Application of 3D printing model of linear accelerator machine to enhance the learning and apprentice performance for the radiological technology student

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Abstract

The teaching of instrumentation has consistently been a fundamental component of undergraduate programs in radiological technology (RT). However, opportunities for students to engage in direct, hands-on operation of linear accelerator (LINAC) machines during their education and training are often constrained by financial limitations and time restrictions. Therefore, this study aims to integrate a 3D-printed model into LINAC machine topic and evaluate its effectiveness in teaching RT undergraduate students. To achieve this, a physical LINAC model was developed using fused deposition modeling 3D printing technology, with access facilitated through open-source software. To enhance comprehension, color coding was incorporated along with explanatory color cards. A total of 114 participants were randomly assigned to either a control group or a 3D model group. Comparative analysis of theoretical assessment scores revealed that the 3D model group performed significantly better than the control group, with a p-value of < 0.05. Furthermore, the increased opportunity for hands-on training prior to apprenticeships resulted in reduced anxiety and improved clinical performance among participants in the 3D model group. To assess student perceptions regarding the integration of this novel 3D technology into LINAC teaching, participant feedback was collected. Results indicated that over 94% of students recognized the alternative teaching method as essential for enhancing both their theoretical understanding and practical skills. In conclusion, the incorporation of modern 3D-printed models into RT education demonstrates considerable potential for enriching teaching and training activities, ultimately contributing to improved educational outcomes in radiological technology programs.

Keywords: 3D-printed model, alternative education, learning outcomes, apprentice performance, radiological technologists

Introduction

In Thailand, radiological technology (RT) students are required to develop proficiency in three core areas: diagnostic imaging, nuclear medicine, and radiotherapy. This broad training is essential because RT graduates are responsible not only for patient positioning but also for the operation and quality assurance of medical imaging and treatment equipment. While general X-ray and computed tomography machines are commonly available in both clinical and educational settings, linear accelerators (LINACs) are much less accessible to students (Yuan et al., 2021). They are used specifically in radiotherapy and are limited by their high cost, space requirements, maintenance demands, and strict radiation safety regulations (McMenamin et al., 2014; Raja & Sultana, 2012). As a result, most undergraduate RT programs in Thailand are unable to provide LINAC machines solely for educational use, presenting a major challenge in preparing students for real-world radiotherapy practice.

Currently, most RT programs rely heavily on lecture-based instruction, which often proves insufficient for cultivating the spatial and technical understanding necessary for clinical performance. Students frequently report difficulty visualizing complex machine structures and feel unprepared when transitioning from theory to practice. While hospital-based observational tours are sometimes used to supplement classroom teaching, these experiences are often limited by factors such as short durations, large student cohorts, machine availability, and staff workload. Furthermore, the increasing complexity of radiotherapy equipment can contribute to cognitive overload, reducing student engagement and knowledge retention. Conventional 2D images, videos, or even digital 3D renderings are often unable to fully convey spatial dimensions or provide the hands-on experience needed for meaningful learning (Garcia et al., 2018; McMenamin et al., 2014).

Emerging educational technologies such as virtual reality (VR) and augmented reality (AR) offer immersive environments and have been adopted in many medical disciplines to simulate anatomical structures and clinical settings. However, these technologies are associated with high development and maintenance costs and often lack the tactile feedback essential for equipment-based skill acquisition (Li et al., 2024). In contrast, 3D-printed models provide a cost-effective and physically interactive alternative. By enabling learners to touch, rotate, and manipulate physical replicas of equipment. This 3D printing supports the development of psychomotor skills, spatial reasoning, and procedural understanding which these abilities are essential in radiotherapy training (Garcia et al., 2018; Li et al., 2024; McMenamin et al., 2014).

The demand for innovative educational tools in medical and allied health science programs has grown rapidly in recent years (Sahney et al., 2006; Tzima et al., 2019; Yuan et al., 2021). A wide range of technologies such as digital media, mobile applications, and

three-dimensional tools have been shown to improve learning outcomes and skill acquisition (Kaufmann et al., 2000; Sahney et al., 2006; Tzima et al., 2019). These tools are used not only for theoretical instruction but also for practical training (Bliznakova et al., 2023; Garcia et al., 2018). As a result, it is increasingly important for educators to adopt these technologies to enhance students' conceptual understanding, support hands-on learning, and build confidence in operating clinical equipment. Among these innovations, 3D-printed physical models have emerged as highly effective tools for optimizing educational activities. They have been successfully applied in various disciplines, particularly in anatomy, surgery, dental procedures, and simulation-based training (Salazar et al., 2022; Soares et al., 2013). These models can increase student motivation and engagement through interactive learning experiences (Kaufmann et al., 2000). To support the development of spatial awareness and visual recognition skills in radiotherapy instrumentation, we have incorporated 3D-printed LINAC prototypes into our curriculum. However, the use of 3D printing in radiotherapy education in Thailand remains limited.

Alternative teaching methods, such as 3D virtual simulations and hospital tours, are also available for training students in LINAC operation. Nevertheless, these approaches are often costly and logistically challenging. A major drawback is that they offer limited learning opportunities per student, reducing the chance for hands-on interaction with the equipment and potentially affecting skill development and confidence (Pagnucci et al., 2015; Yuan et al., 2021). In contrast, 3D-printed models are cost-effective, durable, reproducible, and accurate. These characteristics make them especially valuable for institutions with limited access to advanced technologies or clinical facilities—such as universities in rural or resource-constrained settings (Cercenelli et al., 2022; Sá dos Reis et al., 2017; Wu et al., 2018).

To address this gap, the present study aims to design and implement a 3D-printed model of a LINAC machine and integrate it into the radiotherapy instrumentation curriculum for third-year RT students. The effectiveness of this approach is evaluated in terms of student learning outcomes, performance during hospital-based apprenticeships, and perceptions of satisfaction and usefulness. Specifically, the study seeks to answer the following research questions: (1) Does the use of a 3D-printed LINAC model improve students' knowledge outcomes compared to traditional teaching methods? (2) What is the within-group improvement in knowledge and skill performance among students using the 3D model approach? and (3) How do students perceive the usefulness and satisfaction of learning with the 3D-printed LINAC model?

Material and methods

Fabrication of a 3D model

To generate the 3D model, we utilized a freely accessible online repository, available at 3dwarehouse.sketchup.com, to acquire a graphically designed 3D model file of LINAC. This file was subsequently converted into a format compatible with 3D printing. Specifically, it was imported and stored in the standard tessellation language (.STL) format before being uploaded to the 3D printer's driver software for fabrication. The creation of the 3D geometry of the LINAC involved an automated segmentation process to differentiate the gantry and couch components. Following segmentation, manual corrections were applied to refine any inaccurately segmented areas, ensuring an accurate representation of the machine. These modifications were performed using the free version of FlashPrint software (Neotech, Bangkok, Thailand), which also facilitated the addition of support structures necessary for 3D printing.

To fabricate the external geometry of the LINAC model, we employed a Flashforge Guider III 3D printer (Neotech, Bangkok, Thailand), which operates on fused deposition modeling (FDM) technology. This printer features a large build platform (300×250×340 mm) and a maximum printing speed of 250 mm/s. The printed LINAC model achieved a resolution of approximately 0.0025 mm along the z-axis, while for the x- and y-axes, a 0.4 mm extruder tip diameter was used. The model was constructed using PLA thermoplastic filament (3DD PLA MATTE, 1.75 mm, white filament; Neotech, Bangkok, Thailand). The PLA filament spool was manually loaded into the extruder head before initiating the 3D printing process. Printing commenced as the filament was heated, melted, and deposited in successive layers, solidifying upon cooling. After each layer was completed, the extrusion head repositioned itself to continue the process until the entire model was fabricated. Each layer of the assembled model maintained a consistent thickness. During printing, overhanging features and complex geometries could not be constructed in empty space. Therefore, support material was extruded to uphold these structures and prevent distortion of the model. To facilitate the removal of the printed model from the printer, we utilized a flexible steel plate platform with a magnetic and bendable surface, allowing for easy detachment from the build plate. The fabrication process required approximately four hours for the gantry component and one hour for the couch component. Upon completion, the support materials were manually removed with ease. Fig. 1 illustrates the prototypes of the separately printed couch and gantry components.

Further, the model was color-coded to enhance educational clarity. Each component was painted in a distinct color: purple for the gantry, orange for the collimator, pink for onboard imaging (OBI), red for the electronic portal imaging device (EPID), green for the couch, and blue for the turntable floor. This color-coding system was designed to help students visually differentiate the machine's key components and their corresponding functions. Fig. 2 presents an example of the instructional color cards, which associate each component with its designated color to facilitate student learning. The 3D-printed LINAC model was

pre-designed and developed by the research team, ensuring structural accuracy and alignment with pedagogical objectives.
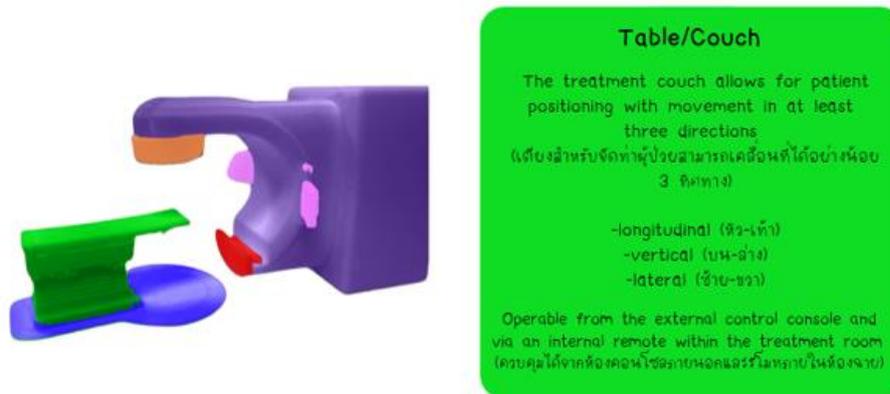
Fig. 1

Prototypes of the separately fabricated couch and gantry components of the LINAC machine, constructed using PLA.

Fig. 2

Representation of the unique color-coded design for different LINAC components, including an example of the instructional green color cards provided to the experimental student group.

Student participants

This study included 114 third-year undergraduate students enrolled in a Radiotherapy Instruments course at a private university in Thailand, all of whom participated in a hospital-based apprenticeship program. The research received approval from the local institutional ethics committee review board, and participants were subsequently assigned to one of two groups through a computer-generated randomization process. This method ensured an equal probability of allocation to either the control group (N = 57) or the

experimental group (N = 57), thereby minimizing selection bias. The first group received teaching by conventional technique, which comprised 2D illustrations and video demonstrations to explain the structural components and functions of the LINAC machine. The second group followed the same conventional teaching approach but with the addition of an interactive session utilizing a 3D-printed LINAC model as a supplementary learning tool.

To ensure comparability between the two groups, the teaching structure was standardized across both conditions. The LINAC modality topic was delivered over a two-week period, with each session lasting 90 minutes per week. Equal learning time was allocated to both groups to eliminate potential bias that could arise from differences in instructional duration. By maintaining a consistent timeframe, any observed differences in learning outcomes could be attributed solely to the integration of the 3D model rather than disparities in the time allocated for instruction. The teaching process for both groups began with lecture-based instruction, during which students received theoretical explanations supported by visual aids, including diagrams and video, to illustrate the key components and operational mechanisms of the LINAC system. The lecturer systematically guided students through each part of the machine, ensuring comprehension of its structure and function. Since students were not involved in the fabrication of the 3D-printed model, no prior training in model construction was necessary.

To enhance reproducibility and instructional clarity for the experimental group, the intervention was delivered through a structured, time-bound session designed to promote active learning, spatial reasoning, and peer collaboration. The session began with a 5-minute introduction in which the lecturer presented the 3D-printed LINAC model and explained its instructional purpose. A sample instructional script included: "This is a scaled 3D-printed model of the LINAC. Today, you'll use this model to explore and understand each component, such as the gantry, collimator, and treatment couch. The colored labels will help you identify each part. Our goal is to connect these physical structures with their clinical functions." This was followed by a 5-minute live demonstration, during which the lecturer physically handled the model, rotated it, and explained each major component while linking its physical structure to its clinical function. For example: "Here is the collimator, shown in orange. It's responsible for shaping the radiation beam.

Following the demonstration, students were divided into ten smaller groups of five to six students, and each group received one model for a 15-minute hands-on activity. Students interacted with the models by identifying, rotating, and discussing the components using color-coded labels and printed checklists as guides. This group-based interaction encouraged peer explanation and collaborative exploration of the LINAC's design and operation. During the final 5 minutes of the session, the lecturer circulated among the groups to facilitate discussion, answer questions, and pose scenario-based prompts such as

"Which component is responsible for beam collimation?" These guided questions were intended to reinforce theoretical knowledge and promote critical thinking.

This hands-on learning approach enabled them to examine and observe key structural features in greater detail, thereby enhancing their understanding of theoretical concepts. To ensure all students had sufficient access to the 3D-printed models, an adequate number of models were prepared, with each small group assigned one model. Additionally, the group-based approach fostered a more interactive learning environment by encouraging collaborative learning, where students could discuss and analyzed the model together, thereby strengthening their comprehension of the subject matter. Throughout this process, the lecturer played an active role in facilitated discussions, answered questions, and offered additional explanations to maximize engagement and support effective learning from the 3D-printed models.

Analysis of learning knowledge and apprenticeship competency

To validate the comparability of the two groups before instruction, a pre-test evaluation was conducted to assess students' prior knowledge of radiotherapy concepts, ensuring that any observed differences in post-test performance could be attributed to the instructional class rather than pre-existing disparities. The evaluation of learning outcomes following the LINAC machine education focused on two key aspects: knowledge acquisition and practical skill development. To assess theoretical understanding, a structured post-test was administered, consisting of 30 multiple-choice questions. This assessment was designed to measure students' theoretical understanding of LINAC components, an area where 3D learning enhances spatial awareness and component recognition.

The test covered both internal and external components of the LINAC machine and was structured into four main sections: recognition of LINAC components by name, identification of the spatial position of each component, understanding of external components, safety mechanisms, and their functions within the overall LINAC system. For instance, students were required to identify which LINAC component generates high-energy electrons, determine which component is positioned above the treatment couch and moves in a circular motion around the patient, and locate the EPID within the system. Additionally, the test included questions that evaluated students' understanding of functional consequences, such as the effects of removing the flattening filter and the axes of patient movement permitted by the treatment couch. These test items were carefully designed to align with key learning objectives and provide a valid and reliable measure of students' understanding of LINAC system components. Each question was scored as correct or incorrect, with a maximum score of 30 points. The grading criteria were based on accuracy, with higher scores indicating greater comprehension of LINAC components. To ensure consistency in the quality and difficulty of the assessments, the same set of pre-

and post-test items was used (Asghar et al., 2022; Moonkum et al., 2025). The outcome measured by their accuracy as test score which read by optical mark reader. To verify test reliability, Cronbach's Alpha coefficient was calculated, yielding a value of 0.77, indicating acceptable internal consistency (Tavakol & Dennick, 2011).

In addition to assessing post-test accuracy, the error rate was analyzed to evaluate students' comprehension. The error rate was calculated as the proportion of incorrect responses relative to the total number of test items. This was determined by dividing the number of incorrect responses by the total number of test items and subsequently multiplying the result by 100 to express it as a percentage. This measure provided insight into the extent of errors made by students, allowing for a comparative analysis of learning effectiveness across different teaching methods.

To further investigate the long-term impact of the 3D model, a retention accuracy test was conducted four months after the initial learning session. This assessment was carried out during the first day of students' apprenticeship training, where they were required to engage with real clinical cases involving LINAC machines. During the four-month interval, the students did not have further access to the 3D-printed model, as it was used exclusively during the academic learning phase. The model was retained and stored at the university as part of the instructional resources and was not available at the clinical site. The two supervisors were responsible for apprenticeship competency assessed by a total of 16 questionnaire items with scoring 1 to 5, the higher score mean the superior student's competency.

The questionnaire was designed to assess students' practical competencies specifically related to the operation of the LINAC machine, with a focus on learner confidence, response time, and task completion efficiency. The evaluation criteria included key aspects of LINAC operation, ensuring a comprehensive assessment of students' proficiency in handling radiotherapy procedures. For instance, the assessment examined how effectively students operated the EPID for image verification before treatment. Additionally, it evaluated students' confidence levels when setting up the LINAC machine for patient treatment and their ability to efficiently adjust the gantry and collimator angles according to the prescribed treatment plan. Furthermore, students were assessed on their adherence to quality assurance (QA) protocols, ensuring the safe and accurate operation of the LINAC system. The evaluation also considered students' receptiveness to supervisor feedback and their ability to integrate suggestions to enhance their LINAC operational skills. These aspects provided a structured framework to measure both technical proficiency and adaptability in a clinical radiotherapy setting. To validate the reliability of the 16-item competency questionnaire, an inter-rater reliability analysis was conducted by two independent supervisors with over five years of experience in radiotherapy training. Cohen's kappa coefficient was calculated, yielding a result of 0.79, indicating substantial

agreement between evaluators (McHugh, 2012). To minimize bias, each assessment item was reviewed and analyzed by two independent reviewers, ensuring an objective evaluation of students' apprenticeship competency.

3D model satisfying assessment

A structured questionnaire consisting of 12 items was administered to the experimental group at the end of the apprenticeship to assess the usefulness satisfaction of the newly developed LINAC 3D prototype model. To measure satisfaction, a 10-point scale was employed following the methodology outlined in Wake et al., study (Wake et al., 2019). The scale was categorized into four levels of perceived helpfulness, ranging from "No Help" (1–2), "Mild Help" (3–5), "Moderate Help" (6–8), and "Great Help" (9–10). Each questionnaire item was designed to assess a specific aspect of the 3D model's effectiveness in enhancing student learning, comprehension, and engagement. Additionally, an open-ended section was included to allow students to express their opinions and suggest potential improvements.

Statistical analysis

Descriptive statistical measures, including mean, standard deviation (SD), and interquartile range (IQR), were employed to summarize the measurement data. The percentage difference (PD) between the control and experimental groups for both theoretical and apprenticeship scores was calculated (Moonkum et al., 2022; Tochaikul, 2021). To analyze differences between groups, an independent samples t-test was performed to compare post-test scores between the control and experimental groups. All analyses were conducted using OriginPro software, with a significance level set at a 95% confidence interval. Additionally, the error rate was assessed, and Cohen's effect size (d) was calculated to determine the magnitude of the observed differences.

Results

The implementation of three-dimensional printing technology for LINAC machines has enabled the scaling down of models, especially for external components used in LINAC machine learning. This advancement received positive feedback from students, who expressed high levels of satisfaction with the models. An in-depth quantitative assessment comparing the 3D prints to the original machine revealed a 99% structural size reduction without compromising the distinguishability of the main components. Notably, all nine radiological technologists were able to correctly identify the structural elements with nearly 100% accuracy, even without explicit instructions.

This study included 114 students from a private university in Thailand who were enrolled in a radiotherapy instruments course and later participated in a hospital-based

apprenticeship program. The descriptive statistics for pre- and post-test scores are summarized in Table 1. To confirm that both groups had comparable baseline knowledge, a between-group comparison of pre-test scores was performed. The result of the independent samples t-test (p = 0.21) indicated no statistically significant difference, confirming successful randomization. Following the instructional intervention, a between-group comparison of post-test scores revealed that the experimental group outperformed the control group. Students who received 3D model–enhanced instruction achieved a mean post-test score of 24.0 ± 1.5, compared to 21.3 ± 1.8 in the control group. This difference approximately 13% was substantially greater than the pre-test difference of only 1%, suggesting a marked improvement attributable to the 3D model intervention.

Moreover, a within-group analysis was conducted to evaluate the magnitude of improvement in the experimental group from pre- to post-test. According to Cohen's (1988) guidelines, a d value greater than 0.8 is considered a large effect size, meaning that the 3D model had a substantial impact on apprenticeship performance (Cohen, 2013). The effect size of 1.72 for the pre-post improvement within the experimental group suggests that the 3D model-based learning intervention had a very strong effect on students' skill development.

The error rate was calculated for both the control and experimental groups to assess differences in accuracy. The control group demonstrated an average error rate of 28.90%, whereas the experimental group exhibited a lower error rate of 19.90%. This reduction in error rate suggests that the incorporation of hands-on learning through the 3D model contributed to an improvement in students' ability to accurately recognize LINAC components.

Finally, Fig. 3 revealed that the overview of the score recorded and Q calculated in the participants which control and experimental group were mainly within Q2 at the pre-test period. Concurrently, majority of the control group were within Q3 while the experimental group were within Q4 which means the experimental participants have a superior learning knowledge than the control participants.

Table 1

Comparison of learning outcomes among student subgroups.

Test Phase	Group	Maximum score	Minimum score	Mean (SD)	PD	p-value
Pre-test	Control	16.00	8.00	13.20 (2.45)	1.14%	0.21
	Experimental	16.50	8.50	13.35 (2.60)		
Post-test	Control	25.00	18.00	21.33 (1.79)	12.66%	< .001
	Experimental	28.50	22.00	24.03 (1.54)		

Note. Mean (SD) = Mean and standard deviation. PD = Percentage Difference between control and experimental groups. A two-tailed independent sample t-test was used to assess significance.

Fig. 3

Grouped bar chart showing student performance distribution by quartile for control and experimental groups (pre- and post-test).
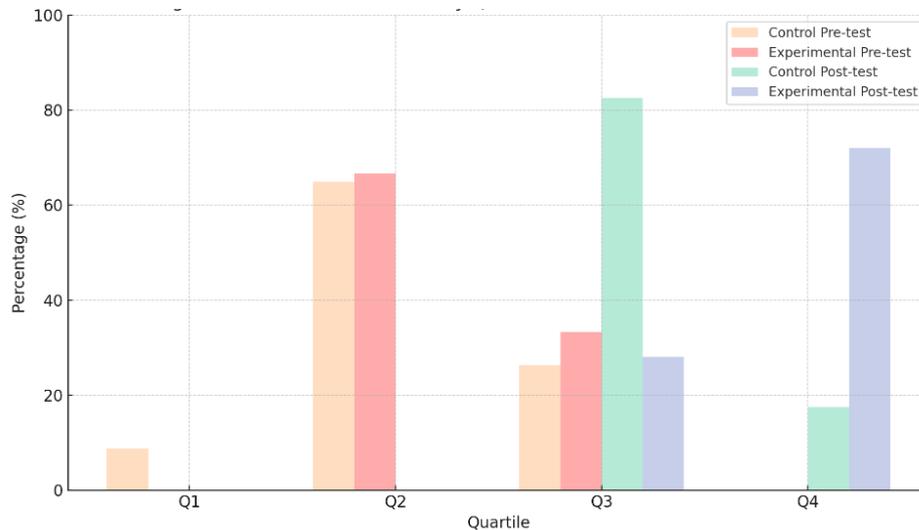
Additionally, a comparison of apprenticeship skills between the control and experimental groups yielded consistent results. In this study, apprenticeship performance was evaluated using a 16-item questionnaire, with each item representing a key competency related to the training. A five-point rating scale (ranging from 1 to 5) was utilized to assess student responses. However, rather than employing a traditional 1-to-5 scale for analysis, apprenticeship performance was assessed using a pass/fail criterion. A passing threshold was set at a score greater than 3, indicating that the student met the competency criteria for that particular item. For each student, the total number of questionnaire items in which they achieved a passing score was counted, resulting in an individual performance score ranging from 0 to 16.

The average performance score for both the control and experimental groups was then calculated by determining the mean number of items passed by students in each group. The results demonstrated that the control group achieved an average performance score of 8.5 ± 2.4, while the experimental group attained a mean score of 11.5 ± 2.1, indicating a higher level of proficiency among students in the experimental group. Statistical analysis using the paired t-test revealed that this difference was highly statistically significant, with a p-value of less than 0.001 at a 95% confidence interval, confirming the robustness of the observed improvement. Cohen's d of 1.29 suggests that the difference between the experimental and control groups is not only statistically significant but also practically meaningful.

Moreover, the evaluators identified an obvious difference in distinguish between different types of the components, correct test items, identify functions on discussing test

and individual performance skills between the two groups. The experimental group exhibited higher accuracy on their initial attempts and displayed reduced test completion times among the participants. Participants in the integrated 3D model group also exhibited higher levels of confidence compared to the traditional group. Furthermore, the enhanced performance of the experimental group, observed four months after the initial learning session, indicates effective long-term knowledge retention.

This improvement can be attributed to the hands-on learning approach facilitated by the 3D-printed model, which played a crucial role in reinforcing memory recall and practical skill application. Although the integration of 3D-printed models increased students' efficiency in understanding the structural and functional aspects of LINAC equipment, it did not directly contribute to their proficiency in proper maintenance and careful operation of the devices, necessitate supervised clinical training. Similarly, critical aspects related to established radiation protection protocols such as patient verification, dose delivery and adherence to clinical safety guidelines require direct practical training in a clinical setting. These safety considerations are fundamental to real-world clinical practice and extend beyond the scope of what can be achieved through the use of 3D-printed models.

The satisfaction evaluation was conducted after the completion of both academic learning and the related apprenticeship involving LINAC machine operations. The satisfaction evaluation was conducted by calculating the average score from all 12 questionnaire items using a 10-point satisfaction scale, as presented in Table 2. Based on student responses, the overall perceived usefulness of the 3D-printed models was rated at an average of 8.21, categorizing it within the "Moderate Help" to "Great Help" range.

Of the 57 participants, 49.1% (n = 28) rated their satisfaction at the highest level, scoring within the green zone (9–10), which corresponds to "Great Help." An additional 40.4% (n = 23) rated within the yellow zone (7–8), indicating "Moderate Help," while 10.5% (n = 6) rated below 7, reflecting "Little Help." These percentages provide clearer insight into the distribution of student satisfaction levels and contextualize the findings within the full sample.

The highest-rated items were "Integration of 3D models has impacted your academic learning knowledge in the LINAC machine topic" and "Unique colors of 3D models improve your memory retention and recall of information" both receiving an average score of 9.11. These results suggest that students particularly valued the 3D models for their ability to enhance knowledge retention and conceptual understanding of the LINAC system.

Conversely, the lowest-rated item was "3D models with color-coded cards contribute to your understanding of the maintenance of LINAC structures," which received an average score of 4.81. This finding indicates that while the models were effective in conveying theoretical concepts and improving visualization, they were perceived as less helpful for

illustrating maintenance procedures. This observation aligns with previous feedback from apprenticeship evaluators, who similarly noted the need for improvement in this issue.

In addition to the numerical satisfaction ratings, a thematic analysis of the students' open-ended responses was conducted to gain deeper insights into their experiences using the 3D-printed LINAC models. To enhance the analytical rigor and clarity of this analysis, we applied a structured thematic analysis framework based on Braun and Clarke's six-phase approach (Ahmed et al., 2025). These phases included familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. This structured approach strengthened both the validity and transparency of the qualitative findings. Representative quotations were also incorporated to illustrate key themes.

Three primary themes emerged from the data. First, many students expressed that the models significantly enhanced their conceptual understanding and engagement. They described the models as "an innovative educational tool that provides a tangible, interactive representation of machinery," allowing them to engage more meaningfully with complex subject matter. Second, students reported increased confidence and readiness when transitioning to real clinical settings, noting that "this hands-on experience increased their confidence when working with actual equipment in clinical settings" and "3D printing models have the potential to bridge the gap between theoretical knowledge and practical application, ultimately improving educational outcomes." These sentiments reinforce the observed improvements in post-test scores and clinical performance. Third, several constructive suggestions were identified, including the development of a modular 3D model that students could assemble and disassemble, the inclusion of moving parts to simulate LINAC operation, and enhancements to the color-coded cards such as adding detailed descriptions or QR codes linking to multimedia explanations of component functions and maintenance procedures. These qualitative findings not only support the quantitative data but also offer valuable direction for further development of 3D learning tools to maximize their pedagogical effectiveness in radiological technology education.

Table 2

Reported overall helpful satisfaction feedback questionnaire of the integration of 3D LINAC models in radiological technology undergraduate program (n = 57).

No.	Item	Mean Score	Perceived Helpfulness Level
1	Quality and detail of the 3D models material used	7.18	Mild help
2	3D models in helping you understand LINAC structures	8.28	Moderate help
3	3D models improved your ability to visualize and comprehend LINAC machine concepts	7.98	Mild help
4	Integration of 3D models has impacted your academic learning knowledge in LINAC machine topic	9.11	Great help

5	3D models making learning more engaging and interactive	8.96	Moderate help
6	3D models have enhanced your overall performance in apprentice	7.98	Mild help
7	3D models have enhanced your ability to work effectively with LINAC machine in a clinical setting	8.68	Moderate help
8	3D models have increased your confidence in operating LINAC machine after using 3D models for practice	8.49	Moderate help
9	The unique color designs of 3D models enhance your ability to differentiate and identify key features in LINAC structures	8.98	Moderate help
10	Unique colors of 3D models improve your memory retention and recall of information	9.11	Great help
11	3D models with color card help you understand the functionality of LINAC structures	9.11	Great help
12	3D models with color card contribute to your understanding of the maintenance of LINAC structures	3.30	No help

Discussion

The findings of this study underscore the educational advantages of integrating 3D-printed models into radiotherapy instrumentation training. Compared to conventional lecture-based methods, the incorporation of tangible, handheld LINAC models resulted in significantly higher post-test scores among students in the experimental group ($p < 0.01$). This improvement highlights the potential of hands-on, interactive learning tools to enhance knowledge acquisition and long-term retention. The tactile and visual engagement offered by the 3D model may have facilitated deeper cognitive processing, as supported by Jansen et al., who reported that physical visualizations foster better information retention than 2D representations (Jansen et al., 2013). Similarly, Lynch & Chatterjee emphasized the importance of tactile experiences in object handling, noting their contribution to more meaningful learning outcomes (Lynch & Chatterjee, 2008).

Moreover, this study observed a narrowing of the standard deviation in post-test scores within the experimental group, indicating reduced variability in learning performance. This suggests that 3D model-based teaching not only improves average outcomes but also promotes more consistent comprehension among learners. This finding aligns with earlier reports by Moonkum et al. and Seitzman et al., studies who demonstrated that experiential and visually engaging interventions reduce performance gaps and build student confidence (Moonkum et al., 2025; Seitzman et al., 2020). Further supporting this notion, the observed reduction in error rate from 28.9% in the control group to 19.9% in the experimental group reflects improved structural recognition and procedural accuracy, which are essential competencies in clinical radiotherapy.

From a design perspective, the 3D-printed LINAC model was developed to replicate the original machine at an approximate 1:10 scale. Following Garcia et al., who suggested that size, anatomical accuracy, and context must be tailored to educational objectives, the model

was printed with high dimensional precision (±0.15 mm) (Garcia et al., 2018). Importantly, printing the gantry and couch separately prevented structural distortion from negative airspace, a challenge often observed in single-piece prints. The integration of color-coded components in the 3D models appeared to further enhance visual recognition and long-term memory retention. Students reported that color differentiation helped them identify individual LINAC components more clearly and recall their functions more accurately. These results support previous research by Santos et al. and Singg & Mull studies, which demonstrated that color-coded educational materials can effectively aid attention, recall, and comprehension (Santos et al., 2019; Singg & Mull, 2017).

The unique pedagogical contribution of this study lies in its implementation of a low-cost, reusable, and scalable 3D-printed LINAC model specifically designed to meet radiotherapy learning outcomes. In terms of cost-effectiveness, the model was produced using a FDM printer with PLA filament technologies known for affordability, accessibility, and ease of use. The total cost of producing one LINAC model was approximately $10 (excluding printer and reusable materials), significantly lower than the cumulative cost of hospital-based instruction. Unlike virtual simulations that require costly software and may lack tactile realism, this approach provides physical interaction and self-paced exploration (Li et al., 2024). It offers a practical solution for institutions that lack access to clinical machines or face resource constraints (Asghar et al., 2022; Cercenelli et al., 2022).

Although students did not participate in the coding or design process, the model itself was purpose-built based on clinical specifications and learning objectives. The design emphasized anatomical accuracy, functional resemblance, and instructional relevance. It incorporated pedagogical features such as modular assembly, color-coded components, and dimensionally accurate scale printing. These features ensured that the model was not merely a replica, but an active educational tool. The design process thus served both educational and research aims bridging gaps between engineering precision and curricular needs in radiotherapy education.

Feedback from students and supervisors further validated the value of the 3D model-enhanced approach. Students reported that interacting with color-coded models improved their ability to identify, differentiate, and understand LINAC components. Notably, 94% of the students agreed that 3D models enhanced their learning outcomes, a satisfaction rate comparable to prior studies by Bliznakova et al. and Valverde et al., studies where 90-95% of participants expressed favorable attitudes toward 3D-printed instructional materials (Bliznakova et al., 2023; Valverde et al., 2022). Students also appreciated the opportunity for repeated and independent manipulation of the model an experience not typically feasible in hospital tours, which are often constrained by time, availability of machines, and large student cohorts. Supervisors observed that students trained with 3D models demonstrated greater confidence, required less time to perform tasks, and responded to

questions more accurately during clinical rotations. These observations are consistent with previous findings from Wu et al. and Yuan et al., studies who emphasized the role of 3D models in increasing clinical preparedness and competency in medical education (Wu et al., 2018; Yuan et al., 2021).

Despite these benefits, certain limitations must be acknowledged. While the LINAC model was highly effective for basic structural recognition and introductory training, it lacked movable parts and internal components necessary for simulating maintenance procedures. This shortcoming was reflected in the lowest student satisfaction score (mean = 3.30) related to maintenance-related understanding. Therefore, future model iterations should consider modular designs that incorporate detachable or articulated elements to simulate beam collimation, calibration, and quality assurance protocols. Studies by Pham & Dimov and Celorrio-Barragué et al., studies have shown that such refinements can extend the applicability of 3D models into more advanced training contexts (Celorrio-Barragué et al., 2019; Pham & Dimov, 2012).

Conclusion

Three-dimensional printing is likely to play a significant role in medical teaching. This study proposes that the integration of 3D printed model can be adopted into the radiotherapy instrumentation curriculum. Our research indicates that the application of 3D printing for LINAC machine offers advantages over traditional teaching methods. The incorporation of 3D-printed models significantly enriches the teaching-learning process, as evidenced by improvements in examination scores and apprenticeship evaluations, reflecting both short- and long-term knowledge retention. Furthermore, students benefit from hands-on experience, as the availability of 3D physical models have been shown the enhance skill retention and boosts confidence. The cost of fabricating these models is reasonable, and student satisfaction with the 3D models is high. Therefore, 3D printed models represent a promising alternative teaching tool for undergraduate curricula in radiological technology, particularly in where resources and instruments may be limited.

Abbreviations
RT: radiological technology, LINAC: linear accelerator, VR: virtual reality, AR: augmented reality, (.STL): standard tessellation language, FDM: fused deposition modeling, OBI: onboard imaging, EPID: electronic portal imaging device, QA: quality assurance, SD: standard deviation, IQR: interquartile range and PD: percentage difference.

Author's contributions
The individual contributions of authors to the manuscript should be specified in this section.

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Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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