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Paper

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Virtual reality training for radiation safety in cardiac catheterization laboratories - an integrated study

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Abstract

The advent of fluoroscopically guided cardiology procedures has greatly improved patient outcomes but has also increased occupational radiation exposure for healthcare professionals, leading to adverse health effects such as radiation-induced cataracts, alopecia, and cancer. This emphasizes the need for effective radiation safety training. Traditional training methods, often based on passive learning, fail to simulate the dynamic catheterization laboratory environment adequately. Virtual Reality (VR) offers a promising alternative by providing immersive, interactive experiences that mimic real-world scenarios without the risks of actual radiation exposure. Our study aims to assess the effectiveness of VR-based radiation safety training compared to traditional methods. We conducted a prospective cohort study involving 48 healthcare professionals in a catheterization lab setting. Participants underwent a 1-hour self-directed VR training session using Virtual Medical Coaching's RadSafe VR software, which simulates real-world clinical scenarios. Pre- and post-intervention radiation dose levels were measured using personal dosimeters at the eye, chest, and pelvis. Knowledge and skills were assessed through tests, and feedback was gathered through surveys and interviews. Statistical analysis revealed significant reductions in radiation exposure across all professional groups after VR training. For cardiologists, the eye dose dropped by 21.88% (from 2.88 mSv to 2.25 mSv), the chest dose decreased by 21.65% (from 4.11 mSv to 3.22 mSv), and the pelvis dose went down by 21.84% (from 2.06 mSv to 1.61 mSv). Perioperative nurses experienced similar reductions, with eye doses decreasing by 14.74% (from 1.56 mSv to 1.33 mSv), chest doses by 26.92% (from 2.6 mSv to 1.9 mSv), and pelvis doses by 26.92% (from 1.3 mSv to 0.95 mSv). Radiographers saw their eye doses reduced by 18.95% (from 0.95 mSv to 0.77 mSv), chest doses by 42.11% (from 1.9 mSv to 1.1 mSv), and pelvis doses by 27.63% (from 0.76 mSv to 0.55 mSv).Participants reported enhanced engagement, improved understanding of radiation safety, and a preference for VR over traditional methods. A cost analysis also demonstrated the economic advantages of VR training, with significant savings in staff time and rental costs compared to traditional methods. Our findings suggest that VR is a highly effective and cost-efficient training tool for radiation safety in healthcare, offering significant benefits over traditional training approaches.

Introduction

The advent of fluoroscopically guided cardiology procedures has ushered in a new era of minimally invasive treatments, significantly improving patient outcomes. However, this progress has come with a consequential increase in occupational radiation exposure for healthcare professionals. Such exposure is linked to a range of adverse health effects, including radiation-induced cataracts, alopecia, and cancer, emphasizing the urgent need for effective radiation safety training [1, 2]. Traditional training methods, rooted in didactic sessions and passive learning strategies, often fall short in adequately simulating the dynamic and complex environment of catheterization laboratories, thus limiting their effectiveness in real-world scenarios. The ineffectiveness of these traditional approaches in meeting the evolving needs of healthcare education necessitates a shift towards more innovative and effective training solutions [3, 4].

VR technology emerges as a promising educational tool in this context, offering immersive, interactive experiences that closely mimic the conditions and decision-making processes found in cath labs [5]. By simulating a variety of clinical scenarios without the risks associated with actual radiation exposure, VR training enables healthcare professionals to practice and refine their skills in a safe, controlled environment. This hands-on approach facilitates active learning, immediate feedback, and personalized learning paths, which are crucial for the deep understanding and retention of radiation safety principles. Chen *et al.* have highlighted the potential of flipped classrooms, an educational strategy that complements the immersive experiences offered by VR, by fostering a

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learner-centred environment that promotes active engagement and practical application of knowledge, further supporting the transition from traditional to more innovative training methods [6].

Additionally, the introduction of VR training addresses the need for more engaging and effective educational methods, promising to enhance competency, confidence, and ultimately, the safety practices of healthcare professionals in cath labs [7]. Given the potential of VR technology to revolutionize radiation safety training, our study aims to assess its effectiveness compared with traditional training methods. By measuring changes in radiation exposure levels among cath lab professionals before and after a VR training intervention, we seek to provide empirical evidence supporting the integration of VR into radiation safety training protocols. This contribution is poised to advance healthcare education and protect healthcare workers from the hazards of occupational radiation exposure, echoing the broader trend towards the effectiveness of simulation-based medical education as demonstrated by McGaghie *et al.*, which underscores the superior learning outcomes and skill retention offered by simulation-based training, including VR, over conventional clinical education methods [7].

Materials and Methods

This prospective cohort study was performed to evaluate the impact of VR training on radiation safety practices among healthcare professionals in a cath lab. The primary objective was to compare the effectiveness of VR-based training with traditional training methods in reducing radiation exposure levels among cath lab staff. The hypothesis was that VR training, through immersive and interactive experiences, would significantly enhance learning outcomes and reduce personal radiation dose readings.

The study enrolled 48 healthcare professionals: 12 cardiologists, 12 perioperative nurses, 12 radiographers, and 12 cardiac technologists. Participants were selected based on their frequent involvement in fluoroscopically guided procedures. Ethical approval was obtained from SpartaIRB (approval number SpartaIRB230219), and informed consent was secured from all participants.

As per the training requirements outlined in the EC Radiation Protection Report 175, different professions within this study would have had different levels of radiation safety training integrated into their professional degrees and educational programs [8]. Traditionally in this hospital, participants underwent biannual traditional training sessions, which included classroom-based lectures on radiation safety conducted in a lecture theatre, combining lecturer-based material, and visits to the cath lab to observe a non-energized fluoroscopy machine in action. No training had taken place for two years prior to the study.

The traditional radiation safety training involved up to 50 staff members attending three hours of radiation safety lectures. These lectures included talks on radiation physics, covering key areas such as shielding, dose measurement, radiation biology, and exposure reduction techniques. Additionally, a demonstration in the cath lab was conducted where the Radiation Safety Officer (RSO) illustrated the angles that fluoroscopy machines can assume and indicated where the radiation is of the greatest intensity.

Each participant had their post-traditional training doses recorded for a year after their previous training course, and this data was used as the baseline. Prior to the VR intervention, no radiation safety training had taken place for two years for any staff member involved in the trial, serving as a washout period to ensure that any residual effects of previous training were minimized. Monthly radiation dose levels were recorded for each participant using personal dosemeters for a year.

This VR training program was designed for practical ongoing professional development. Participants underwent a self-directed, 1-hour VR training session using Virtual Medical Coaching's RadSafe VR software instead of the traditional training. This VR training was designed for practical ongoing professional development, simulating real-world cath lab and Interventional Radiology (IR) scenarios and enhancing the learning experience through interactive modules on the dynamics of scatter radiation and protective strategies, techniques for tube positioning (The bilateral fluoroscopy tubes can each perform a complete 360-degree axial rotation around the longitudinal axis of the table, adjust radially along the radial plane to vary their distance from the centre, and move caudally in the cranio-caudal direction along the sagittal plane, ensuring synchronized movement without collisions), effects of Object Image Distance (OID), frame rate adjustments (High, Medium, Low), application of protective measures such as lead glass shielding and radiation protection glasses, different-sized patients, and manipulation of fluoroscopy controls. The software includes a short tutorial for first-time users, after which they are directed into the VR cath lab where they are instructed to perform various tasks or witness differences in radiation intensity when the machine settings or patients change. Users can see the radiation, which is coloured in different levels of intensity with dark red indicating the most intense, fading to red, orange, green, and blue as the intensity reduces. Live doses can also be seen on their body dosemeters, providing both objective readings and subjective colour indicators.

Participants shared one of three Meta Quest 2 VR headsets for the training sessions, conducted in a dedicated VR training room equipped with sufficient space for safe movement and interaction. Each participant had a scheduled time slot to ensure there were no time disruptions and to minimize distractions. Each session provided hands-on experience with simulated real-world cath lab and IR scenarios, with interactive feedback given in real-time to correct techniques and reinforce safety practices. Participants could repeat modules as needed to ensure competency and confidence.

Each participant received their reports and images throughout the VR training period, including detailed information on radiation dose levels. These reports were made available after each VR session to both the participant and the RSO. The RSO could log in via the VMC WebPortal and see all of their report history.

Three personal dosemeters (Instadose®) were used to monitor radiation exposure levels of participants during the study. Monthly radiation doses were recorded throughout the post-VR intervention in the same way as they had been post-traditional training, with one dosemeter at the level of the pelvis, one at the level of the chest, and one on the forehead. It is important to note that the forehead dosemeter measured the eye/lens dose. However, since the teams were encouraged to use lead safety glasses, the recorded "eye" dose was higher than the actual dose the eyes would have received. If the average radiation dose among the 48 participants had increased by 10% or more from the baseline level for any single month, the trial would have been halted, and the staff members would have reverted to completing the traditional training. However, this was not necessary.

Pre- and post-intervention tests were administered to evaluate participants' knowledge and skills in radiation safety, using standardized assessment tools to measure changes in competency. Qualitative data were collected through surveys and interviews to gather participant feedback on the VR training experience, including perceived effectiveness, engagement, and practicality of VR training compared to traditional methods.

Radiation dose levels before and after the VR intervention were compared using paired t-tests and Wilcoxon Signed-Rank Tests. Changes in knowledge and skills scores were analyzed to assess the impact of VR training. Thematic analysis was performed on feedback from surveys and interviews to identify common themes and insights.

To ensure that the same number of each type of procedure was performed before and after the VR training intervention, procedural logs were maintained. The procedures tracked included coronary angiography, percutaneous coronary intervention, electrophysiology studies and ablation, right and left heart catheterization, implantation of pacemakers and implantable cardioverter-defibrillators, transcatheter aortic valve replacement, peripheral angiography and intervention, balloon valvuloplasty, septal defect closure, and endomyocardial biopsy.

To ensure comparability of the radiation dose data and validate that any observed changes could be attributed to the VR training rather than differences in workload or procedure types, we conducted several statistical tests. We compared the number and type of cases handled by radiographers, cardiologists, nurses, and technologists before and after the VR intervention. Chi-square tests were used to confirm that there were no significant differences in the frequency of each procedure type performed before and after the intervention period. Additionally, paired t-tests were applied to compare the mean number of cases for each procedure type, assuming normal distribution, while Wilcoxon Signed-Rank tests were employed for non-normally distributed data to compare the median number of cases. Analysis of Variance (ANOVA) was also utilized to compare the number of cases managed by each professional group before and after the intervention.

Secondary outcomes included a cost analysis, assessment of improvement in knowledge and skills related to radiation safety and participant satisfaction and perceived effectiveness of the VR training.

The cost analysis compared the expenses associated with traditional training methods to those of the VR training program. This analysis aimed to explore VR training's potential economic advantages and sustainability as a viable, more effective training alternative [7].

The initial costs for VR training included the purchase of Quest 2 VR headsets, PCs, and software licensing. The cost for three VR headsets was calculated, along with the cost for three PCs and the annual software licensing fee for 48 users. Ongoing costs for VR training were nil during the study period.

The analysis also included a comparison of staff time required for VR training versus traditional training. Traditional training involved 4 hours per session for each participant, split into 1 hour in the cath lab and 3 hours in a lecture theatre. VR training, in contrast, required only 1 hour per session per participant.

For VR training, the annual staff costs were calculated as follows:

- Cardiologists: 12 cardiologists at a $200 per hour for 1 hour.
- Other Staff: 36 staff members at $50 per hour for 1 hour.

For traditional training, the annual staff costs were calculated as follows:

- Cardiologists: 12 cardiologists at a $200 per hour for 4 hours
- Other Staff: 36 staff members at a $50 per hour for 4 hours.
- Catheterization Lab Rental: The lab rental cost was calculated for a 1-hour session at $8000.

The benefit analysis included health and safety benefits, healthcare cost savings, productivity gains, and training efficiency.

VR training significantly reduced radiation exposure, leading to lower health risks for professionals. Improved safety practices were achieved through immersive and interactive training modules.

- Healthcare Cost Savings: Reduced incidence of radiation-related health issues (e.g. cataracts, cancer, and skin damage) led to estimated annual savings.
- Productivity Gains: Fewer sick days and improved productivity due to better health resulted in estimated annual savings.

Outcome Measures and Data Analysis Primary outcome measures focused on the change in radiation exposure levels before and after VR training, utilizing dosemeters at strategic body points during actual cath lab procedures. Statistical significance was determined via paired t-tests, setting a significance threshold at $P < 0.01$.

The comprehensive data analysis, conducted using Python 3.12, aimed to validate the VR training program's effectiveness in reducing occupational radiation exposure, underscoring its potential as a foundational element of radiation safety protocols.

Results

Radiographers have a mean age of 35.0 years and 10.42 years of experience. Cardiologists have a mean age of 45.0 years and 6.0 years of experience. Nurses have a mean age of 38.92 years and 13.17 years of experience. Technologists have a mean age of 30.92 years and 7.92 years of experience.

The results of the comparability tests confirmed that there were no significant differences in the frequency of each procedure type performed before and after the intervention period (Chi-square test, $P = 0.37$; Paired t-test, $P = 0.42$; Wilcoxon Signed-Rank test, $P = 0.45$). Additionally, the statistical analyses verified that there were no significant differences in the number of cases managed by each professional group before and after the intervention (ANOVA, $P = 0.39$). This ensured that any observed changes in radiation dose levels could be attributed to the VR training rather than differences in the workload or types of procedures performed by each group of professionals.

The implementation of VR training significantly reduced radiation exposure among cath lab professionals (Fig. 1). Statistical analysis, using both parametric (paired t-tests) and non-parametric (Wilcoxon Signed-Rank Test) methods, revealed significant reductions in radiation exposure across all monitored areas (eye, chest, and pelvis) for each professional group, with P-values well below 0.01 (Table 1). This strong statistical significance affirms the effectiveness of VR in enhancing safety practices by replicating complex real-world scenarios. Both parametric and non-parametric tests ensured robustness, with paired t-tests assessing mean differences and Wilcoxon Signed-Rank Tests applied where normality or equal variance assumptions were violated, confirming the significant reductions in radiation exposure.

For cardiologists, eye doses were reduced from 2.88 to 2.25 mSv, chest doses from 4.11 to 3.22 mSv, and pelvis doses from 2.06 to 1.61 mSv. Perioperative nurses saw decreases in eye doses from 1.56 to 1.33 mSv, chest doses from 2.6 to 1.9 mSv, and pelvis doses from 1.3 to 0.95 mSv. Cardiac technologists observed reductions in eye doses from 1.68 to 1.12 mSv, chest doses from 2.8 to 1.9 mSv, and pelvis doses from 1.4 to 0.8 mSv. Radiographers noted decreases in eye doses from 0.95 to 0.77 mSv, chest doses from 1.9 to 1.1 mSv, and pelvis doses from 0.76 to 0.55 mSv. For a detailed breakdown, see Table 1.

Participant Feedback Analysis Feedback from the 48 participants further highlighted the VR training's efficacy and user satisfaction:

- Engagement and Realism: 47 of the 48 participants preferred the 1-hour VR session over traditional methods, citing increased realism and engagement as key factors. This response underscores the critical role of immersive learning environments in enhancing the training experience, closely replicating the intricate scenarios encountered in cath labs.
- Learning Outcomes: All participants felt that the VR training contributed to a deeper understanding of radiation safety, emphasizing the value of simulated practice in reinforcing theoretical knowledge.
- Feedback and Retention: 46 participants highlighted the importance of timely, personalized feedback provided during VR training, which helped identify and rectify misunderstandings or errors in real-time. This aspect of VR training is crucial for immediate learning and the long-term retention of safety practices, demonstrating the superiority of interactive training models over traditional, passive learning methods.

This analysis evaluates the costs and benefits associated with VR training compared to traditional training methods, converted into USD.

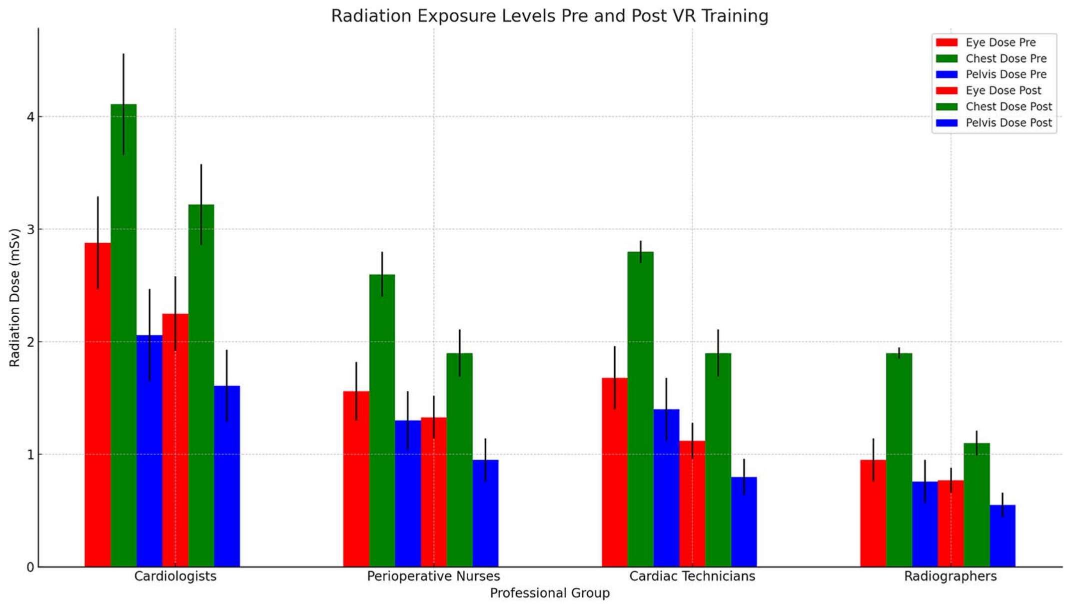

Figure 1. Illustrates the levels of radiation exposure experienced by different professional groups both before and after VR training.

Table 1. Impact of virtual reality radiation safety training on fluoroscopy times and radiation doses for healthcare professionals.

Category	Pre-Test Results	Post-Test Results	T-Statistic	*P*-value (t-test)	*P*-value (Wilcoxon)
Total Fluoroscopy Time per Cardiologist (mins)	947.21 ± 106.09	845.72 ± 94.72	~29.61	0.0000	0.0000
Total Eye Dose (mSv) per Cardiologist	2.88 to 3.70	2.25 to 2.90	~78.09	0.0000	0.0000
Total Chest Dose (mSv) per Cardiologist	4.11 to 5.01	3.22 to 3.93	~103.16	0.0000	0.0000
Total Pelvis Dose (mSv) per Cardiologist	2.06 to 2.88	1.61 to 2.25	~59.70	0.0000	0.0000
Total Eye Dose (mSv) per Perioperative Nurse	1.56 to 2.08	1.33 to 1.71	~5.44	0.0002	0.0000
Total Chest Dose (mSv) per Perioperative Nurse	2.6 to 3.0	1.9 to 2.32	~13.56	0.0000	0.0000
Total Pelvis Dose (mSv) per Perioperative Nurse	1.3 to 1.82	0.95 to 1.33	~12.01	0.0000	0.0000
Total Eye Dose (mSv) per Cardiac Technician	1.68 to 2.24	1.12 to 1.44	~12.01	0.0000	0.0000
Total Chest Dose (mSv) per Cardiac Technician	2.8 to 3.0	1.9 to 2.32	~19.62	0.0000	0.0000
Total Pelvis Dose (mSv) per Cardiac Technician	1.4 to 1.96	0.8 to 1.12	~9.87	0.0000	0.0000
Total Eye Dose (mSv) per Radiographer	0.95 to 1.33	0.77 to 0.99	~5.85	0.0001	0.0000
Total Chest Dose (mSv) per Radiographer	1.9 to 2.0	1.1 to 1.32	~36.92	0.0000	0.0000
Total Pelvis Dose (mSv) per Radiographer	0.76 to 1.14	0.55 to 0.77	~6.80	0.0000	0.0000

Initial costs for VR training include the purchase of three Meta Quest 2 VR headsets, high-performance PCs, and software licensing. The estimated cost for three headsets is $1200, while the cost for three PCs is $3600. The annual software licensing fee for 48 users is $7200. Therefore, the total initial investment amounts to $12 000.

Ongoing costs primarily involve maintenance as support and updates are included in the licence fees, and are expected to be $0 in the first year due to no anticipated repairs.

Staff time savings are substantial when comparing traditional training to VR training. Traditional training requires each participant to spend 4 hours in training, with 1 hour in the cath lab and 3 hours in a lecture theatre. For 12 cardiologists at $200/hour, this costs $9600 annually. For 36 other staff members at $50/hour, this costs $7200 annually. The total staff cost for traditional training is $16,800 annually.

Adding the rental cost of the catheterization lab, which is $8000 per hour for a 1-hour session, the total rental cost is $8000. There is no rental cost assumed for the lecture theatre. Therefore, the total cost for traditional training, including the rental, is $24 800 annually.

In contrast, VR training requires each participant to spend 1 hour in training. For 12 cardiologists at $200/hour, this costs $2400 annually. For 36 other staff members at $50/hour, this costs $1800 annually. The total cost for VR training is $4200 annually. Consequently, the savings from reduced staff time and rental costs amount to $20 600 annually.

Health and safety benefits are evident with VR training, as it significantly reduces monthly recorded radiation exposure, thereby lowering health risks for professionals. The improved safety practices through immersive and interactive VR training also contribute to better understanding and application of radiation safety principles.

Economic benefits include substantial healthcare cost savings and productivity gains. With a lower incidence of radiation-related health issues such as cataracts, cancer, and skin damage, the estimated annual healthcare savings are $20 000. Furthermore, reduced sick days and improved productivity due to better health and fewer radiation-related ailments contribute to an estimated annual saving of $10 000.

Training efficiency is enhanced with VR, providing standardized and repeatable training experiences that ensure consistent quality across all trainees. The interactive VR modules also improve engagement and retention of safety protocols, leading to better long-term compliance and safety practices. The total annual benefits, combining healthcare cost savings, productivity gains, and staff time savings, amount to $50 600.

In the initial year, the total costs, including headsets, PCs, software licensing, and staff time, amount to $16 200. The total benefits for the same period are $50 600, resulting in a net benefit of $34 400. In subsequent years, the total annual costs are reduced to $7200 for software licensing, while the total annual benefits remain at $50 600, leading to a net annual benefit of $43 400.

The cost analysis further supported the economic viability of VR training. Traditional training methods resulted in expenses exceeding ~$27 000, primarily due to instructor fees, equipment use, and space rental. In contrast, the VR training program, utilizing a SaaS-based subscription model, was significantly more cost-effective at ~$9000 annually. This finding highlights VR training's potential as a sustainable and economically advantageous alternative for radiation safety training, offering a compelling argument for its broader adoption within healthcare education.

Discussion

The integration of VR in medical education marks a transformative shift away from traditional training methods towards an immersive approach that significantly bolsters learning outcomes and user engagement. This paradigm shift is supported by findings in the literature, such as the systematic reviews by Barteit *et al.* and Kim *et al.* which underscore the effectiveness of head-mounted VR devices in enhancing medical education. These studies highlight VR's unique ability to facilitate active learning and immediate feedback, crucial components for the development of competencies in complex medical procedures [9, 10]. Our research contributes to the expanding evidence base, demonstrating that VR's simulation capabilities can markedly advance competency development beyond what conventional methods offer [11–13].

Complementing our conclusions, Zhao *et al.* and Jenkins-Price-Lucas provide a comparative analysis that attests to VR's superior teaching efficiency [14–16]. They noted significant benefits in terms of knowledge retention and understanding, which resonates with our observations on the immersive qualities of VR training environments. Additionally, our study's cost analysis echoes their findings, showcasing VR as a cost-effective, sustainable alternative to traditional educational methodologies [11]. The economic advantages and the adaptability afforded by SaaS models illustrate VR's potential as a scalable solution to the logistical and financial hurdles commonly encountered in healthcare education.

The cost–benefit analysis indicates that significant annual benefits, including reduced radiation exposure, healthcare savings, productivity gains, and staff time savings quickly offset the initial investment in VR training. With an initial investment of $16 200 and an annual net benefit of $43 400, the break-even point is reached in ~ 4.5 months. After reaching this break-even point, the program continues to provide substantial net benefits. These findings advocate for integrating VR into radiation safety training protocols, marking a significant step toward advanced, engaging, and effective learning experiences in medical education.

Feedback from participants in our study further highlighted VR's effectiveness in delivering real-time feedback and fostering immersive experiences that enhance learning outcomes, supporting insights from previous research [6]. This input emphasizes VR's superior capacity to engage learners, facilitate a deeper understanding of critical safety principles, and promote the long-term retention of essential safety practices [16]. Particularly, a recent study by Rainford *et al.* on student perceptions of 3-D VR simulation in radiation protection training for radiography and medical students found that VR was highly preferred for its interactive and engaging nature, reinforcing the positive feedback observed in our own study [5].

The immersive and interactive experiences offered by VR training have shown significant potential in closely mimicking real-world scenarios without the associated risks of actual radiation exposure. This aspect is particularly crucial in the context of increasing occupational radiation risks in fluoroscopically-guided cardiology procedures. Our investigation, encompassing a diverse group of healthcare professionals, leveraged Virtual Medical Coaching's radiation protection software to administer VR training sessions. The significant reduction in radiation exposure levels post-VR training across all professional groups, coupled with a cost analysis that highlighted VR training's economic advantages over traditional methods, underscores VR's potential for broader adoption [7].

Future research should focus on the scalability of VR training and its long-term impacts on healthcare practices. Additionally, exploring the integration of emerging technologies such as artificial intelligence and augmented reality could further enhance the effectiveness and realism of VR training, offering even more profound benefits for medical education and professional development [17, 18].

Conclusion

Our study underscores the pivotal role of VR in advancing radiation safety training within healthcare education. By offering an immersive, interactive learning environment, VR training significantly reduces radiation exposure risks for healthcare professionals while also providing a cost-effective and engaging educational tool. The positive participant feedback and substantial reductions in radiation exposure highlight VR's effectiveness and potential to reshape training methodologies in healthcare settings. As the medical community continues to explore and integrate VR technologies, the promise of safer clinical environments and improved patient care outcomes becomes increasingly tangible. Future research and technological advancements will undoubtedly expand VR's application, making it an indispensable tool in the pursuit of excellence in healthcare education and practice.

Limitations

Despite the positive findings, this study has several limitations that should be considered. Firstly, the study involved a relatively small sample size of 48 healthcare professionals, which may affect the generalizability of the results to a broader population. Future studies with larger sample sizes are necessary to confirm the findings and ensure they are representative of a wider demographic of healthcare workers. Secondly, each VR training session was limited to one hour. While this duration was sufficient for initial training, it may not be adequate for achieving and maintaining optimal safety practices over the long term. Extended or more frequent training sessions might be required to ensure the comprehensive and sustained adoption of improved radiation safety practices. Lastly, the primary focus of this study was on immediate and short-term outcomes following the VR training intervention. There is a need for studies with longer follow-up periods to evaluate the long-term retention of knowledge and skills acquired through VR training. Assessing the durability of the training effects over time would provide a more complete understanding of the benefits and limitations of VR-based radiation safety training. Addressing these limitations in future research will be crucial for validating the effectiveness of VR training programs and ensuring their broader applicability in enhancing radiation safety practices in healthcare settings.

Conflict of interest

None declared.

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