessed using a 10-item binary checklist designed to evaluate whether participants could correctly execute key workflow steps in the radiation therapy dry-run and collision-management scenario. Each checklist item was scored as 0 when the step was incorrect or not performed and 1 when the step was performed correctly, yielding a total procedural performance score ranging from 0 to 10 for each participant. The checklist captured core procedural tasks spanning patient setup, treatment plan selection, automation, mismatch recognition, couch auto-move, navigation to the first treatment field, gantry motion observation, protection-stop acknowledgement, collision reset, and appropriate dry-run exit. A total of 66 participants were included in the procedural performance analysis, with 40 participants assigned to the 3D VR training cohort and 26 participants assigned to the Traditional 2D training cohort.

Overall, participants trained using the 3D VR modality demonstrated higher procedural performance than those trained using the Traditional 2D modality. The 3D VR cohort achieved a mean checklist score of 8.85 out of 10 with a standard deviation of 1.25, compared with a mean score of 6.88 out of 10 with a standard deviation of 1.53 in the Traditional 2D cohort. This represents an absolute mean difference of approximately 1.97 checklist points in favor of the VR-trained participants. The median score was also higher in the 3D VR group, with a median of 9.0 compared with 7.0 in the Traditional 2D group. The score range further illustrates the performance separation between groups. VR participants scored between 4 and 10, while Traditional 2D participants scored between 3 and 9. Importantly, the highest possible score of 10 was achieved by 14 participants in the 3D VR cohort, representing 35.0% of that group, whereas no participant in the Traditional 2D cohort achieved a perfect score. The summary is visualized in Figure 53.

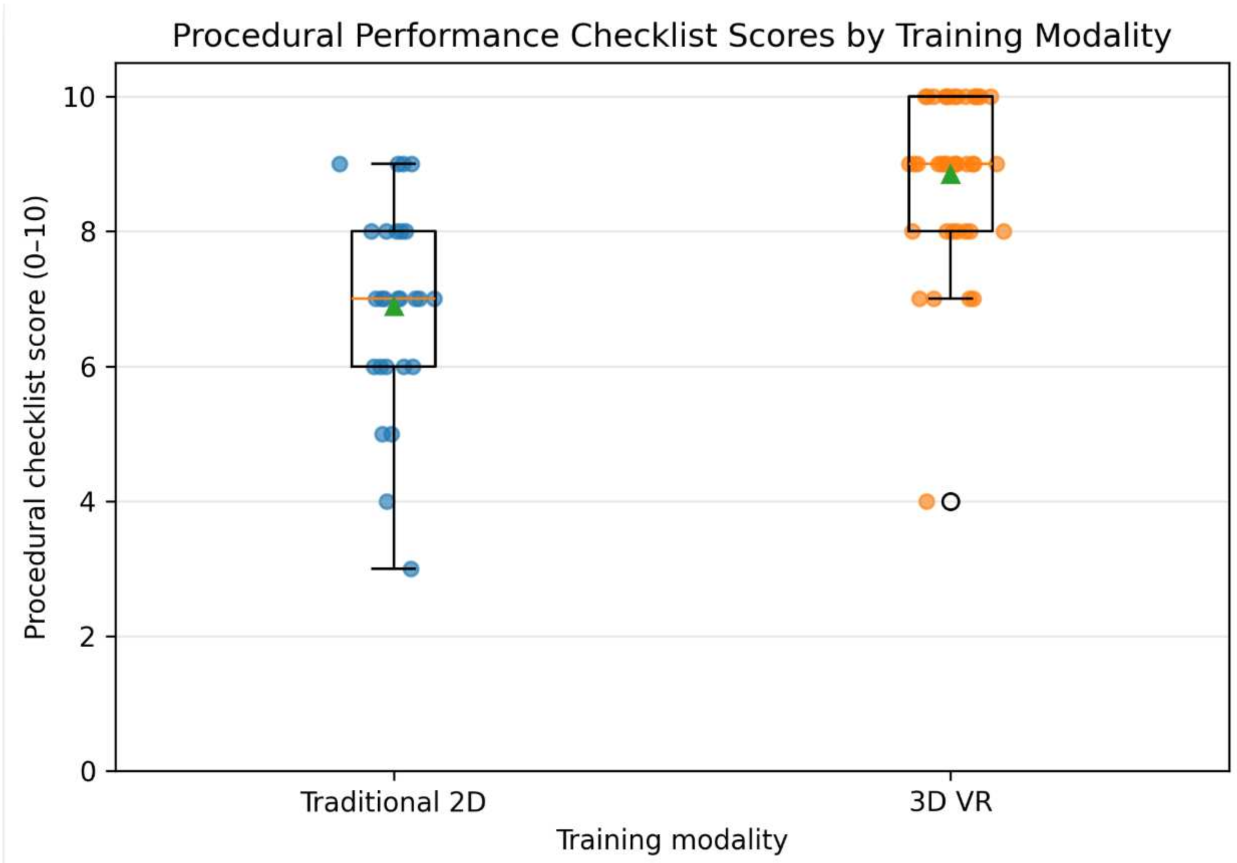

Figure 53: Scores by Training Modality

The distribution of scores suggests that VR training supported more consistent high-level procedural execution. In the 3D VR cohort, 28 of 40 participants, or 70.0%, achieved a score of 9 or 10. By contrast, only 4 of 26 participants, or 15.4%, in the Traditional 2D cohort achieved a score of 9, and none achieved a score of 10. Lower scores were more common in the Traditional 2D cohort. Seventeen of 26 participants, or 65.4%, scored 7 or below, compared with only 5 of 40 participants, or 12.5%, in the 3D VR cohort. These findings indicate that VR training was associated not only with a higher average performance score but also with a greater concentration of learners near the upper end of the performance scale.

Welch's independent-samples *t*-test was selected to compare procedural checklist scores between the 3D VR and Traditional 2D cohorts because the groups had unequal sample sizes, with 40 participants in the VR cohort and 26 participants in the Traditional 2D cohort, and because equality of variance could not be assumed a priori. Welch's *t*-test is appropriate for comparing two independent group means when sample sizes and/or variances differ, as it adjusts the degrees of freedom to provide a more robust test than the conventional Student's *t*-test under unequal variance conditions. The assumptions for Welch's *t*-test include independence of observations, a continuous or approximately continuous outcome, approximate normality of the outcome distribution within each group, and absence of extreme outliers. In this study, independence was satisfied because each participant contributed one checklist score and participants were assigned to only one training cohort. The procedural checklist total score was treated as an approximately continuous performance outcome ranging from 0 to 10. Group variability was comparable but not identical, with standard deviations of 1.25 for the VR cohort and 1.53 for the Traditional 2D cohort; therefore, Welch's test was preferred because it does not require the equal-variance assumption. The sample sizes were also sufficient for the test to be reasonably robust to modest deviations from normality.

An exploratory inferential comparison using Welch's *t*-test supported the observed difference between groups. The VR cohort achieved a higher mean procedural checklist score than the Traditional 2D cohort, with mean scores of 8.85 and 6.88, respectively. The mean difference was 1.97 points, with a 95% confidence interval of 1.24 to 2.69. This difference was statistically significant, Welch's $t(45.87) = 5.46$, $p < .001$. The standardized effect size was large, with Cohen's $d = 1.44$ and Hedges' $g = 1.42$. These findings indicate that the VR cohort performed significantly better on procedural task completion than the Traditional 2D cohort.

Although the results should be interpreted within the context of the study design and sample size, the magnitude and consistency of the effect suggest a meaningful educational advantage for immersive VR-based procedural training over conventional 2D instruction for this task sequence.

Item-level analysis provides additional insight into the procedural areas where VR training appeared most beneficial. The largest between-group difference was observed for confirming patient setup at isocenter. In the 3D VR group, 37 of 40 participants, or 92.5%, correctly completed this step, compared with 14 of 26 participants, or 53.8%, in the Traditional 2D group. This 38.7 percentage-point difference suggests that the spatial and embodied nature of VR training may have helped learners better understand and perform setup verification using room lasers and patient alignment cues. A similarly large difference was observed for performing the collision reset. In the VR cohort, 34 of 40 participants, or 85.0%, completed this step correctly, compared with 14 of 26 participants, or 53.8%, in the Traditional 2D group. This finding is particularly important because collision reset is a safety-critical task that requires learners to recognize the protection stop, understand the system state, and perform the correct recovery sequence.

VR participants also showed stronger performance on steps involving dynamic machine operation and situational monitoring. For starting gantry motion and observing for collision, 92.5% of VR-trained participants completed the task correctly, compared with 65.4% of Traditional 2D participants. For acknowledging the protection stop, the VR group again achieved 92.5% correct completion, compared with 69.2% in the Traditional 2D group. These differences suggest that VR may provide an advantage for tasks requiring real-time interaction, visual attention, and procedural sequencing under simulated clinical conditions. Because learners in the VR environment could rehearse machine movement, observe spatial relationships, and respond to system prompts, they may have developed a more operational understanding of how to manage treatment delivery interruptions.

The 3D VR cohort also outperformed the Traditional 2D cohort in identifying position mismatch, exiting the dry run properly, navigating to the first treatment field, and auto-moving the couch to the planned position. Position mismatch was correctly identified by 95.0% of VR participants compared with 73.1% of Traditional 2D participants. Exiting the dry run properly was completed by 95.0% of VR participants compared with 76.9% of Traditional 2D participants. Navigation to the first treatment field was completed correctly by 82.5% of VR participants compared with 69.2% of Traditional 2D participants. Auto-moving the couch to the planned position was completed by 85.0% of VR participants compared with 73.1% of Traditional 2D participants. These findings indicate that VR training supported stronger procedural continuity across both early setup steps and later machine-control steps.

The only checklist item where the Traditional 2D cohort performed slightly better was adding automation to the plan. In this step, 84.6% of Traditional 2D participants completed the task correctly compared with 82.5% of VR participants. This small difference suggests that some menu-based or instruction-driven tasks may be effectively taught through conventional didactic materials, particularly when the step is relatively discrete and rule-based. However, the broader pattern across the checklist indicates that VR offered a clear advantage for spatial, sequential, and safety-critical workflow components.

Taken together, the procedural checklist results demonstrate that 3D VR training was associated with superior procedural skill acquisition compared with Traditional 2D training as shown Figure 54. The VR-trained participants achieved higher total scores, showed less clustering in the lower-performance range, had a substantially higher proportion of near-perfect and perfect performances, and demonstrated stronger completion rates across most individual workflow steps. These findings support the use of immersive VR simulation as an effective training modality for radiation therapy workflows that require procedural sequencing, spatial awareness, machine interaction, and safety-oriented decision-making. In the context of radiation therapy education, where access to physical LINAC systems is limited and supervised practice opportunities may be constrained, VR-based training appears to provide a meaningful supplemental approach for preparing learners to perform complex clinical procedures with greater accuracy and confidence.

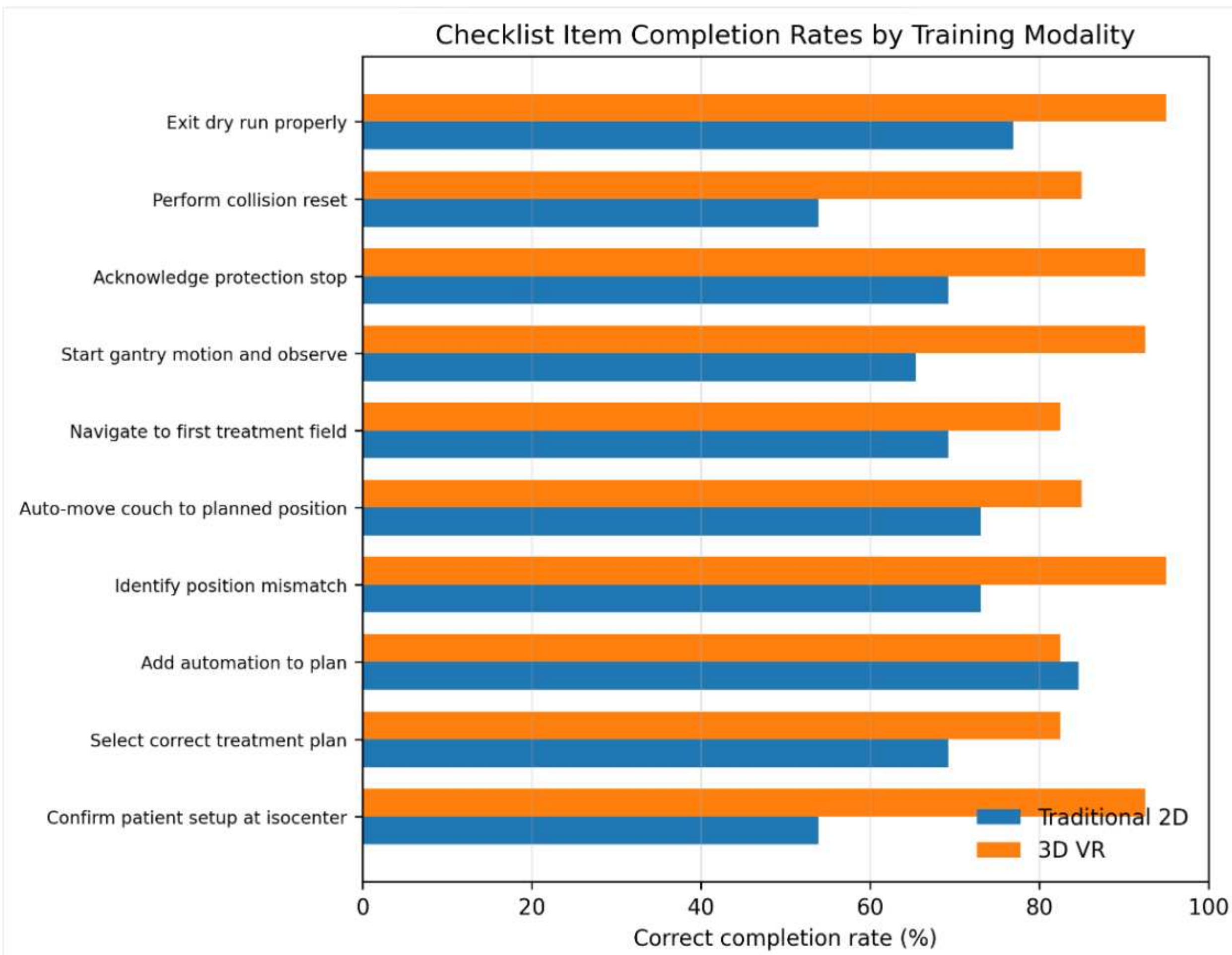

Figure 54: Task Completion rates by Training Modality

Summary of Expert Rating, Completion times and Error rates

Expert-rated clinical performance was evaluated using a five-domain global rating rubric designed to capture holistic clinical readiness after training. The rubric assessed Technical Accuracy, Workflow Fluency, Error Recognition and Correction, Clinical Judgment, and Overall Competence. Each domain was scored on a 5-point behaviorally anchored scale, where higher scores reflected stronger clinical performance and greater readiness for supervised or independent practice. Domain scores were summed to generate an Expert Total score ranging from 5 to 25, and an Expert Mean score ranging from 1 to 5. In addition to expert ratings, two objective performance measures were recorded: time to complete the clinical workflow and total error count. The analysis included 66 participants, with 40 participants in the 3D VR training cohort and 26 participants in the Traditional 2D training cohort. The results are shown in Figure 55.

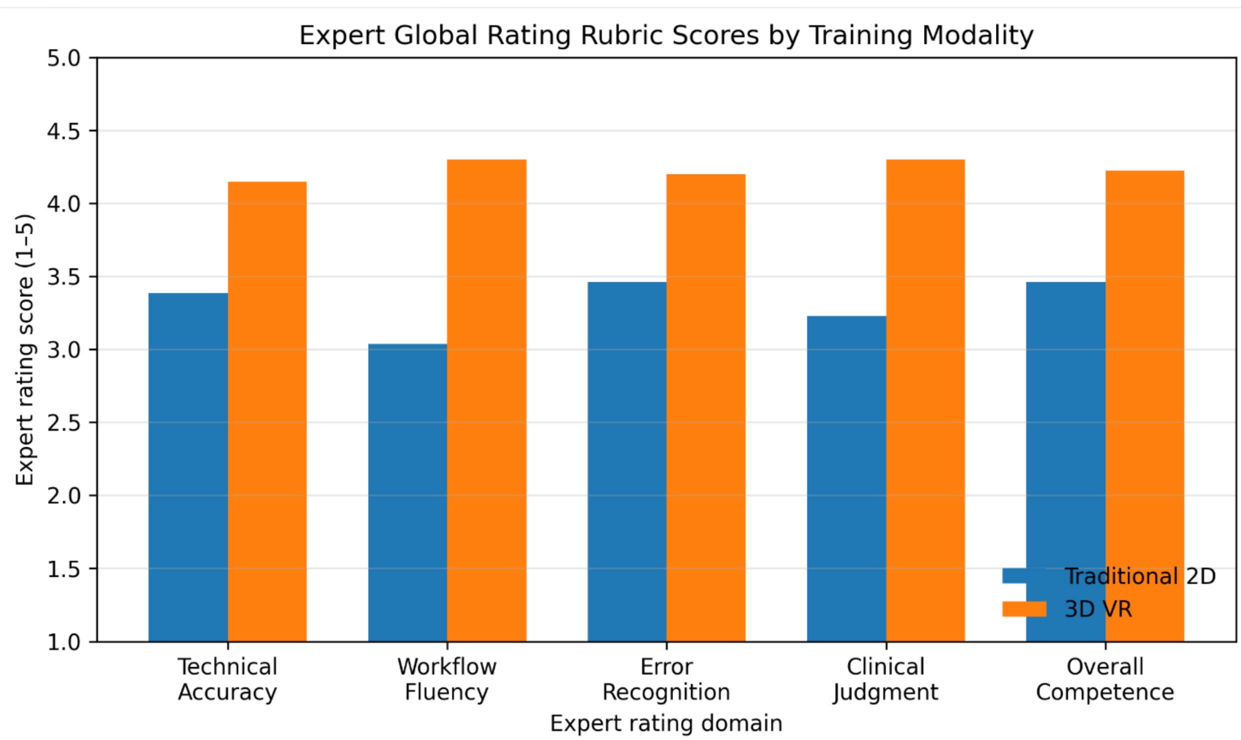

Figure 55: Expert Rating Scores by Training Modality

Overall, the 3D VR cohort demonstrated substantially stronger expert-rated performance than the Traditional 2D cohort. The VR group achieved a mean Expert Total score of 21.18 out of 25, compared with 16.58 in the Traditional 2D group. The corresponding Expert Mean score was 4.24 for VR participants and 3.32 for Traditional 2D participants. This represents a mean difference of 0.92 points on the 5-point expert rating scale in favor of VR training. The VR group also showed a narrower and higher performance range, with Expert Mean scores ranging from 4.0 to 4.6, whereas Traditional 2D scores ranged from 2.6 to 3.6. Notably, every participant in the VR cohort achieved an Expert Mean score of at least 4.0, while no participant in the Traditional 2D cohort reached this threshold. This pattern suggests that VR training was associated not only with higher average performance but also with a shift of the entire cohort toward clinically stronger performance levels.

Domain-level results further support the advantage of the 3D VR training condition. For Technical Accuracy, VR participants achieved a mean score of 4.15, compared with 3.38 in the Traditional 2D cohort. This indicates that VR-trained participants performed the required technical steps more accurately and with fewer deviations from the expected workflow. In Workflow Fluency, the VR group achieved a mean score of 4.30, compared with 3.04 in the Traditional 2D group. This was one of the largest domain-level differences and suggests that immersive rehearsal helped participants move through the clinical workflow more smoothly and with less hesitation. Because radiation therapy delivery depends on sequencing, spatial awareness, and timely recognition of system states, workflow fluency is a particularly relevant indicator of readiness for clinical practice.

The VR cohort also demonstrated stronger Error Recognition and Correction, with a mean score of 4.20 compared with 3.46 in the Traditional 2D cohort. This finding suggests that

VR training may have helped learners recognize procedural deviations or system prompts more effectively and respond with appropriate corrective actions. In Clinical Judgment, the VR group achieved a mean score of 4.30, compared with 3.23 for Traditional 2D. This domain is especially important because it reflects the learner's ability to make safe and appropriate decisions during a simulated clinical workflow. The fact that all VR participants scored 4 or higher in Clinical Judgment suggests that immersive simulation may be particularly valuable for developing safety-oriented decision-making under realistic workflow conditions. Finally, Overall Competence was higher in the VR cohort, with a mean score of 4.23 compared with 3.46 in the Traditional 2D group, indicating stronger perceived readiness for supervised clinical practice.

The proportion of participants achieving high domain scores also favored the VR cohort. In Technical Accuracy, 92.5% of VR participants scored 4 or higher, compared with 38.5% of Traditional 2D participants. In Workflow Fluency, 92.5% of VR participants scored 4 or higher, compared with only 19.2% of Traditional 2D participants. In Error Recognition and Correction, 90.0% of VR participants achieved a score of 4 or higher, compared with 53.8% in the Traditional 2D group. Clinical Judgment showed the most striking separation, with 100.0% of VR participants scoring 4 or higher, compared with 30.8% of Traditional 2D participants. For Overall Competence, 92.5% of VR participants scored 4 or higher, compared with 53.8% of Traditional 2D participants. These results indicate that VR training produced a larger proportion of learners rated as above the minimum competency threshold across all major clinical performance dimensions.

Objective performance measures showed a similar pattern. VR-trained participants completed the workflow faster than Traditional 2D participants. The mean completion time in the VR cohort was 17.43 minutes, compared with 26.22 minutes in the Traditional 2D cohort, representing an average reduction of 8.79 minutes. The median completion time was also lower in the VR group, at 17.4 minutes, compared with 26.3 minutes in the Traditional 2D group. The time range for VR participants was 10.9 to 23.3 minutes, whereas the Traditional 2D group ranged from 18.5 to 32.6 minutes. Thirty-three of 40 VR participants completed the workflow within 20 minutes, compared with only 1 of 26 participants in the Traditional 2D cohort. This suggests that VR training supported more efficient task execution, likely by allowing learners to rehearse the procedural sequence in a spatially realistic environment before assessment.

Error count results also favored the VR cohort. VR participants committed an average of 0.88 errors, compared with 3.00 errors in the Traditional 2D cohort. The median error count was 1 in the VR group and 3 in the Traditional 2D group. Sixteen VR participants completed the assessment with zero recorded errors, compared with only one participant in the Traditional 2D group. In the VR cohort, error counts ranged from 0 to 3, whereas the Traditional 2D group ranged from 0 to 5. The Traditional 2D cohort had a larger concentration of participants with multiple errors, including eight participants with three errors, five with four errors, and four with five errors. This distribution suggests that conventional 2D instruction may be less effective for reducing preventable procedural errors in complex machine-based workflows.

Exploratory inferential comparisons were conducted using Welch's independent-samples t-tests to evaluate between-group differences in expert-rated performance, task completion time, and objective error count. Welch's test was selected because the VR and Traditional 2D cohorts had unequal sample sizes and because the test does not require the assumption of equal variances between groups. As shown in Table 12, statistically significant differences favored the VR cohort across all retained performance outcomes.

Table 12 : Welch's t-test comparisons

Outcome Measure	3D VR Mean (SD)	Traditional 2D Mean (SD)	Mean Difference	Welch's *t*	df	95% CI for Difference	*p*-value	Hedges' *g*
Expert Mean Rating	4.24 (0.19)	3.32 (0.25)	0.92	16.32	45.87	0.81 to 1.03	< .001	4.34
Task Completion Time, minutes	17.43 (2.83)	26.22 (3.85)	−8.79	−10.02	42.30	−10.56 to −7.02	< .001	−2.66
Error Count	0.88 (0.91)	3.00 (1.33)	−2.13	−7.12	40.15	−2.73 to −1.52	< .001	−1.92

The VR cohort achieved a significantly higher Expert Mean score than the Traditional 2D cohort, with mean scores of 4.24 and 3.32, respectively. This 0.92-point difference on the 5-point expert rating scale was statistically significant, Welch's $t(45.87) = 16.32$, $p < .001$, 95% CI [0.81, 1.03], with a very large standardized effect size, Hedges' $g = 4.34$. Task completion time was also significantly lower in the VR cohort, with VR-trained participants completing the workflow 8.79 minutes faster on average than participants in the Traditional 2D cohort. This difference was statistically significant, Welch's $t \approx -10.02$, $p < .001$, 95% CI [−10.56, −7.02], with a large effect size, Hedges' $g = -2.66$. Error count was significantly lower in the VR group, with participants committing 2.13 fewer errors on average than the Traditional 2D group. This difference was also statistically significant, Welch's $t \approx -7.12$, $p < .001$, 95% CI [−2.73, −1.52], with a large effect size, Hedges' $g = -1.92$.

Collectively, these Welch's t-test results indicate that the descriptive performance advantages observed for the VR cohort were statistically supported. VR-trained participants were rated as more clinically competent, completed the workflow more efficiently, and committed fewer procedural errors than participants trained using Traditional 2D instruction.

Taken together, these findings demonstrate that the 3D VR training modality was associated with stronger expert-rated clinical performance, faster workflow completion, and fewer procedural errors compared with Traditional 2D training. The largest observed advantages were in workflow fluency, clinical judgment, completion time, and error reduction, all of which are central to clinical readiness in radiation therapy. These results suggest that immersive VR simulation may provide a meaningful training advantage by enabling learners to practice procedural sequencing, machine interaction, spatial reasoning, and safety-critical decision-making in a realistic but risk-free environment. For radiation therapy education, where access to physical LINAC systems is limited and clinical practice opportunities must be balanced against patient safety and operational constraints, VR-based training appears to be a promising supplemental approach for accelerating competency development and improving preparedness for real-world clinical workflows.

Thematic Analysis

Questions Q39 and Q40 of the training effectiveness survey shown in survey instruments captured qualitative feedback from participants regarding the perceived strengths and limitations of the VR training experience. Q39 asked participants what aspects of VR training they found most effective or beneficial, while Q40 asked what challenges or limitations they experienced while using the VR training system. After excluding blank responses and the Qualtrics header row, 38 usable Q39 responses and 34 usable Q40 responses were available for thematic review. The comments were analyzed using a multi-label thematic approach, meaning that a single response could contribute to more than one theme when it addressed multiple issues.

Question 39 Analysis

Overall, Q39 feedback was strongly positive and centered on the educational value of immersive, realistic, hands-on simulation. The most frequently identified benefit was immersion and realism, which appeared in 18 of 38 responses. Participants repeatedly described the VR environment as "immersive," "realistic," "almost real," and closely modeled after the real clinical environment. Several comments emphasized that the VR setup made participants feel as though they were physically present in the treatment room. This sense of presence appeared to be a major driver of perceived learning value. Participants reported that the 3D environment helped them visualize the LINAC, patient, couch, controls, and treatment room layout in a way that static 2D materials could not fully reproduce. One participant noted that entering the real room after VR felt familiar, suggesting that the simulation may have supported environmental orientation and transfer of learning.

A second major Q39 theme was hands-on interaction and active procedural practice, identified in 12 responses. Participants valued being able to "touch and feel," operate controls, use the joystick, hold down motion-enable buttons, navigate around the room, and actively perform the workflow rather than only reading or watching instructions. This feedback supports the argument that VR training provided experiential learning rather than passive content delivery. The interactive nature of the simulator helped participants engage with the clinical workflow as a sequence of actions, decisions, and system responses. This is particularly relevant for radiation therapy workflows, where procedural accuracy depends not only on knowing what should happen but also on performing steps in the correct order while observing machine and patient-positioning cues.

A third important benefit was spatial awareness and 3D visualization, reflected in 8 responses. Participants specifically noted that VR helped them understand the location of machine components, the size of the radiation machine, and the spatial relationship between the gantry, patient, couch, and controls. This is an important finding because radiation therapy procedures are highly spatial. Learners must understand room geometry, machine motion, patient alignment, and collision risk. The comments suggest that VR helped learners build a more complete mental model of the treatment environment, especially compared with traditional instructional materials that may flatten or fragment spatial information.

Participants also described VR as engaging, enjoyable, and focused, with 8 responses emphasizing that the system was fun, interesting, game-like, or reduced distractions. Several participants used enthusiastic language such as “loved it,” “awesome,” and “so much fun.” While enjoyment alone is not sufficient evidence of learning, engagement is important in training environments because it may increase attention, motivation, and willingness to repeat practice. One participant specifically noted that the immersive format limited distractions during training. This suggests that VR may create a protected learning space where learners are more fully focused on the task sequence.

Another theme in Q39 was knowledge transfer, retention, and confidence, observed in 7 responses. Participants stated that VR made it easier to translate knowledge, apply concepts, understand complex procedures, remember workflow steps, and build confidence. These comments align with the quantitative findings showing stronger procedural performance and expert-rated competence in the VR cohort. The qualitative data help explain why VR may have produced these outcomes: learners experienced the training as realistic, embodied, memorable, and directly connected to clinical practice.

Participants also valued guided workflows and instructional scaffolding, reflected in 5 responses. Comments highlighted clear instructions, guided workflows, good protocol documentation, and the ability to have instructions available while performing procedures. This suggests that learners appreciated having structured guidance embedded within the VR experience. Importantly, this theme connects directly to future design improvements. Guidance should remain available during early learning but should be adjustable or removable during assessment so independent performance can be measured.

A smaller but meaningful group of responses emphasized repeatability, convenience, and reduced dependence on physical machine access, reflected in 4 responses. Participants noted that VR allowed repeated workflow practice without physically resetting the machine, without occupying a treatment vault, and without using clinical machine time. This is one of the strongest educational and operational arguments for VR in radiation therapy training. Physical LINAC access is limited, expensive, and often prioritized for patient care. VR offers a way to increase practice opportunities without disrupting clinical operations. Two responses also emphasized the benefit of safe, low-pressure practice, noting that mistakes in VR do not risk machine functionality. This is important for safety-critical workflows because learners can rehearse errors, recovery steps, and uncommon events without patient or equipment risk.

Question 40 Analysis

Q40 feedback was more critical and identified the major barriers that should be addressed in future iterations. The most frequent limitation was lack of technical reliability, network instability, casting issues, glitches, freezing, crashing, and system slowness, appearing in 13 of 34 responses. Participants reported that casting stopped due to Wi-Fi issues, the app was unstable or slow, the system froze, tracking was inconsistent, and the application crashed. These issues disrupted the training flow and, in some cases, created confusion. This theme is important because technical interruptions can reduce immersion, increase frustration, and confound learning outcomes. For future studies, technical reliability should be treated as a measurable usability variable. The study protocol should log crashes, freezes, Wi-Fi/casting failures, tracking loss, latency, and reboot events.

The second major limitation was headset comfort, visual strain, and motion discomfort, identified in 10 responses. Participants described the headset as heavy, uncomfortable, difficult to position, and problematic for glasses. Some reported fogged glasses, eye strain, dizziness, or motion discomfort. One participant noted that sitting improved the experience. These comments indicate that physical ergonomics can directly affect training tolerance and perceived usability. Future studies should systematically capture headset comfort, visual clarity, corrective eyewear use, and simulator discomfort before and after training. Practical improvements may include lighter headsets, better strap adjustment, prescription inserts, anti-fog solutions, seated options, and shorter or segmented training sessions.

A third major Q40 theme was controller/input precision, button selection, and hand-pendant realism, also appearing in 10 responses. Participants reported difficulty learning controllers, hitting hotspots, completing the three-button sequence, using virtual controls, and interpreting hand-pendant states. One comment specifically noted that the virtual hand pendant did not replicate the light-up icons present on actual pendants, making collision interlock recovery more confusing. This is an important design finding because radiation therapy workflows require precise interaction with machine controls. Future VR development should improve input fidelity through clearer button affordances, more forgiving interaction zones, haptic feedback, controller training, and potentially a tracked physical hand-pendant device.

The fourth theme was learning curve, orientation, boundary setup, and navigation, reflected in 7 responses. Some participants needed time to get comfortable with the virtual environment, boundary condition, and basic controls. This suggests that VR unfamiliarity may initially compete with clinical learning. Future studies should include a standardized VR orientation module before the clinical training scenario. This orientation should teach basic movement, object selection, menu interaction, controller use, and safety boundary setup before participants begin the radiation therapy workflow.

Additional Q40 themes included limited guidance, feedback, and use-case breadth; visual fidelity and field-of-view limitations; and cognitive load or auditory distraction. Participants wanted more advanced clinical scenarios, better feedback, and more guidance when they had questions. Some noted that limited realism, image resolution, field of view, and system responsiveness reduced training impact. One detailed response described the combined burden of reading prompts, squeezing controls, pressing buttons, rotating the machine, and managing environmental noise, suggesting that some parts of the simulation increased cognitive load.

Taken together, Q39 and Q40 show a clear pattern. Participants perceived VR as highly valuable because it was immersive, realistic, spatially informative, hands-on, engaging, repeatable, and clinically relevant. However, its effectiveness was limited by lack of technical reliability, headset ergonomics, controller precision, VR learning curve, and insufficient guidance in moments of uncertainty. For the manuscript, these findings support the conclusion that VR is not merely a novel presentation format; it functions as an experiential learning environment that can support procedural understanding and clinical readiness. At the same time, the feedback identifies concrete design priorities for the next study: improve platform stability, reduce headset burden, enhance controller and hand-pendant fidelity, add a structured orientation period, provide adjustable guidance, expand clinical scenarios, and integrate real-time performance feedback.

Question 41 Analysis

Question Q41 asked participants, “How could the VR training system be improved to better meet your learning needs?” The responses provide valuable qualitative insight into how learners experienced the VR simulator and what refinements would make the system more effective for future radiation therapy training. A total of 38 nonblank Q41 responses were available for analysis, and all were from participants in the VR 3D cohort. The Traditional 2D cohort did not provide responses for this VR-specific question. The comments were reviewed thematically and grouped into several major categories: expansion of clinical use cases, real-time guidance and feedback, headset comfort and accessibility, controller and interaction improvements, orientation and workflow support, technical reliability, and study design refinements.

Figure 56 shows the thematic distribution of participant suggestions for improving the VR training system. Responses to Q41 were coded using a multi-label thematic approach. The most frequent recommendations focused on expanding clinical scenarios, adding audio/visual guidance, integrating real-time feedback and scoring, improving headset comfort, and refining controller or hand-pendant interactions.

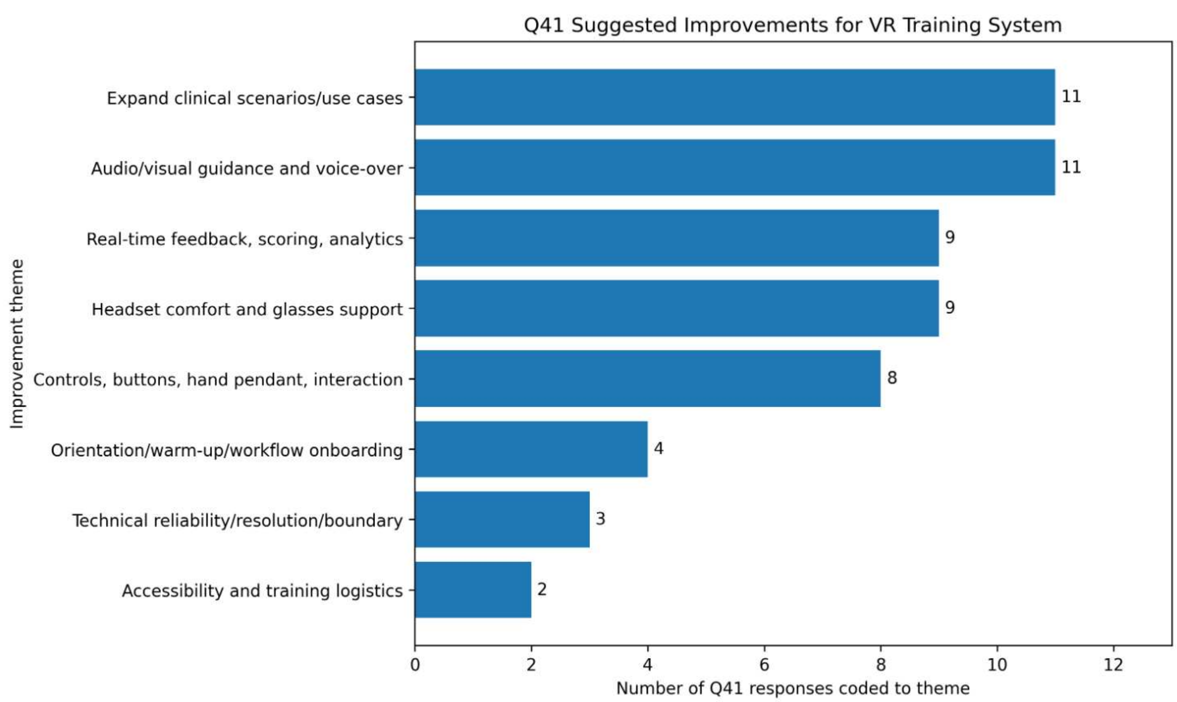

Figure 56: Theme Frequency Chart

The most common suggestion was to expand the number and variety of clinical use cases. Participants repeatedly requested "more use cases," "more clinical use cases," "more realistic case scenarios," "advanced clinical use cases," and "adaptive scenarios." This indicates that learners saw value in the VR platform but wanted broader exposure to different clinical situations. The existing use case appears to have demonstrated the potential of immersive simulation, but participants wanted the experience to extend beyond a single workflow or narrow procedural sequence. For the next study, the VR curriculum should include multiple case types with increasing complexity. Examples may include standard patient setup, mismatch correction, collision detection and recovery, machine protection events, patient protection events, emergency stop scenarios, couch and gantry motion management, imaging verification, and unexpected workflow interruptions. Including varied scenarios would allow the study to evaluate whether VR supports not only task-specific procedural learning but also transfer of learning across different radiation therapy workflows.

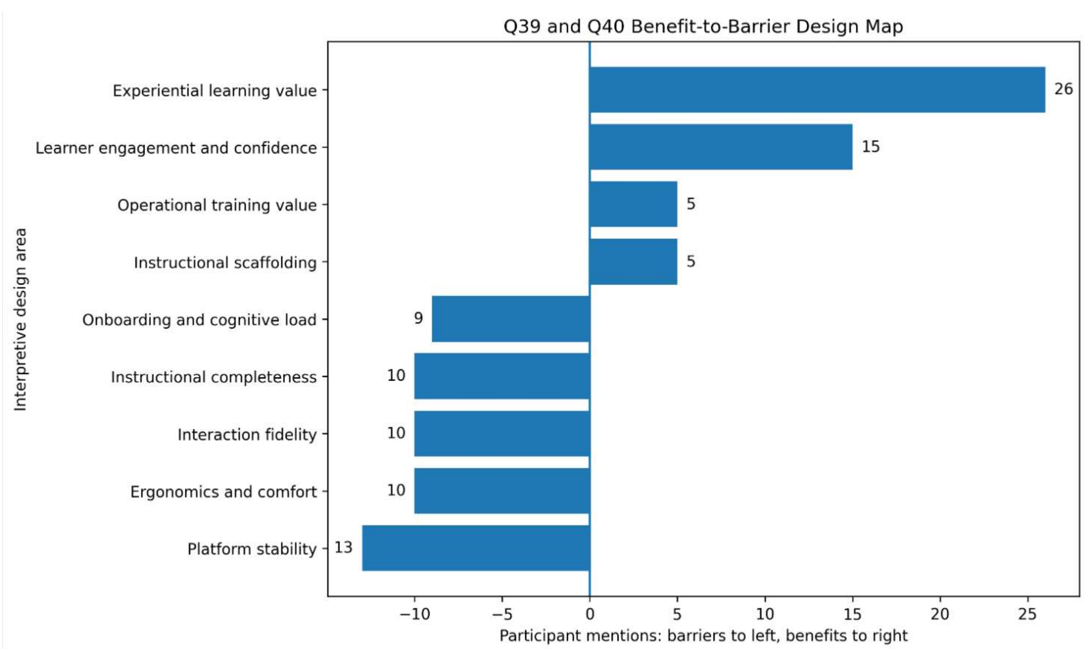

Figure 57: Benefit-to-Barrier Design Map

The plot in Figure 57 demonstrates that participants saw VR as strong for experiential learning, engagement, confidence, and operational training value, while the barriers were mostly implementation issues such as platform stability, headset comfort, controller realism, onboarding, and instructional completeness.

A second major theme was the need for real-time feedback, scoring, and performance analytics. Several participants requested “real time feedback and scoring,” “clearer performance metrics,” “detailed performance analytics,” “personalized feedback,” and “greater feedback integration.” These comments suggest that learners wanted the simulator to function not only as a practice environment but also as an instructional and assessment tool. In the next study, the VR system should include immediate formative feedback after each task, such as whether the learner selected the correct button, followed the correct sequence, acknowledged system warnings appropriately, or completed the step within an expected time window. At the end of each scenario, the system could generate a structured performance report showing completion time, number of errors, missed steps, repeated actions, safety-critical mistakes, and comparison to expert workflow benchmarks. This would align well with the existing study design, which already includes procedural checklist scores, expert rubric ratings, time to completion, and error counts.

A third important theme was the desire for more guided instruction through audio, visual cues, and voice-over support. Participants suggested “voice cues,” “audio feedback,” “audio instructions,” “guided workflows,” “visual or audio guidance,” and “someone explaining the procedures as a voice over.” Some participants also noted that highlighting important buttons or areas was helpful but inconsistent. One participant explained that when attention cues were not applied uniformly across monitors or controls, it caused confusion about which object or button to select. This feedback is highly actionable. The next version of the VR simulator should implement a consistent multimodal guidance system, combining visual highlights, text prompts, audio narration, and context-sensitive hints. Importantly, guidance should be adjustable. A novice mode could provide step-by-step prompts, highlighted controls, and voice explanations. An intermediate mode could provide fewer cues. An assessment mode could remove guidance entirely so that independent procedural competence can be evaluated.

Headset comfort and accessibility emerged as another major theme. Participants commented that the headset was too heavy, uncomfortable, difficult with glasses, or caused glasses to fog. Several explicitly requested better support for people wearing glasses. One participant even suggested removing the need for a headset. These comments are important because physical discomfort can affect learner engagement, immersion, and training duration. For the next study, headset ergonomics should be treated as a formal usability variable rather than an incidental observation. The protocol should document headset type, fit, session duration, whether participants wear glasses, discomfort level, and any symptoms such as eye strain or fogging. The study should also consider using lighter headsets, prescription lens inserts, glasses spacers, anti-fog options, adjustable straps, and seated training options. Comfort should be measured before and after training using a short usability and simulator comfort questionnaire.

Participants also identified issues with controllers, button selection, joystick movement, and hand-pendant realism. Several comments requested better hand pendant functionality, easier button selection, better left and right joystick movement, and a hand-pendant-type device instead of generic VR controllers. One participant suggested simplifying the three-button sequence used to clear the fault, while another noted confusion caused by multiple red buttons near the couch. This feedback suggests that interaction fidelity is critical for radiation therapy training. Since real clinical workflows depend heavily on physical controls, pendant operation, and precise button sequencing, the next study should improve input realism. A tracked hand pendant, haptic controller, or physical mock controller could increase procedural transfer. At minimum, the VR interface should make selectable controls easier to target and should reduce ambiguity between similar buttons. The system should also record interaction-level data, such as wrong button presses, repeated attempts, and time spent searching for controls.

Another theme was the need for better orientation before learners enter the full procedure. One participant wanted "a better picture of where all the buttons are first," while another said they felt lost because they were not familiar with the equipment. These comments suggest that some learners may benefit from a structured pre-scenario orientation module. For the next study, the VR training should include a short guided walkthrough of the treatment room, LINAC components, couch controls, hand pendant, in-room monitor, collision reset controls, and relevant safety systems. This orientation could be separated from the main assessment scenario so that participants are not penalized for unfamiliarity with the virtual environment itself.

Figure 58 shows which improvement themes appeared together in the same participant responses. For example, "expanded clinical scenarios" frequently co-occurred with "real-time feedback, scoring, and analytics," suggesting that participants wanted not only more cases but also richer instructional feedback within those cases.

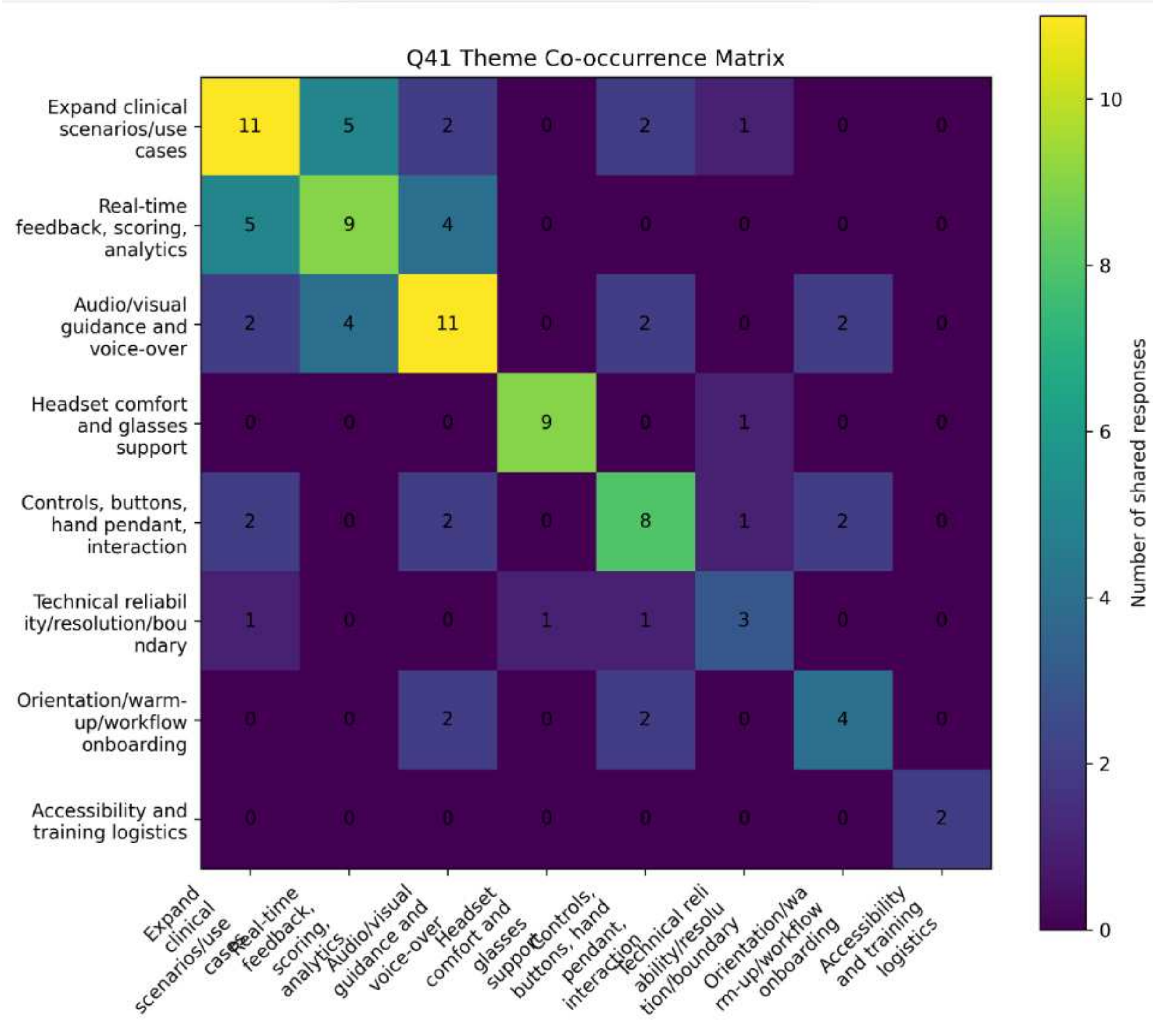

Figure 58: Co-Occurrence Matrix

Technical refinements were also requested. Participants mentioned improving resolution, boundary settings, glitches, and button responsiveness. These comments point to the importance of technical reliability as a determinant of learning effectiveness. For the next study, technical issues should be logged systematically, including tracking problems, casting interruptions, boundary problems, latency, resolution limitations, controller misalignment, and software glitches. These events should be analyzed separately because they may influence performance outcomes independent of learning.

Finally, several comments have direct implications for study design. One participant stated that the warm-up should be useful and should be part of the experiment. This is an important methodological suggestion. Future studies should standardize a brief VR acclimation period before training begins, especially for participants with limited VR experience. The next study should also stratify or control for prior VR exposure, prior radiation therapy experience, comfort with gaming or controllers, and corrective eyewear use.

Overall, Q41 feedback indicates that participants viewed VR training as promising but wanted it to become more adaptive, guided, comfortable, clinically expansive, and analytically rich. For the next study, the VR platform should evolve from a single immersive training module into a structured competency-development environment with multiple scenarios, progressive difficulty, real-time feedback, standardized orientation, improved ergonomics, stronger controller fidelity, and built-in performance analytics. These refinements would strengthen both the educational value of the simulator and the methodological rigor of future comparative studies evaluating VR-based radiation therapy training.

Hypothesis Testing Summary

The three hypotheses were tested using the quantitative and qualitative outcome measures collected across knowledge, procedural performance, expert-rated competence, efficiency, error count, learner confidence, preparedness, usability, and perceived effectiveness. For between-group comparisons of continuous outcomes, Welch's independent-samples *t*-tests were used because the 3D VR and Traditional 2D cohorts had unequal sample sizes and equal variances were not assumed. Statistical significance was evaluated using an alpha threshold of $p < .05$. The null hypothesis for each comparison stated that there would be no statistically significant difference between the 3D VR and Traditional 2D cohorts.

Hypothesis 1 stated that radiation therapists trained using VR technology would acquire necessary skills and reach competency more efficiently compared with those trained through traditional methods. This hypothesis was supported. The VR cohort demonstrated higher knowledge acquisition and retention, stronger procedural checklist performance, higher expert-rated clinical competence, shorter completion time, and fewer procedural errors than the Traditional 2D cohort. Baseline knowledge scores were statistically equivalent between groups, with the VR cohort scoring 6.93 and the Traditional 2D cohort scoring 6.88 on the pre-test, indicating comparable starting knowledge. After training, the VR cohort achieved a higher post-test score of 12.88 compared with 9.04 in the Traditional 2D cohort, $p < .001$. Retention scores also favored VR, with the VR group maintaining a score of 12.63 compared with 8.88 in the Traditional 2D group, $p < .001$. Procedural checklist scores were also significantly higher in the VR cohort, with mean scores of 8.85 versus 6.88, Welch's $t(45.87) = 5.46$, $p < .001$. Expert-rated clinical competence showed a similar pattern, with the VR cohort achieving a higher Expert Mean score of 4.24 compared with 3.32 for the Traditional 2D cohort, $p < .001$. VR-trained participants also completed the workflow faster, averaging 17.43 minutes compared with 26.22 minutes, $p < .001$, and committed fewer errors, averaging 0.88 errors compared with 3.00 errors, $p < .001$. Therefore, the null hypothesis of no difference in skill acquisition, competency, efficiency, and error reduction was rejected.

Hypothesis 2 stated that trainees who undergo VR training would exhibit higher levels of confidence and feel more prepared for real-world clinical scenarios than those who receive traditional training. This hypothesis was also supported. Learner-reported psychological readiness outcomes consistently favored the VR cohort. Perceived Preparedness was significantly higher in the VR group, with a mean score of 4.62 compared with 3.22 in the

Traditional 2D group, Welch's $t = 9.85$, $p < .001$. Instructional Effectiveness was also higher for VR, with mean scores of 4.75 versus 3.45, Welch's $t = 7.92$, $p < .001$. Ease of Use favored the VR group as well, with mean scores of 4.48 versus 3.88, Welch's $t = 3.64$, $p < .001$. Cognitive Comfort showed a particularly large difference, with the VR cohort reporting a mean score of 4.55 compared with 2.95 for the Traditional 2D cohort, Welch's $t = 8.65$, $p < .001$. These findings indicate that VR participants reported significantly greater preparedness, perceived instructional value, usability, and cognitive comfort. Therefore, the null hypothesis of no difference in confidence and preparedness was rejected.

Hypothesis 3 stated that radiation therapy trainees would perceive VR as a highly usable and effective tool for training, with positive attitudes toward its adoption in the educational curriculum**.** This hypothesis was supported by both Likert-scale survey findings and open-ended qualitative responses. Quantitatively, the VR cohort reported high ratings for instructional effectiveness, ease of use, preparedness, and cognitive comfort, with all domain means above 4.4 on a 5-point scale. Qualitative responses further indicated that participants perceived VR as immersive, realistic, engaging, hands-on, and valuable for understanding LINAC workflows, patient setup, spatial relationships, and collision-management procedures. Participants also identified areas for improvement, including headset comfort, glasses support, controller familiarity, hand-pendant realism, technical stability, expanded clinical scenarios, real-time feedback, and guided instruction. These comments suggest that participants viewed VR positively as a training modality while also identifying practical refinements needed for future implementation. Therefore, the hypothesis that trainees would perceive VR as usable, effective, and appropriate for educational adoption was supported. The summary of the testing results are captured in Table 13.

Table 13: Summary of Hypothesis Testing Results

Hypothesis	**Outcome Measures Used for Testing**	**Statistical Test or Analysis**	**Key Results**	**Decision**
H1: VR training will improve skill acquisition and competency efficiency compared with traditional training.	Knowledge post-test, knowledge retention, procedural checklist score, expert mean rating, completion time, error count	Welch's independent-samples *t*-tests	VR outperformed 2D on post-test knowledge, retention, checklist score, expert rating, completion time, and error count; all primary comparisons favored VR, $p < .001$	Supported; reject null
H2: VR-trained trainees will report higher confidence and preparedness for real-world clinical scenarios.	Perceived preparedness, instructional effectiveness, ease of use, cognitive comfort	Welch's independent-samples *t*-tests	VR reported higher preparedness, instructional effectiveness, ease of use, and cognitive comfort; all comparisons were significant, $p < .001$	Supported; reject null
H3: Trainees will perceive VR as usable, effective, and appropriate for adoption in training curricula.	Likert-scale survey responses and open-ended responses Q39, Q40, Q41	Descriptive statistics and thematic analysis	VR ratings were high across usability and effectiveness domains; qualitative feedback described VR as immersive, realistic, hands-on, engaging, and clinically useful, while identifying refinements for future studies	Supported

In this study, the p-value represents the probability of observing a difference between the 3D VR and Traditional 2D cohorts as large as, or larger than, the observed difference if there were truly no difference between the two training methods. A significance threshold of $\alpha = .05$ was used for hypothesis testing. Therefore, p-values below .05 were interpreted as statistically significant evidence that the observed group difference was unlikely to be due to random sampling variation alone.

CHAPTER 4: DISCUSSION, LIMITATIONS & CONCLUSION

Discussion

When viewed together, the findings from RQ1, RQ2, and RQ3 present a coherent story about the educational value of immersive VR in radiation therapy training. The immersive intervention did not merely improve one dimension of performance. Instead, it shifted the entire training profile of participants in a favorable direction: stronger acquisition, better retention, more accurate execution, fewer errors, higher expert judgments of competence, greater efficiency, and stronger confidence that was aligned with rather than detached from performance.

These results matter not merely because the VR group scored higher on a written test, but because the cognitive gains aligned with better practical performance. Procedural checklist totals were higher in the VR cohort, indicating stronger execution of safety-critical steps. Expert ratings were also substantially higher in the VR group, with an especially large effect size for overall competence. When performance was operationalized through efficiency and error reduction, the VR group again showed clear superiority, completing tasks significantly faster and with fewer observable errors.

The most compelling feature of the integrated dataset is convergence across measurement types. In educational research, especially in applied clinical contexts, it is common to see interventions that improve perception without improving action, or that improve immediate post-test scores without delivering transfer to authentic performance. That pattern was not observed here. The same training modality that increased knowledge gains also improved procedural checklists, expert ratings, workflow efficiency, and delayed execution. This convergence increases confidence that the findings represent a real training advantage rather than an artifact of measurement choice.

From the standpoint of cognitive load theory, the results make sense. Traditional 2D instruction required learners to reconstruct the treatment environment mentally from fragmented sources. The immersive VR condition reduced this fragmentation by embedding action, sequence, and spatial relations in one representational space. This likely reduced extraneous cognitive load at both encoding and retrieval. The stronger retained knowledge trajectory, the lower error rates, and the particularly large advantage on spatially complex tasks are all consistent with this interpretation.

The findings are equally consistent with experiential learning theory. VR participants did not simply hear about a workflow or see it depicted. They enacted it. They occupied the room, confronted the geometry of the machine, and experienced the temporal sequence of events through interaction. These concrete experiences likely facilitated stronger schema formation and stronger transfer to the physical LINAC. The value of immersive rehearsal was especially evident in safety-relevant scenarios such as collision reset, where learners must integrate perception, anticipation, and procedure.

The RQ2 findings add an essential psychological dimension. In high-stakes clinical domains, confidence matters because hesitation, uncertainty, and disorientation can impair performance even when knowledge exists in principle. However, confidence is beneficial only when it is calibrated. The negative correlation between confidence and error count suggests that the immersive condition produced confidence that was deserved. Participants were not simply more enthusiastic; they were safer and more effective. This is a meaningful distinction because educational interventions that generate false confidence can be dangerous in clinical contexts.

The usability findings further clarify that "immersion" should not be treated as a vague or decorative quality. In this study, the practical value of immersion appears to have resided in continuity: the virtual space looked and behaved enough like the real environment that learners could later recognize it. Terms used by participants such as familiarity, realism, comfort, and workflow clarity point to a training mechanism in which the virtual environment became a rehearsal for the physical environment. That continuity is likely one reason why VR trainees completed tasks faster and with fewer spatially driven errors.

At the same time, the study appropriately avoids overclaiming. The usability barriers reported by participants were real. Headset ergonomics, controller learning curve, and occasional technical interruptions matter for implementation and can influence learner comfort or early engagement. Yet the educational value of the VR condition remained evident despite these barriers. This suggests that as hardware continues to improve and onboarding becomes more refined, the instructional advantage of immersive simulation may become even more pronounced rather than less.

The integrated results also have implications for how training effectiveness should be conceptualized in radiation therapy education. Effective training is not adequately captured by a single endpoint. A more appropriate model is multi-dimensional and sequential: trainees must acquire knowledge, translate it into action, develop calibrated confidence, and retain performance over time. The present manuscript suggests that immersive VR contributes positively at each stage of that chain. This is one reason the combined analysis is stronger than any of the three individual manuscripts alone. It shows that the VR advantage is not isolated but systemic.

Another important implication concerns learner variability. Several figures suggest that the immersive modality not only improved average performance but also narrowed performance dispersion. This matters for educational equity and workforce development because conventional methods often leave some learners behind while others succeed due to prior exposure, stronger visualization ability, or chance opportunities for machine access. A standardized immersive platform may help reduce such disparities by providing everyone with the same opportunity for contextualized practice.

Finally, the present results contribute to the broader discussion of how advanced simulation should be positioned in clinical education. The data do not suggest that immersive VR eliminates the value of supervised practice on real equipment or the importance of mentorship in the clinic. Rather, VR appears to be an effective bridge between introductory instruction and authentic clinical execution. It can prepare learners to use limited in-clinic training time more productively, arrive at the bunker with better orientation, and reduce the burden on faculty or clinical staff who would otherwise need to remediate basic unfamiliarity in real time.

A useful way to interpret the integrated findings is through the lens of readiness formation. Readiness in clinical education is not a single attribute but an emergent state produced when several conditions align: the learner can retrieve relevant knowledge, recognize the environment, anticipate the next action, detect when something is wrong, and proceed with enough confidence to act without freezing. Table 5, Table 6, and the step-level findings visualized in Figure 42 through Figure 52 collectively suggest that immersive VR improved each of these components. Stronger knowledge gains provided the conceptual substrate, higher checklist and expert scores reflected better organized action, lower error counts indicated more dependable safety behavior, and the confidence measures suggest that trainees experienced the resulting competence as felt preparedness rather than as abstract knowledge alone.

This has implications for how educators should think about the common transition gap between classroom learning and bunker performance. In many clinical programs, learners perform adequately in discussion or written assessments but then experience a marked drop in fluency when placed near real equipment. The present data imply that a substantial share of this gap may arise not from inability to learn, but from a mismatch between the representational form of instruction and the representational demands of execution. Two-dimensional instruction asks trainees to mentally construct a three-dimensional workflow from fragmented cues. Immersive VR reduces the need for that late reconstruction by allowing the learner to build a situated mental model during training itself. When the learner later encounters the physical LINAC, the task feels more like recognition than translation, which is a fundamentally different cognitive burden.

There is also a safety-culture dimension to these results. Radiation therapy practice depends on disciplined attention to environment, sequence, and recovery behaviors when automation does not proceed as expected. Training modalities that normalize repeated exposure to safety-critical steps may do more than improve performance on a test; they may shape how novices come to understand caution, situational awareness, and the meaning of machine behavior. The lower failure rates seen in the VR group for collision reset, protective stop handling, gantry motion, and isocenter-related steps suggest that immersive rehearsal may help learners encode safety not as an afterthought or rule list, but as part of the normal structure of the task. That is educationally valuable because clinical safety is often strongest when correct protective actions are embedded in procedural habit.

Another important point is that the immersive advantage appears to operate at both the individual and cohort level. At the individual level, trainees exposed to VR showed better personal performance and more stable retention. At the cohort level, the narrower distributions seen in several figures imply more uniform learning across the group. This matters operationally because educational programs are responsible not only for raising average performance but also for reducing the number of learners who remain underprepared after standard instruction. A modality that both lifts mean performance and compresses variance is especially valuable in resource-constrained clinical education because it reduces the downstream need for ad hoc remediation and closer supervision of a minority of trainees who did not fully translate the initial instruction into execution.

Finally, the results support a more mature framing of immersive VR as infrastructure rather than novelty. Once the intervention is evaluated through the same standards used for other serious educational technologies—transfer, retention, expert judgment, reliability, and implementation constraints—it becomes possible to discuss VR in operational terms. Departments can ask where in the curriculum immersive rehearsal adds the most value, which scenarios should be prioritized for development, how often refresher practice should occur, and how performance data might be integrated into broader competency portfolios. This moves the conversation away from whether VR is interesting and toward whether it can reliably shoulder part of the burden of clinical preparation. The present results suggest that it can.

Comparison with Prior Literature

The findings of this study are consistent with the broader health professions education literature showing that simulation-based and VR-based training can improve knowledge, skill acquisition, and learner performance compared with conventional instructional methods. Cook et al. reported that technology-enhanced simulation in health professions education was associated with large effects on knowledge, skills, and learner behaviors, supporting the use of simulation for competency development in clinical training (Cook et al., 2011). Similarly, Kyaw et al. found that VR-based education improved post-intervention knowledge and skill outcomes compared with traditional education or other digital learning approaches, while also noting that more research was needed on immersive and interactive VR formats and on clinical practice outcomes (Kyaw et al., 2019). The present study aligns with these findings by demonstrating that 3D VR training improved knowledge acquisition, knowledge retention, procedural checklist performance, expert-rated competence, task efficiency, and error reduction compared with Traditional 2D instruction. However, this study extends prior work by evaluating not only immediate knowledge gains, but also retained knowledge, hands-on procedural execution, expert ratings, completion time, and objective error counts within a radiation therapy workflow.

The results also support prior work suggesting that immersive VR is especially valuable when learners must develop spatial understanding, procedural sequencing, and applied decision-making. Radiation therapy workflows require learners to understand the geometric relationship among the patient, couch, gantry, treatment field, and safety systems. Traditional 2D instruction can explain these concepts, but it often presents them as static images or stepwise descriptions. In contrast, immersive VR allows learners to experience the treatment environment as an integrated spatial system. This may explain why the VR cohort in the present study demonstrated stronger workflow fluency, clinical judgment, and procedural performance. These findings are consistent with educational theories and prior VR learning research suggesting that immersion and interaction can support active learning, contextual encoding, and transfer from conceptual knowledge to applied performance. Prior reviews of immersive VR in education have similarly emphasized that VR can improve learning when it is intentionally designed around meaningful interaction rather than used only as a novel visualization tool.

The present findings are also consistent with literature highlighting the value of simulation for safe practice in high-risk clinical environments. Radiation therapy training is constrained by limited access to physical LINAC systems, competing clinical demands, patient-safety considerations, and the need to avoid unnecessary machine disruption. Simulation-based education addresses these barriers by allowing repeated practice in a controlled environment before learners perform tasks in the clinical setting. In this study, VR-trained participants completed the workflow faster, committed fewer errors, and received higher expert ratings than participants trained using Traditional 2D instruction. These results suggest that VR may help learners develop procedural readiness before entering the physical treatment environment, which is particularly important for safety-critical workflows such as patient setup, auto-move verification, collision awareness, protection-stop recognition, and collision reset.

This study also adds to prior literature by linking self-reported confidence and preparedness with objective performance outcomes. Previous VR education studies have frequently measured learner satisfaction, engagement, or perceived usefulness, but fewer studies have triangulated these perceptions with expert-rated clinical performance, task completion time, and error counts. In the present study, VR participants reported higher preparedness, instructional effectiveness, ease of use, and cognitive comfort than the Traditional 2D cohort. Importantly, these subjective gains were supported by objective improvements in performance. This suggests that VR did not merely increase learner enthusiasm or perceived confidence; rather, it supported calibrated psychological readiness grounded in demonstrable competence. This distinction is important because confidence without competence may increase risk in clinical environments, whereas confidence aligned with fewer errors and stronger expert ratings indicates more meaningful readiness for supervised clinical practice.

The qualitative findings further reinforce and extend prior literature. Participants described VR as immersive, realistic, hands-on, engaging, and useful for understanding the LINAC environment. These themes are consistent with prior reports that VR can improve learner engagement and support understanding of complex procedures. At the same time, participants identified barriers commonly reported in VR education studies, including headset comfort, controller familiarity, technical stability, visual limitations, and the need for more guidance and feedback. These findings suggest that while VR has strong educational potential, its effectiveness depends on careful instructional design, reliable technical implementation, ergonomic hardware, and appropriate learner onboarding. Therefore, the results support the growing consensus that VR should not be treated as a stand-alone technology intervention, but as a structured simulation-based learning environment requiring scenario design, feedback mechanisms, usability refinement, and alignment with competency-based outcomes.

Overall, this study both confirms and extends the existing literature. It confirms prior evidence that VR and technology-enhanced simulation can improve knowledge and skills in health professions education. It extends that literature by applying immersive VR to radiation therapy training and by demonstrating improvements across multiple levels of outcome measurement, including knowledge retention, procedural checklist completion, expert-rated competence, workflow efficiency, error reduction, and learner preparedness. These findings address a gap identified in prior VR education reviews, namely the need for studies that move beyond learner satisfaction and immediate post-test knowledge to evaluate applied performance and clinical transfer. In doing so, this study provides evidence that immersive VR can serve as a scalable and effective training modality for competency development in high-risk, technology-intensive clinical domains such as radiation therapy.

Implications for Practice

The practical implications of these findings are substantial for radiation therapy programs, clinical departments, and technology developers. First, immersive VR offers a way to expand access to high-quality practice without depending on scarce treatment-room availability. This is especially valuable in settings where clinical throughput limits novice exposure. Second, the use of VR before hands-on machine sessions could allow educators to reserve physical bunker time for higher-value coaching rather than basic orientation. Third, the strong results on preparedness and confidence suggest that VR may improve the transition from classroom learning to supervised clinical contribution.

Beyond initial training, immersive platforms may also support onboarding to new workflows, rehearsal before infrequently performed procedures, remediation for learners who need additional repetition, and continuing professional development for practicing staff. Because the technology is scalable and repeatable, it aligns with the broader healthcare need for training systems that are flexible, cost-aware, and capable of maintaining competence in technology-intensive environments.

For educators designing curricula, one practical model would be staged integration. Foundational conceptual instruction can still be delivered through lectures, readings, or demonstrations, but immersive rehearsal can be inserted before first exposure to the live bunker so that students arrive with a spatially grounded understanding of the room, machine, and task sequence. After that first immersive exposure, targeted clinical supervision can focus on nuance, communication, and contextual variation rather than spending valuable machine time on basic orientation. This sequence is attractive because it uses each modality for what it does best: didactic instruction for conceptual framing, immersive simulation for situated rehearsal, and clinical supervision for adaptation in authentic patient-facing contexts.

There are also potential operational and economic implications. Access to treatment rooms, instructors, and equipment time is often the rate-limiting factor in scaling radiation therapy education. A reusable VR platform cannot eliminate the need for real-equipment experience, but it can shift a meaningful portion of early repetition away from the clinical bottleneck. That may permit more deliberate scheduling of on-machine exposure, reduce the number of orientation errors that must be corrected in the bunker, and allow instructors to devote scarce face-to-face time to higher-value coaching. In departments facing staffing constraints, geographic dispersion, or onboarding needs across multiple sites, such efficiencies may be as important as the pedagogical benefits themselves.

From a quality-improvement perspective, immersive platforms may also support a continuous learning ecosystem rather than a one-time educational event. Scenarios can be reused for remediation, annual refreshers, introduction of workflow updates, or rehearsal of uncommon but high-consequence events. If paired with analytics, they may eventually provide educators with fine-grained information about where learners slow down, which steps produce hesitation, and which safety-critical decisions require more targeted reinforcement. The present findings do not directly test such an analytics model, but they provide a strong justification for pursuing it because they show that performance within and after immersive training is educationally meaningful rather than merely experiential.

Limitations

Several limitations should be considered. Expert ratings were derived from a limited number of raters, which prevented formal inter-rater reliability analysis. Future studies should include additional raters and calibration procedures. The study also examined transfer in a controlled assessment environment rather than during live patient treatment, so direct extrapolation to patient-facing outcomes should be made with caution. Although the sample size was sufficient to detect large effects, replication across multiple institutions and learner groups would strengthen generalizability. Finally, the retention window in this study was relatively short. Longer follow-up is needed to determine how durable the observed advantages remain over months of real clinical activity.

Cross-question synthesis

The most useful way to interpret the combined findings is as a chain of educational influence. Immersive VR first improved how learners encoded the task environment and workflow sequence. That stronger encoding then appeared as larger knowledge gains and better retention. Because the underlying schema was stronger, participants executed more steps correctly, with better timing and fewer observable errors. More successful execution then reinforced confidence and preparedness, producing a form of self-efficacy that matched actual capability. Finally, because the experience was contextualized and memorable, those benefits remained visible at delayed assessment. Seen in this way, RQ1, RQ2, and RQ3 are not separate stories but successive manifestations of the same instructional advantage.

This interpretation also helps explain why the immersive advantage was most pronounced in spatially complex and safety-critical steps rather than in every step equally. Tasks such as plan selection or other rule-based confirmations can often be learned through conventional explanation because they depend heavily on declarative recall. By contrast, isocenter setup, gantry motion, collision reset, and protective-stop handling require learners to integrate location, orientation, body position, machine state, and sequence in real time. These are precisely the situations in which spatially grounded rehearsal should matter most. The heatmap pattern observed in Figure 50 strongly supports that mechanistic interpretation.

The combined results further suggest that immersive VR may serve an equalizing function within training cohorts. Traditional instruction often favors learners who already possess strong visualization skills, prior machine familiarity, or informal opportunities for repeated observation. A virtual environment can reduce dependence on those background advantages by allowing every learner to rehearse the same scenario under the same conditions for as long as needed. The narrower distributions seen in several of the VR figures are therefore educationally important: they imply that immersive training may not only raise the mean, but also reduce the number of learners who remain uncertain or underprepared after instruction.

There is also a workforce-development implication. Radiation oncology programs, like many technology-intensive healthcare fields, must prepare learners in environments where expert supervision time and equipment access are both limited resources. If a significant share of basic spatial orientation, workflow familiarization, and early error correction can be shifted into immersive rehearsal before clinical machine time, then scarce faculty and bunker access can be reserved for higher-level coaching. That is not simply an instructional benefit; it is an operational benefit that could improve throughput and consistency in education programs.

A further limitation of the study was the occurrence of VR-related discomfort or motion-related symptoms among a subset of participants assigned to the VR 3D training condition. Based on responses to Q40, which asked participants to describe challenges or limitations experienced while using the VR training system, 9 of 39 VR 3D participants, or 23.1%, reported some form of discomfort, including motion sickness, dizziness, eye strain, headset discomfort, physical discomfort from the headset, or general comfort-related issues. Using a more conservative definition limited only to explicit reports of motion sickness, dizziness, or motion-related discomfort, 4 of 39 VR 3D participants, or 10.3%, reported symptoms consistent with simulator sickness. Importantly, none of these participants discontinued the study; all participants continued with the VR training and completed the assessment successfully. Nevertheless, these findings suggest that while immersive VR training was feasible overall, headset-based simulation may produce physical or visual discomfort for some learners. This limitation should be considered when interpreting the usability and acceptability of the VR intervention, particularly for individuals who may be more susceptible to simulator sickness or headset-related discomfort. Future studies should systematically document simulator-sickness symptoms, headset comfort, and visual strain, and may consider mitigation strategies such as shorter exposure periods, seated options, acclimatization time, headset-fit adjustments, and alternative non-immersive training pathways when needed.

A final point concerns the relationship between realism and utility. Educational technology is sometimes critiqued for pursuing realism as an aesthetic goal rather than as an instructional one. The present findings suggest that realism is valuable when it functions as representational continuity: the more clearly the learner can map the training environment onto the physical environment, the less cognitive effort is required at the moment of transfer. In this study, realism appears to have mattered because it reduced the translation burden between learning and doing. That makes immersive fidelity a pedagogical variable, not just a design flourish.

This cross-question perspective also clarifies why the combined manuscript is stronger than three separate reports. RQ1 establishes that learners acquired and retained more of the target knowledge and procedural structure. RQ2 shows that these gains were accompanied by stronger feelings of readiness and lower uncertainty. RQ3 then demonstrates that the benefits were visible where it matters most: during execution on physical equipment, at the level of precise steps, error propensity, and delayed stability. Considered independently, each research question answers a legitimate educational concern. Considered together, they create a chain of evidence that is much harder to dismiss. The argument is not merely that VR is enjoyable, or that it boosts survey scores, or that it improves a single test. The argument is that immersive rehearsal produces a coherent shift in the learner's relationship to the clinical task from fragmented understanding to enacted workflow knowledge, to reliable performance under realistic conditions.

There is a broader methodological lesson here for simulation research in health professions education. Educational technologies are often evaluated too narrowly, either through satisfaction data that overstate effectiveness or through single-point performance tests that underexplain how the effect was produced. A more robust model is to ask four linked questions: Did the training improve what the learner understood? Did it improve what the learner could do? Did it improve how ready the learner felt to act? And did those gains remain visible when the learner confronted the real task after time had passed? The present study approximates that model and thereby offers a template for future investigations of simulation in other technology-dense clinical domains.

Directions for Future Research

Future work should extend this integrated framework in several directions. Multi-site studies would help determine whether the present findings generalize across different curricula, institutional cultures, and levels of trainee experience. Longer-term studies could examine whether immersive VR reduces supervision burden, accelerates time to independent performance, or improves patient-safety-related process outcomes. Additional research should also explore adaptive feedback, AI-guided coaching, and scenario libraries that scale from foundational machine operations to more advanced treatment workflows. Finally, future usability work should continue to refine ergonomics, controller onboarding, and system stability so that technical friction is minimized and the instructional benefits of immersive rehearsal can be fully realized.

Future research should also examine dosage and sequencing questions. It remains to be determined how much immersive exposure is necessary to achieve the gains observed here, whether shorter repeated sessions outperform single longer sessions, and at what point diminishing returns emerge. Relatedly, studies could compare different curricular placements of VR—before lecture, after lecture, before first bunker exposure, or as an interleaved refresher between clinical experiences—to identify the most efficient educational design. These questions are especially relevant for programs that must justify implementation under time and staffing constraints.

Another important avenue concerns outcome expansion beyond learner-level performance. Over time, the strongest case for immersive radiation therapy training will come from demonstrating effects on the broader clinical system: reduced onboarding time, reduced need for corrective intervention during supervised practice, improved standardization across sites, fewer near misses during early independent work, and better preparedness for upgrades or workflow changes. Such studies are more difficult to conduct, but they would connect educational effectiveness to departmental operations and patient-safety priorities. The present manuscript establishes a strong learner-performance foundation on which those higher-level evaluations can be built.

Conclusion

This study provides strong empirical evidence that immersive three-dimensional virtual reality training is a pedagogically powerful and clinically meaningful approach for radiation therapy education. Across all three research questions, VR training consistently outperformed Traditional 2D instruction in knowledge acquisition, knowledge retention, procedural skill development, expert-rated clinical competence, workflow efficiency, error reduction, confidence, preparedness, and transfer of learning to hands-on clinical execution. Although both cohorts began with comparable baseline knowledge scores, the VR cohort demonstrated substantially greater post-training gains and sustained retention over time. VR-trained participants also achieved higher procedural checklist scores, stronger expert ratings, faster task completion, and fewer errors, indicating that immersive simulation supported not only cognitive learning but also applied procedural competence and clinical readiness.

The findings show that the educational value of VR extends well beyond novelty or learner engagement. VR functioned as an integrated experiential learning environment in which trainees could actively construct procedural understanding, rehearse complex LINAC workflows, develop spatial awareness, and practice safety-critical decision-making in a controlled and consequence-free setting. This immersive rehearsal appeared especially beneficial for spatially complex and high-risk workflow components, where traditional instruction is often limited by abstraction, fragmented visualization, and restricted access to physical treatment equipment. By enabling repeated practice without occupying a clinical vault or exposing patients and equipment to risk, VR offers a scalable solution to one of the central challenges in radiation therapy education: preparing learners for high-stakes clinical environments when access to real machines is limited.

Importantly, VR training also enhanced psychological readiness. Participants trained in VR reported greater confidence and preparedness, and these self-perceptions were supported by objective performance outcomes rather than detached from them. The alignment between confidence, expert-rated competence, reduced error rates, and improved workflow fluency suggests that VR fostered calibrated confidence rather than overconfidence. This distinction is critical in radiation therapy, where safe practice depends not only on knowing the correct workflow but also on recognizing system states, responding appropriately to interruptions, and executing procedures with composure and judgment. By reducing unfamiliarity, improving spatial orientation, and supporting decisional fluency before trainees enter the physical treatment environment, VR helped bridge the gap between classroom learning and clinical execution.

The qualitative findings further contextualize these quantitative outcomes. Participants described VR as immersive, realistic, engaging, hands-on, and valuable for understanding the treatment room, LINAC components, machine motion, patient setup, and collision-management workflow. At the same time, learner feedback identified practical barriers that should guide future development, including headset comfort, glasses support, controller familiarity, hand-pendant realism, technical stability, system responsiveness, and the need for expanded clinical scenarios, real-time feedback, and adaptive instructional guidance. These usability findings do not diminish the demonstrated effectiveness of VR; rather, they provide a clear roadmap for refining the platform into a more mature competency-development system.

Collectively, this study positions immersive VR as more than an adjunct to conventional instruction. It is a scalable, reproducible, and evidence-supported training modality capable of accelerating competency development, enhancing confidence and preparedness, and supporting accurate transfer of learning to clinical radiation therapy workflows. The results support integrating VR into radiation therapy curricula as a core instructional modality for initial training, skills reinforcement, onboarding to new technologies, and potentially continuing competency assessment. As healthcare education continues to move toward cost-effective, accessible, and safety-centered training models, immersive VR offers a compelling pathway for improving clinical preparation while reducing dependence on limited physical infrastructure. Future studies should build on these findings by evaluating larger and more diverse learner populations, incorporating multiple clinical scenarios with progressive complexity, integrating real-time analytics and feedback, and examining long-term clinical transfer in authentic treatment environments.

REFERENCES

[1] World Health Organization. (n.d.). *Cancer*. World Health Organization. https://www.who.int/health-topics/cancer

[2] Rodriguez, H., Zenklusen, J. C., Staudt, L. M., Doroshow, J. H., Lowy, D. R., & the NCI Clinical Proteomic Tumor Analysis Consortium. (2021). Proteogenomics to inform cancer diagnosis and treatment. *Cell, 184*(7), 1661–1670. https://doi.org/10.1016/j.cell.2021.02.055

[3] National Cancer Institute. (2025, May 15). *Radiation therapy for cancer*. https://www.cancer.gov/about-cancer/treatment/types/radiation-therapy

[4] Grégoire, V., Guckenberger, M., Haustermans, K., Lagendijk, J. J. W., Ménard, C., Pötter, R., Slotman, B. J., Tanderup, K., & Thorwarth, D. (2020). Image guidance in radiation therapy for better cure of cancer. *Molecular Oncology, 14*(7), 1470–1491. https://doi.org/10.1002/1878-0261.12751

[5] Herrmann, H., & Seppenwoolde, Y. (2019). Image guidance: Past and future of radiotherapy. *Clinical Oncology, 31*(9), 557–564. https://doi.org/10.1016/j.clon.2019.05.006

[6] Parodi, K. (2018). Imaging in radiotherapy. *Physics in Medicine & Biology, 63*(14), 14TR01. https://doi.org/10.1088/1361-6560/aacb14

[7] Patel, P., McHugh, A., Bi, X., & Farach, A. (2018). Radiotherapy for inoperable Merkel cell carcinoma: A single-center experience. *Cureus, 10*(3), e2310. https://doi.org/10.7759/cureus.2310

[8] Eaton, D. J., Yang, H. C., Giannotta, S. L., & Yu, C. (2018). Stereotactic radiosurgery for benign brain tumors. *Neurosurgery Clinics of North America, 29*(4), 569–580. https://doi.org/10.1016/j.nec.2018.06.004

[9] Rudra, S., Jiang, N., Rosenberg, S. A., Olsen, J. R., Roach, M. C., Wan, L., Portelance, L., Mellon, E. A., Mokdad, A. A., Hsu, C.-C., Koong, A. C., Herman, J. M., & Chuong, M. D. (2019). Using adaptive magnetic resonance image-guided radiation therapy for treatment of inoperable pancreatic cancer. *Cancer Medicine, 8*(5), 2123–2132. https://doi.org/10.1002/cam4.2100

[10] Boldrini, L., La Porta, L., Gasparotto, C., & Eriksen, J. G. (2024). The future of education in radiation oncology. *Seminars in Radiation Oncology, 34*(4), 468–473. https://doi.org/10.1016/j.semradonc.2024.07.009

[11] Dubois, N., Verfaillie, C., Demez, P., Hannachi, N., Dubois, G., Gibon, D., & De Grove, X. (2022). Training of radiotherapy professionals: Status, content, satisfaction and improvement suggestions in the Greater Region. *BMC Medical Education, 22*, Article 431. https://doi.org/10.1186/s12909-022-03567-5

[12] Tene, T., Chimeno, J., & Vázquez, D. (2024). A systematic review of immersive educational technologies in medical physics and radiation physics. *Frontiers in Medicine, 11*, 1384799. https://doi.org/10.3389/fmed.2024.1384799

[13] Walls, G. M., Hanna, G. G., & McAleer, J. J. (2020). Learning radiotherapy: The state of the art. *BMC Medical Education, 20*, Article 150. https://doi.org/10.1186/s12909-020-02054-z

[14] Kane, P., Briggs, P., & Hargest, R. (2018). Simulation-based education: A narrative review of the use of vignettes in healthcare. *BMJ Simulation & Technology Enhanced Learning, 4*(1), 15–20. https://doi.org/10.1136/bmjstel-2017-000229

[15] Kayed, J. E., Chlela, R., Chahine, M. N., Hallit, S., & Haddad, C. (2024). Serious game for radiotherapy training: Development and implementation of a simulation-based

educational tool. *BMC Medical Education, 24*, Article 1388. https://doi.org/10.1186/s12909-024-05430-1

[16] Sherman, W. R., & Craig, A. B. (2003). *Understanding virtual reality: Interface, application, and design*. Morgan Kaufmann.

[17] Hamilton, D., McKechnie, J., Edgerton, E., & Wilson, C. (2021). Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design. *Journal of Computers in Education, 8*, 1–32. https://doi.org/10.1007/s40692-020-00169-2

[18] Lastrucci, A., Cacace, T., Calandrino, R., Di Murro, L., Iacovelli, N. A., Rigon, G., Rossi, G., Valvo, F., & Fanti, V. (2024). The application of virtual environment radiotherapy for RTT training: A scoping review. *Journal of Medical Imaging and Radiation Sciences*. Advance online publication. https://doi.org/10.1016/j.jmir.2024.02.025

[19] Wong, S., Bridge, P., Appleyard, R., Martin, T., & Halkett, G. K. B. (2024). The use of virtual reality in radiation therapy training. *Journal of Medical Imaging and Radiation Sciences*. Advance online publication.

[20] Hogan, L., Tsang, Y., McNamara, A. L., Chuter, R., Kron, T., Liney, G. P., Martin, J., Rai, R., Rosenberg, I., Siva, S., Hardcastle, N., & Yeo, U. J. (2022). Old dogs, new tricks: MR-Linac training and credentialing of radiation oncology professionals. *Journal of Medical Radiation Sciences, 69*(4), 458–470. https://doi.org/10.1002/jmrs.617

[21] Takvorian, S. U., Lichtensztajn, D. Y., Hlubocky, F. J., Small, W., Jr., & Shulman, L. N. (2020). Developing and sustaining an effective and resilient oncology careforce during the COVID-19 pandemic and beyond. *JCO Oncology Practice, 16*(10), 663–668. https://doi.org/10.1200/OP.20.00291

[22] Bray, F., Laversanne, M., Sung, H., Ferlay, J., Siegel, R. L., Soerjomataram, I., & Jemal, A. (2024). Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA: A Cancer Journal for Clinicians, 74*(3), 229–263. https://doi.org/10.3322/caac.21834

[23] dos-Santos-Silva, I., Gupta, S., Orem, J., & Shulman, L. N. (2022). Global disparities in access to cancer care. *Communications Medicine, 2*, Article 31. https://doi.org/10.1038/s43856-022-00097-5

[24] Marino, P., Mininni, M., Deiana, G., Marino, G., Divella, R., Bochicchio, I., Giuliano, A., Lapadula, S., Lettini, A. R., & Sanseverino, F. (2024). Healthy lifestyle and cancer risk: Modifiable risk factors to prevent cancer. *Nutrients, 16*(6), 800. https://doi.org/10.3390/nu16060800

[25] Prager, G. W., Braga, S., Bystricky, B., Qvortrup, C., Criscitiello, C., Esin, E., Sonke, G. S., Martínez, G. A., Frenel, J.-S., Karamouzis, M., Strijbos, M., Yazici, O., Bossi, P., Banerjee, S., Troiani, T., Eniu, A., Ciardiello, F., Tabernero, J., Zielinski, C. C., ... Ilbawi, A. (2018). Global cancer control: Responding to the growing burden, rising costs and inequalities in access. *ESMO Open, 3*(2), e000285. https://doi.org/10.1136/esmoopen-2017-000285

[26] World Health Organization. (2017). *Guide to cancer early diagnosis*. World Health Organization. https://iris.who.int/handle/10665/254500

[27] World Health Organization. (2024, February 1). *Global cancer burden growing, amidst mounting need for services*. https://www.who.int/news/item/01-02-2024-global-cancer-burden-growing--amidst-mounting-need-for-services

[28] Malone, E. R., Oliva, M., Sabatini, P. J. B., Stockley, T. L., & Siu, L. L. (2020). Molecular profiling for precision cancer therapies. *Genome Medicine, 12*(1), 8. https://doi.org/10.1186/s13073-019-0703-1

[29] Lawler, M., Keeling, P., Kholmanskikh, O., Minnaard, W., Moehlig-Zuttermeister, H., Normanno, N., Philip, R., Popp, C., Salgado, R., Santiago-Walker, A. E., Trullas, A., van Waalwijk van Doorn-Khosrovani, S. B., Vart, R., Vermeulen, J., Vitaloni, M., & Verweij, J. (2024). Empowering effective biomarker-driven precision oncology: A call to action. *European Journal of Cancer, 209*, 114225. https://doi.org/10.1016/j.ejca.2024.114225

[30] Wang, S., Liu, Y., Feng, Y., Zhang, J., Swinnen, J., Li, Y., & Ni, Y. (2019). A review on curability of cancers: More efforts for novel therapeutic options are needed. *Cancers, 11*(11), 1782. https://doi.org/10.3390/cancers11111782

[31] Debela, D. T., Muzazu, S. G. Y., Heraro, K. D., Ndalama, M. T., Mesele, B. W., Haile, D. C., Kitui, S. K., & Manyazewal, T. (2021). New approaches and procedures for cancer treatment: Current perspectives. *SAGE Open Medicine, 9*, 20503121211034366. https://doi.org/10.1177/20503121211034366

[32] National Cancer Institute. (2024, November 8). *Surgery to treat cancer*. https://www.cancer.gov/about-cancer/treatment/types/surgery.

[33] Pollock, R. E., & Morton, D. L. (2003). Principles of surgical oncology. In D. W. Kufe, R. E. Pollock, R. R. Weichselbaum, et al. (Eds.), *Holland-Frei cancer medicine* (6th ed., Chap. 38). BC Decker. https://www.ncbi.nlm.nih.gov/books/NBK13204/

[34] Min, H.-Y., & Lee, H.-Y. (2022). Molecular targeted therapy for anticancer treatment. *Experimental & Molecular Medicine, 54*(10), 1670–1694).

[35] National Cancer Institute. (2022, May 31). *Targeted therapy for cancer*.

[36] National Cancer Institute. (2024, November 8). *Surgery to treat cancer*.

[37] National Cancer Institute. (2025a, May 15). *Radiation therapy for cancer*.

[38] National Cancer Institute. (2025b, May 15). *Chemotherapy to treat cancer*.

[39] National Cancer Institute. (2025c, May 15). *Hormone therapy to treat cancer*.

[40] National Cancer Institute. (n.d.). *Systemic therapy*. *NCI Dictionary of Cancer Terms*.

[41] Delaney, G., Jacob, S., Featherstone, C., & Barton, M. (2005). The role of radiotherapy in cancer treatment: Estimating optimal utilization from a review of evidence-based clinical guidelines. *Cancer, 104*(6), 1129–1137. https://doi.org/10.1002/cncr.21324

[42] Aupérin, A., Le Péchoux, C., Pignon, J.-P., Koning, C., Jeremic, B., Clamon, G., Einhorn, L., Ball, D., Trovo, M. G., Groen, H. J. M., Bonner, J. A., Le Chevalier, T., Arriagada, R., & Burdett, S. (2006). Concomitant radio-chemotherapy based on platin compounds in patients with locally advanced non-small cell lung cancer (NSCLC): A meta-analysis of individual data from 1,764 patients. *Annals of Oncology, 17*(3), 473–483.

[43] Early Breast Cancer Trialists' Collaborative Group (EBCTCG). (2005). Effects of radiotherapy and of differences in the extent of surgery for early breast cancer on local recurrence and 15-year survival: An overview of the randomised trials. *The Lancet, 366*(9503), 2087–2106. https://doi.org/10.1016/S0140-6736(05)67887-7

[44] Rose, P. G., Ali, S., Watkins, E., Thigpen, J. T., Deppe, G., Clarke-Pearson, D. L., & Insalaco, S. (2007). Long-term follow-up of a randomized trial comparing concurrent single-agent cisplatin, cisplatin-based combination chemotherapy, or hydroxyurea during pelvic irradiation for locally advanced cervical cancer: A Gynecologic Oncology Group study. *Journal of Clinical Oncology, 25*(19), 2804–2810. https://doi.org/10.1200/JCO.2006.09.4532

[45] Rose, P. G., Bundy, B. N., Watkins, E. B., Thigpen, J. T., Deppe, G., Maiman, M. A., Clarke-Pearson, D. L., & Insalaco, S. (1999). Concurrent cisplatin-based radiotherapy and chemotherapy for locally advanced cervical cancer. *The New England Journal of Medicine, 340*(15), 1144–1153. https://doi.org/10.1056/NEJM199904153401502

[46] Sauer, R., Becker, H., Hohenberger, W., Rödel, C., Wittekind, C., Fietkau, R., Martus, P., Tschmelitsch, J., Hager, E., Hess, C. F., Karstens, J. H., Liersch, T., Schmidberger, H., & Raab, R. (2004). Preoperative versus postoperative chemoradiotherapy for rectal cancer. *The New England Journal of Medicine, 351*(17), 1731–1740. https://doi.org/10.1056/NEJMoa040694

[47] Timmerman, R., McGarry, R., Yiannoutsos, C., Papiez, L., Tudor, K., DeLuca, J., Ewing, M., Abdulrahman, R., DesRosiers, C., Williams, M., & Fletcher, J. (2006). Excessive toxicity when treating central tumors in a phase II study of stereotactic body radiation therapy for medically inoperable early-stage lung cancer. *Journal of Clinical Oncology, 24*(30), 4833–4839. https://doi.org/10.1200/JCO.2006.07.5937

[48] Spencer, K. (2018). Palliative radiotherapy. *BMJ, 360*, k821. https://doi.org/10.1136/bmj.k821

[49] Barton, M. B., Frommer, M., & Shafiq, J. (2004). Role of radiotherapy in cancer control. *The Lancet Oncology*, *5*(7), 429–439. https://doi.org/10.1016/S1470-2045(04)01511-7

[50] Beadle, B. M., Smith, B. D., & Buchholz, T. A. (2004). The technological evolution of radiation therapy: Managing complexity and improving outcomes. *Seminars in Radiation Oncology*, *14*(3), 195–204. https://doi.org/10.1016/j.semradonc.2004.04.001

[51] Pan, H. Y., Haffty, B. G., Falit, B. P., Buchholz, T. A., Wilson, L. D., Hahn, S. M., & Smith, B. D. (2016). Supply and demand for radiation oncology in the United States:

Updated projections for 2015 to 2025. *International Journal of Radiation Oncology, Biology, Physics, 96*(3), 493–500. https://doi.org/10.1016/j.ijrobp.2016.02.064

[52] SEER Training Modules. (2023, December 21). *Types of radiation therapy*. National Cancer Institute. https://training.seer.cancer.gov/treatment/radiation/radiation-types.html

[53] Evans, J. M., & Matthews, J. (2020). Navigating the complexities of cancer care coordination: A systematic review of the literature. *Health Policy*, *124*(8), 834–842.

[54] Khan, N. F., Ward, A., Watson, E., & Rose, P. W. (2021). The role of primary care in the management of cancer survivors: A systematic review of current evidence and future directions. *European Journal of Cancer Care*, *30*(4), e13425.

[55] Lee, S., & Kim, J. H. (2022). Factors influencing the health-related quality of life of cancer survivors in the transition from clinical care to primary care. *Journal of Cancer Survivorship*, *16*(3), 512–521.

[56] Ballas, L. K., Elkin, E. B., Schrag, D., Minsky, B. D., & Bach, P. B. (2006). Radiation therapy facilities in the United States. *International Journal of Radiation Oncology, Biology, Physics, 66*(4), 1204–1211. doi:10.1016/j.ijrobp.2006.06.035.

[57] Baskar, R., Lee, K. A., Yeo, R., & Yeoh, K.-W. (2012). Cancer and radiation therapy: Current advances and future directions. *International Journal of Medical Sciences, 9*(3), 193–199. doi:10.7150/ijms.3635.

[58] Maroongroge, S., Wallington, D. G., Taylor, P. A., Zhu, D., Guadagnolo, B. A., Smith, B. D., Yu, J. B., & Ballas, L. K. (2022). Geographic access to radiation therapy facilities in the United States. *International Journal of Radiation Oncology, Biology, Physics, 112*(3), 600–610. doi:10.1016/j.ijrobp.2021.10.144.

[59] Carlone, M., Beckham, W., Duzenli, C., Kohli, K., & Tyldesley, S. (2024). Linear accelerator maintenance cost analysis. *Journal of Applied Clinical Medical Physics, 25*(2), e14246. https://doi.org/10.1002/acm2.14246

[60] Hogan, L., Jameson, M., Crawford, D., Alvares, S., Loo, C., Picton, M., Moutrie, Z., Pagulayan, C., Jelen, U., Dunkerley, N., Twentyman, T., de Leon, J., & Batumalai, V. (2023). Old dogs, new tricks: MR-Linac training and credentialing of radiation oncologists, radiation therapists and medical physicists. *Journal of Medical Radiation Sciences, 70*(1), 99–106. https://doi.org/10.1002/jmrs.640

[61] Spencer, K., Defourny, N., Tunstall, D., Cosgrove, V., Kirkby, K., Henry, A., Lievens, Y., & Hall, P. S. (2022). Variable and fixed costs in NHS radiotherapy; consequences for increasing hypofractionation. *Radiotherapy and Oncology, 166*, 180–188. https://doi.org/10.1016/j.radonc.2021.11.035

[62] Van Dyk, J., Zubizarreta, E., & Lievens, Y. (2017). Cost evaluation to optimise radiation therapy implementation in different income settings: A time-driven activity-based analysis. *Radiotherapy and Oncology, 125*(2), 178–185. https://doi.org/10.1016/j.radonc.2017.08.021

[63] Wijeysingha, E. S., Chin, V. Y. W., & Lian, C. P. L. (2021). Utilising virtual environments for radiation therapy teaching and learning. *Journal of Medical Imaging and Radiation Sciences, 52*(4 Suppl.), S83–S95. https://doi.org/10.1016/j.jmir.2021.07.001

[64] Tene, T., Bonilla García, N., Coello-Fiallos, D., Borja, M., & Vacacela Gomez, C. (2024). A systematic review of immersive educational technologies in medical physics and radiation physics. *Frontiers in Medicine, 11*, 1384799. https://doi.org/10.3389/fmed.2024.1384799

[65] Efendi, D., Apriliyasari, R. W., Massie, J. G. P., Wong, C. L., Natalia, R., Utomo, B., Apriyanti, E., & Chen, K.-H. (2023). The effect of virtual reality on cognitive, affective, and psychomotor outcomes in nursing staffs: Systematic review and meta-analysis. *BMC Nursing, 22*, 170. https://doi.org/10.1186/s12912-023-01312-x

[66] Jiang, H., Vimalesvaran, S., Wang, J. K., Lim, K. B., Mogali, S. R., & Tudor Car, L. (2022). Virtual reality in medical students' education: Scoping review. *JMIR Medical Education, 8*(1), e34860. https://doi.org/10.2196/34860

[67] Nassar, A. K., Al-Manaseer, F., Knowlton, L. M., & Tuma, F. (2021). Virtual reality as a simulation modality for technical skills acquisition. *Annals of Medicine and Surgery, 71*, 102945. https://doi.org/10.1016/j.amsu.2021.102945

[68] Sloboda, R. S., et al. (2011). Evaluation of a virtual environment for radiotherapy training. *Journal of Applied Clinical Medical Physics*, *12*(4).

[69] Bannister, H., Selwyn-Smith, B., Wang, J., Wilson, A., Anslow, C., dos Anjos, R. K., Medeiros, D., Robinson, B., Leong, A., & Kane, P. (2019). *LINACVR: VR simulation for radiation therapy education*. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. ACM. https://doi.org/10.1145/3359997.3365692

[70] International Atomic Energy Agency. (2014). *A handbook for the education of radiation therapists (RTTs)* (Training Course Series No. 58). International Atomic Energy Agency.

[71] Kok, D. L., Dushyanthen, S., Peters, G., Sapkaroski, D., Barrett, M., Sim, J., & Eriksen, J. G. (2022). Virtual reality and augmented reality in radiation oncology education: A review and expert commentary. *Technical Innovations & Patient Support in Radiation Oncology, 24*, 78–85. https://doi.org/10.1016/j.tipsro.2022.08.007

[72] Strasser, M., & Senger, M. H. (2024). Behind the scenes: Radiotherapy technical training through professionals' eyes. *Technical Innovations & Patient Support in Radiation Oncology, 30*, 100247. https://doi.org/10.1016/j.tipsro.2024.100247

[73] Gresham, G., Schrack, J. A., Gresham, L., Shinde, A., Andrew Eugene Hendifar, Tuli, R., Rimel, B. J., Figlin, R. A., Meinert, C. L., & Piantadosi, S. (2018a). Wearable activity monitors in oncology trials: Current use of an emerging technology. *Contemporary Clinical Trials*, *64*, 13–21. https://doi.org/10.1016/j.cct.2017.11.002

[74] Griffin, A. C., Topaloglu, U., Davis, S., & Chung, A. E. (2020). From patient engagement to precision oncology: Leveraging informatics to advance cancer care. *Yearbook of Medical Informatics, 29*(1), 235–242. https://doi.org/10.1055/s-0040-1701983

[75] Low, C. A. (2020). Harnessing consumer smartphone and wearable sensors for clinical cancer research. *npj Digital Medicine, 3*, Article 140. https://doi.org/10.1038/s41746-020-00351-x

[76] Bibault, J. F., Giraud, P., & Burgun, A. (2018). Big Data and artificial intelligence in radiation oncology: A primer. *Cancer/Radiothérapie*, *22*(1), 18–24. https://doi.org/10.1016/j.canrad.2017.07.045

[77] Pasquier, D., Lacornerie, T., Daguenet, E., & Lartigau, E. (2020). Virtual reality for radiotherapy: A systematic review. *Technical Innovations & Patient Support in Radiation Oncology*, *13*, 1–9. https://doi.org/10.1016/j.tipsro.2019.11.009

[78] Landry, G., Kurz, C., & Traverso, A. (2023). The role of artificial intelligence in radiotherapy clinical practice. *BJR Open, 5*(1), Article 20230030. https://doi.org/10.1259/bjro.20230030

[79] American Cancer Society. (2025, June 9). *Getting external beam radiation therapy*.

[80] Gamboa, O., Cotes, M., Valdivieso, J., Henriquez, G., Bobadilla, I., Esguerra, J. A., & Wiesner, C. (2021). Estimation of the need for radiation therapy services according to the incidence of cancer in Colombia to 2035. *Advances in Radiation Oncology, 6*(6), 100771. https://doi.org/10.1016/j.adro.2021.100771

[81] U.S. Food and Drug Administration. (2025, December 22). *Recognized consensus standards: Medical devices* (§892.5050 Accelerator, linear, medical, Class 2, product code IYE).

[82] Zhu, H., Elmore, S. N., Barton, M. B., Zubizarreta, E., Lievens, Y., & Hanna, T. P. (2024). Global radiotherapy demands and corresponding radiotherapy-professional workforce requirements in 2022 and predicted to 2050: A population-based study. *The Lancet Global Health*.

[83] International Atomic Energy Agency. (2025). *A framework for the education of radiation therapists* (Training Course Series No. 89). International Atomic Energy Agency.

[84] Campbell, M., Leong, A., & Scherer, P. (2024). Evaluation of RTT education – Is it fit for the present: A report on the ESTRO radiation therapist workshop. *Technical Innovations & Patient Support in Radiation Oncology, 30*, 100246. https://doi.org/10.1016/j.tipsro.2024.100246

[85] Kang, J., Thompson, R. F., Aneja, S., Lehman, C., Trister, A., Zou, J., Obcemea, C., & El Naqa, I. (2021). National Cancer Institute workshop on artificial intelligence in radiation oncology: Training the next generation. *Practical Radiation Oncology, 11*(1), 74–83. https://doi.org/10.1016/j.prro.2020.06.001

[86] Kyaw, B. M., Saxena, N., Posadzki, P., Vseteckova, J., Nikolaou, C. K., George, P. P., Divakar, U., Masiello, I., Kononowicz, A. A., Zary, N., & Tudor Car, L. (2019). Virtual

reality for health professions education: Systematic review and meta-analysis by the Digital Health Education Collaboration. *Journal of Medical Internet Research, 21*(1), e12959. https://doi.org/10.2196/12959

[87] Boero, I. J., Paravati, A. J., Triplett, D. P., Hwang, L., Matsuno, R. K., Gillespie, E. F., Yashar, C. M., & Murphy, J. D. (2016). Importance of radiation oncologist experience among patients with head-and-neck cancer treated with intensity-modulated radiation therapy. *Journal of Clinical Oncology, 34*(7), 684–690. https://doi.org/10.1200/JCO.2015.63.2232

[88] Grover, S., Elmore, S. N., Roshan, V., Fidarova, E., Healy, B., Mehta, M. P., Rosenblatt, E., Abdel-Wahab, M., & Lievens, Y. (2024). Global workforce and access: Demand, education, quality. *Clinical Oncology, 36*(11), e775–e782. https://doi.org/10.1016/j.clon.2024.07.014

[89] Hammad, N., Heilman, S., MacLean, A. R., Qureshi, A., Shiu, R., Brenner, D. R., Cheung, W. Y., Dent, S., Doherty, M., Eng, L., Krzyzanowska, M. K., Petrella, T. M., Porter, G., Sourkes, B., Stober, C., Swami, N., Thavorn, K., Tomiak, E., Xu, W., & Chan, K. K. W. (2023). Competency-based workforce development and education in oncology. *Current Oncology, 30*(2), 1956–1968. https://doi.org/10.3390/curroncol30020150

[90] Kelly, T. (2021). A radiation therapist's guide to health literacy: A narrative review. *Journal of Medical Radiation Sciences, 68*(4), 469–482. https://doi.org/10.1002/jmrs.531

[91] Mireștean, C. C., Pop, O. T., Căinap, C., & Fodor, D. (2022). Education in radiation oncology—Current challenges and difficulties. *Medicina, 58*(4), 495. https://doi.org/10.3390/medicina58040495

[92] Jonassen, D. H. (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? *Educational Technology Research and Development, 39*(3), 5–14. https://doi.org/10.1007/BF02296434

[93] Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice-Hall.

[94] Makransky, G., & Petersen, G. B. (2021). The Cognitive Affective Model of Immersive Learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review, 33*(3), 937–958. https://doi.org/10.1007/s10648-020-09586-2

[95] Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

[96] McGaghie, W. C., Issenberg, S. B., Cohen, E. R., Barsuk, J. H., & Wayne, D. B. (2011). Does simulation-based medical education with deliberate practice yield better results than traditional clinical education? Academic Medicine, 86(6), 706–711. https://doi.org/10.1097/ACM.0b013e318217e119

[97] Issenberg, S. B., McGaghie, W. C., Petrusa, E. R., Gordon, D. L., & Scalese, R. J. (2005). Features and uses of high-fidelity medical simulations that lead to effective learning: A BEME systematic review. Medical Teacher, 27(1), 10–28. https://doi.org/10.1080/01421590500046924

[98] Lateef, F. (2010). Simulation-based learning: Just like the real thing. Journal of Emergencies, Trauma, and Shock, 3(4), 348–352. https://doi.org/10.4103/0974-2700.70743

[99] Boejen, A. (2011). Virtual reality in radiation therapy training: Review of immersive visualization for planning and delivery.

[100] Grilo, A. M., Almeida, B., Rodrigues, C., Gomes, A. I., & Caetano, M. (2023). Using virtual reality to prepare patients for radiotherapy: A systematic review of interventional studies with educational sessions. Technical Innovations & Patient Support in Radiation Oncology, 25, 100203. https://doi.org/10.1016/j.tipsro.2023.100203

[101] Sandhu, K. S., & Vans, M. (2024). Virtual reality (VR) space for radiation oncology education and collaborative learning. Society for Imaging Science and Technology, 354–356. https://doi.org/10.2352/EI.2024.36.2.SDA-354

[102] Gallagher, A., & Cates, C. (2004). Virtual reality training for the operating room and cardiac catheterisation laboratory. Lancet, 364, 1538–1540.

[103] Buttussi, F., & Chittaro, L. (2017). Effects of different types of virtual reality display on presence and learning in a safety training scenario. IEEE Transactions on Visualization and Computer Graphics.

[104] Mao, R. Q., Lan, L., Kay, J., Lohre, R., Ayeni, O. R., Goel, D. P., & de Sa, D. (2021). Immersive virtual reality for surgical training: A systematic review. Journal of Surgical Research, 268, 40–58. https://doi.org/10.1016/j.jss.2021.06.045

[105] Zasadzka, E., Pieczyńska, A., Trzmiel, T., & Hojan, K. (2021). Virtual reality as a promising tool supporting oncological treatment in breast cancer. International Journal of Environmental Research and Public Health, 18(16), 8768. https://doi.org/10.3390/ijerph18168768

[106] Bandura, A. (1997). Self-efficacy: The exercise of control. W.H. Freeman.

[107] Kruger, J., & Dunning, D. (1999). Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. Journal of Personality and Social Psychology, 77(6), 1121.

[108] Sweller, J., Ayres, P., & Kalyuga, S. (2011). Cognitive load theory. Springer.

[109] Yardley, S., Teunissen, P. W., & Dornan, T. (2012). Experiential learning: Transforming theory into practice. Medical Teacher, 34(2), 161–164.

[110] Miller, G. E. (1990). The assessment of clinical skills/competence/performance. Academic Medicine, 65(9), S63–S67.

[111] Epstein, R. M., & Hundert, E. M. (2002). Defining and assessing professional competence. JAMA, 287(2), 226–235.

[112] van der Vleuten, C. P. M., Schuwirth, L. W. T., Driessen, E. W., Dijkstra, J., Tigelaar, D., Baartman, L. K. J., & van Tartwijk, J. (2012). A model for programmatic assessment fit for purpose. Medical Teacher, 34(3), 205–214.

[113] Arthur, W., Bennett, W., Stanush, P. L., & McNelly, T. L. (1998). Factors that influence skill decay and retention: A quantitative review and analysis. Human Performance, 11(1), 57–101. https://doi.org/10.1207/s15327043hup1101_3

[114] Cook, D. A., Hatala, R., Brydges, R., et al. (2011). Technology-enhanced simulation for health professions education: A systematic review and meta-analysis. JAMA, 306(9), 978–988. https://doi.org/10.1001/jama.2011.1234

[115] D.M. Halliday, J.R. Rosenberg, A.M. Amjad, P. Breeze, B.A. Conway, and S.F. Farmer. 1995. A framework for the analysis of mixed time series/point process data—Theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. Progress in Biophysics and Molecular Biology 64, 2 (1995), 237–278.

[116] Atun, R., Jaffray, D. A., Barton, M. B., Bray, F., Baumann, M., Vikram, B., Hanna, T. P., Knaul, F. M., Lievens, Y., Lui, T. Y. M., Milosevic, M., O'Sullivan, B., Rodin, D. L., Rosenblatt, E., Van Dyk, J., Yap, M. L., Zubizarreta, E., & Gospodarowicz, M. (2015).

Expanding global access to radiotherapy. The Lancet Oncology, 16(10), 1153–1186. https://doi.org/10.1016/S1470-2045(15)00222-3

[117] Abdel-Wahab, M., Grover, S., Yap, M. L., Zubizarreta, E., Moraes, F. Y., Gospodarowicz, M., & others. (2024). Radiotherapy and theranostics: A Lancet Oncology Commission. The Lancet Oncology. https://doi.org/10.1016/S1470-2045(24)00407-8

[118] American Association for Cancer Research. (2023). AACR cancer progress report 2023. American Association for Cancer Research. https://cancerprogressreport.aacr.org/

[119] Martin, J. A., Regehr, G., Reznick, R., MacRae, H., Murnaghan, J., Hutchison, C., et al. (1997). Objective structured assessment of technical skill (OSATS) for surgical residents. *British Journal of Surgery, 84*(2), 273–278.

[120] Ilgen, J. S., Ma, I. W. Y., Hatala, R., & Cook, D. A. (2015). A systematic review of validity evidence for checklists versus global rating scales in simulation-based assessment. *Medical Education, 49*(2), 161–173.

[121] Henrico, K., Bezuidenhout, J., Burch, V., & Treadwell, I. (2023). Use of global rating scales and checklists in clinical simulation-based assessments: A protocol for a scoping review. *BMJ Open, 13*, e069960.

[122] Bloom, B. S. (1968). Learning for mastery. *Evaluation Comment, 1*(2), 1–12.

[123] McGaghie, W. C., Issenberg, S. B., Cohen, E. R., Barsuk, J. H., & Wayne, D. B. (2011). Medical education featuring mastery learning with deliberate practice can lead to better health for individuals and populations. *Academic Medicine, 86*(11), e8–e9.

SURVEY INSTRUMENTS

Pre/Post/Retention Knowledge Assessment

Instructions: Select the best answer for each of the following multiple-choice questions.

1. What is the primary function of the LINAC in radiation Therapy
   A. Diagnostic imaging
   B. Generation of therapeutic radiation beams
   C. Patient immobilization
   D. Tumor detection
2. What is the main purpose of performing an automated dry run in the TrueBeam system?
   A. To calibrate the LINAC gantry
   B. To deliver low-dose imaging before treatment
   C. To visually confirm that the gantry will not collide with the patient or equipment
   D. To reposition the couch and table for comfort
3. Which of the following must be held down to initiate couch motion during auto-move?
   A. The collision override button
   B. The navigation wheel on the console
   C. The motion enable bars (MEBs)
   D. The patient safety lock
4. During automation, what does an orange highlight on the in-room machine monitor indicate?
   A. System is offline

B. Position is correct and locked

C. Value is out of planned treatment position

D. Imaging needs to be recalibrated

5. What feature allows the system to move the couch or gantry into the planned position automatically?

A. Manual override

B. Preload planner

C. Auto-move buttons

D. Remote sync

6. What action should you take if the LaserGuard II system stops the gantry due to a perceived collision risk?

A. Exit the treatment room immediately

B. Restart the entire dry run

C. Confirm the alert, assess clearance, and use collision reset if safe

D. Disable the safety interlock manually

7. What components are involved when performing a collision reset?

A. Auto-move button, laser guide, and foot pedal

B. MEBs, collision reset button, and thumbstick/pendant navigation

C. Imaging screen, beam-on switch, and couch lock

D. Patient monitor, setup tab, and verification scan

8. What indicates that the gantry is clear of the collision zone during a collision reset?

A. The couch begins to rotate automatically

B. A green checkmark appears on the monitor

C. An audible "ding" is heard

D. The beam automatically turns on

9. What does a green bar next to a treatment field mean during the automated dry run setup?

A. That the field has not been programmed

B. That the system is offline

C. That automation has been successfully added to the field

D. That patient protection has been disabled

10. What is the safest position to stand during gantry rotation for optimal collision visibility?

A. Behind the treatment console

B. Left side of the couch (patient's right)

C. Right side of the couch (patient's left)

D. Outside the treatment room

11. What is the correct sequence to begin automation after selecting a patient plan?

A. Treat → Add → Add Automation

B. Add → Treat → Add Automation

C. Select plan → Press Beam On → Auto-Move

D. Explore Mode → Setup → Run

12. What should you do if you accidentally release the Motion Enable Bars (MEBs) during automation?

A. The system will resume on its own

B. Motion will stop and must be restarted by re-selecting the treatment field

C. Automation will reset, and you must repeat all setup steps

D. Nothing happens; automation continues

13. What is the purpose of turning on the laser during setup?

    A. To enable imaging of internal organs

    B. To align the gantry angle

    C. To verify the patient is centered at isocenter

    D. To activate patient protection

14. In the Patient Protection module, what triggers the gantry to stop automatically?

    A. A misaligned treatment plan

    B. A sensor detecting motion from the hand pendant

    C. The patient's body entering the LaserGuard II protection zone

    D. A dropped network connection

15. What must you do immediately after a patient protection stop is triggered?

    A. Exit the VR simulator

    B. Override all safety interlocks

    C. Acknowledge the fault using the hand pendant

    D. Call a supervisor to continue

Training Effectiveness Survey

These are 40 MCQ to gauge training effectiveness. A 5-point Likert scale seems to be the most accurate and offers more granularity, capturing a wider range of opinions. A 5-point Likert scale would be like; (1) Strongly Disagree; (2) Disagree; (3) Neither Agree Nor Disagree; (4) Agree; (5) Strongly Agree

1. ID
2. The training method effectively conveyed the necessary theoretical knowledge for radiation therapy
3. The training method helped me develop practical skills required for radiation therapy
4. The learning process was efficient and well-structured.
5. The training helped me understand spatial relationships in the treatment area
6. I can accurately replicate radiation therapy procedures based on the training provided
7. The training allowed me to practice hands-on skills effectively
8. I feel equipped to handle to handle basic machine functions
9. I am confident in my ability to perform tasks safely and efficiently after the training
10. The training method kept me engaged and motivated throughout
11. The learning environment (traditional or VR) felt immersive and realistic
12. I was able to focus better and retain information effectively in this training environment
13. I feel confident in my ability to maneuver the machine and its various parts
14. The training method significantly improved my confidence in performing basic tasks on the machine

15. I feel confident in troubleshooting issues that may arise during radiation therapy procedures
16. I am confident in my ability to communicate effectively with patients and colleagues in a clinical setting
17. I feel well-prepared to perform basic tasks required on the machine
18. The training provided me with the necessary skills to adapt to unexpected situations during radiation therapy procedures
19. The training included sufficient opportunities to practice skills in realistic settings
20. The training accurately reflected the challenges encountered in real-world radiation therapy.
21. The training method was engaging and motivated me to learn
22. I stayed focused and actively participated throughout the training sessions
23. Compared to traditional training methods, this training method better prepared me for real-world scenarios
24. The VR training system was easy to use and navigate
25. The controls and interface of the VR training system were intuitive
26. I experienced minimal technical issues during the VR training sessions
27. The VR training system was comfortable to use for extended periods
28. The VR training improved my understanding of radiation therapy concepts
29. The VR system provided a realistic simulation of clinical scenarios
30. The VR training enhanced my ability to perform technical tasks required in radiation therapy
31. The training helped me feel better prepared for real-world clinical work

32. VR training offered unique learning opportunities that are not available through traditional methods.
33. The VR training was engaging and kept me focused throughout the session
34. I found the VR training to be a motivating way to learn radiation therapy concepts
35. The immersive environment of VR made the training more enjoyable than traditional methods.
36. I believe VR is a valuable tool for radiation therapy training
37. I would recommend VR training to other radiation therapy trainees
38. Compared to traditional training, VR provides a superior learning experience
39. What aspects of VR training did you find most effective or beneficial? [Open ended]
40. What challenges or limitations did you experience while using the VR training system? [Open ended]
41. How could the VR training system be improved to better meet your learning needs? [Open ended]

Keep Blank