Original Research

Revista Brasileira de Física Médica (2026) 20:859

Development and Validation of an Immersive Virtual Reality Simulator for X-Ray Operator Training

Desenvolvimento e Validação de um Simulador de Realidade Virtual Imersiva para Treinamento de Radiologistas

Bruno Key Kawano[1], Fernando Barcellos Razuck[2], Gabriel Gonçalves[3] Ricardo Nakamura[1]

[1]University of São Paulo, 05508-010, São Paulo, S.P., Brazil.
[2]Coordination for the Improvement of Higher Education Personnel (CAPES), Brasília, Brazil.
[3]Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.

Abstract

Performing X-ray examinations involves health risks related to ionizing radiation. Therefore, training future professionals can be difficult due to practical limitations and the behavior of ionizing radiation in space, considering its propagation and limitations due to material barriers. In this sense, the work described here aims to present a Pedagogical Validation for radiological examinations using immersive virtual reality (VR) for the practical training of healthcare professionals, aiming to mitigate exposure to ionizing radiation during the execution time, following the principle "As Low as Reasonably Achievable" (ALARA). The validation was developed by a multidisciplinary team, with specialists in Computer Science and Radiological Protection. Software engineering practices were adopted through an iterative development process. The Validation implementation used the Unity 3D game engine, which has been adopted in similar projects. The simulation system was validated through the collection and analysis of qualitative data and semi-structured interviews with 10 volunteer medical students, who positively evaluated learning through VR, with an overall score of 90%. The current project cycle focuses on X-ray examinations, and based on the results, the system may be expanded to include other radiological examinations, such as Computed Tomography. This work is expected to assist in the training of operators of medical-hospital equipment that uses ionizing radiation, aiming at the safety of patients and healthcare professionals.

Keywords: ALARA; X-ray; hands-on training; medical education; radiation protection; virtual reality; pedagogical validation.

Resumo

A realização de exames de Raio-X envolve riscos à saúde relacionados à radiação ionizante. Desta forma, o treinamento de futuros profissionais pode ser de difícil acesso, devido às limitações práticas e ao comportamento da radiação ionizante no espaço, tendo em vista a sua propagação e limitação frente a barreiras materiais. Neste sentido, o trabalho aqui descrito tem por objetivo apresentar uma Validação Pedagógica para exames radiológicos utilizando realidade virtual imersiva (RV), para o treinamento prático de profissionais de saúde, visando atenuar a exposição à radiação ionizante durante o tempo de execução, seguindo o princípio "As Low As Reasonably Achievable" (ALARA). A validação foi desenvolvida por uma equipe multidisciplinar, com especialistas em Ciências da Computação e em Proteção Radiológica. Foram adotadas práticas de engenharia de software por meio de processo iterativo de desenvolvimento. A implementação da Validação envolveu a aplicação do motor de jogos Unity 3D, que tem sido adotado em projetos similares. A validação do sistema de simulação foi realizada por meio da coleta e análise de dados qualitativos e de entrevistas semi-estruturadas, junto a 10 estudantes voluntários do curso de graduação em Medicina, que avaliaram positivamente a aprendizagem por meio da RV, com score geral de 90%. No atual ciclo de projeto está sendo abordado o exame de Raio-X e, com base nos resultados obtidos, o sistema poderá ser ampliado para contemplar outros tipos de exames radiológicos, como Tomografia Computadorizada. Espera-se com este trabalho auxiliar no treinamento dos operadores de equipamentos médicos-hospitalares que aplicam a radiação ionizante, visando a segurança dos pacientes e profissionais em saúde.

***Palavras-chave**: ALARA; Raio-X; treinamento prático; educação médica; proteção radiológica; realidade virtual; validação pedagógica.*

1. Introduction

1.1. Radiation Protection and Radiodiagnosis in Brazil

Ionizing Radiation (IR) is a radiation that has the ability to remove an electron from an atom, a process called ionization in which pairs of negative ions and positive ions are formed. In Medicine, IR is widely used to detect and treat diseases using equipment such as linear accelerators, CT scans, and X-rays (1).

Regarding the application of IR in Medicine in Brazil, millions of people are diagnosed and treated with radiotherapy, radiodiagnosis, and nuclear medicine (NM) procedures. Approximately 63 million radiodiagnostic exams and 9 million radiotherapy procedures are performed annually, serving 450,000 patients (1).

According to the National Nuclear Energy Commission (CNEN), Brazil currently has 432 nuclear medicine services, and these services perform diagnostic or therapeutic procedures that use radiopharmaceuticals on a daily basis (1).

In addition, the use of IR-emitting equipment also continues to grow in Brazil. There are approximately 72,039 IR-generating equipment. Of these, there are 3,057 CT scanners representing 1.58 devices/100,000 inhabitants and 20,929 simple X-ray machines, representing 10.79 devices/100,000 inhabitants (equivalent to 16.28 devices/100,000 inhabitants) and 224 CT scanners (equivalent to 2.55 devices/100,000 inhabitants) (1).

These numbers indicate a growing trend toward the use of IR equipment, which in turn demands an increasing number of qualified professionals.

Regarding Brazilian legislation, according to CNEN Resolution No. 164 of 2014, which amends item 5.4.3.1 of CNEN Standard NN 3.01 (Basic Guidelines for Radiological Protection), which defines the medical optimization of radiological protection applicable to the field of Nuclear Medicine, a safe exposure dose of 20 mSv (millisievert) – a unit that measures the biological effects of radiation – was established for Occupationally Exposed Individuals (OEI), and a dose of 1 mSv for the general public. These doses refer to whole-body exposure over one year (2).

1.2. New Technologies for Teaching Radiodiagnosis

In this sense, the search for advanced diagnostic methods and the increase in the number of patients with complex clinical conditions imply a greater application of IR in care, which can result in greater exposure, since the use of diagnostic radiology represents the greatest cause of human exposure to artificial sources of radiation (3). Therefore, the ALARA principle (As Low as Reasonably Achievable) should always be respected in radiation exposure (1; 3).

So, safety is extremely important in building knowledge in radiological protection, being fundamental in the teaching-learning process in the area (4).

Regarding Medical education in Brazil, with the changes brought about by the National Curriculum Guidelines (DCN), Medical courses have begun to focus on a pedagogical project that places the student as the protagonist, while the teacher acts as a facilitator in the teaching-learning process, often using active methodologies (5).

Since practical classes on the subject are limited due to the health risks associated with radiation exposure, virtual reality (VR), augmented reality (AR) and mixed reality simulations can be used, which do not pose any harm to trainees (6).

So, it is believed that practicing the ALARA principle in VR can provide insights into radiation sources as it results in less exposure. A range of radiation measurements from alpha, beta, and gamma sources can then be performed based on the implementation of mathematical models that govern radiation phenomena (6).

Active teaching methodologies range from the use of low-cost synthetic parts to virtual simulations. Studies using these technologies have proven their enriching potential in assessments that achieved results equal to and better than teaching carried out only with traditional practices (5; 7; 8).

Two examples of active methodologies that can be cited are Augmented Reality (AR) and Virtual Reality (VR), which simulate reality without putting the health of users or the environment at risk. As pointed out in the literature, VR is defined as a digital environment, created computationally, that can be experienced interactively as if it were real, in an artificially created universe; on the other hand, AR is the use of software that allows the insertion of real objects into a virtual world or the insertion of a virtual object into a real environment (5).

However, the literature indicates that VR and AR are still somewhat unknown technologies that need to be discussed and disseminated further. Encouraging new technological resources for students, in addition to offering an interactive environment, can facilitate educational learning (5).

VR technologies are currently being used to provide safe immersion for training and education in a variety of industries, including medical, automation, automotive, aviation, and nuclear. More specifically, VR can aid in training and preparation for developing a safety culture, and, due to its accessibility, it is being adopted for radiation training. Thus, radiation visualization combined with VR enables enhanced awareness and protection, reducing health risks and enabling safe task planning in radioactive environments (6).

Surgical training methods are evolving with technological advances, including the application of VR (9; 10). For example, in the medical field, VR has already been applied in Radiotherapy (in the planning of sessions) and in ultrasound (through three-dimensional ultrasound - 3D, with color images and in real time), image termination, smaller and lighter transducers, higher image resolution, and automatic measurement of volumes (8).

Despite its growing use in medical education, metaverse applications vary in interventions, target populations, and outcomes. Currently, no comprehensive review offers a holistic view of its educational applications (11).

The need for safe training in radiological protection and the advantages of using VR for medical training motivate the development of the training simulator described in this work. It is important to emphasize the need for adequate, continuous training for professionals working in this area, which will undoubtedly improve the quality of the service provided to the population (2).

2. Materials and Methods

This paper aims to develop and validate a prototype radiological examination simulator using immersive virtual reality, for future use in the training of healthcare professionals, through Pedagogical Validation.

The Validation was evaluated by 10 volunteers, all fifth-year medical students from UNIFESP (Federal University of São Paulo).

The work was coordinated by a Professor from the Computer Science course at USP and an Assistant Professor, who, in this case, was a final-year Computer Science student at USP, who used part of the research for his Final Year Project.

Regarding Radiation Protection, a consultant from the Institute of Radiation Protection and Dosimetry (IRD), a CNEN-affiliated institute, was invited.

To this end, this consultant gave a class to the project's Coordinators, as well as to the students, on the fundamentals of Radiation Protection, such as the inverse square law, shielding, material attenuation, the issue of distance and time, the inverse square of distance, types of radiation, biological effects, and the ALARA fundamentals.

In this context, a Didactic Sequence (DS) was developed, divided into 3 classes, totaling 20 hours, as presented in Table 1.

Stage	Class	Hours	Proposed Activities
Introduction	1	4	•Presentation of the Work Proposal (1h) •Review Class about Radioactivity and Radiation Protection (3h)
Pedagogical Validation - Scenario Development	2	12	•Specification •Development •Initial validation •Final validation
Final Discussion	4	4	•Analysis of the results obtained and general discussion about the DS

Source: The Author (2026).

At the end of the activities, the students answered four statements, aiming only to evaluate the ease of use and usefulness of the virtual reality system, without any evaluation of its pedagogical impact, as follows:

1) It was simple to learn to use this software.
2) Using this software would improve learning.
3) Using this software makes my learning more interesting.
4) Software like this has the potential to be useful.

The focus of this validation is to place radiology professionals in training in different scenarios to identify ionizing radiation in examinations using the visual tool, thereby enabling users to understand how radiation behaves in the environment and train professionals in risk situations.

The Validation was divided into four main parts:

• Specification - where the requirements and scope of the project were defined;
• Development - the creation of the project itself;
• Initial validation - with the help of professors and experts; and
• Final validation - carried out with medical students, who evaluated the project in terms of ease of use and usefulness of the project, through the collection and analysis of qualitative data.

Software engineering practices were adopted through interactive processes. The project implementation involves the application of the Unity 3D game engine (12; 13).

The development of the radiation visualization model is divided into modeling the behavior of various types of ionizing radiation and radiation attenuation by objects. The behavior of ionizing radiation can be modeled using a variety of predefined initial properties of particle emitters available in the Unity game engine (6).

To implement virtual reality in the simulator, the Open XR API library was used, responsible for integrating Unity with immersive visualization devices.

In addition, Blender (Blender Foundation), a 3D modeling software, was also used to make adjustments and edits to objects in the simulated environment.

Thus, the following technologies were chosen for the project:

• Unity – was the engine for the development and execution of the simulator, since it is already widely used for simulators in the health area;
• Blender – was chosen as the modeling tool to edit and model objects;
• 3D scanning – for complex objects that cannot be obtained online, scanning techniques were used via cell phone applications to generate models.
• Virtual Reality: the training will be carried out in virtual reality to generate a greater sense of immersion.
• Meta Quest 2 and 3: the project was tested and developed to work with Meta's virtual reality glasses.

It is worth noting that most of the objects in the simulator were obtained online from free license repositories. To create the virtual reality environment, the Open XR resource tree was used, including models for the user's hands. These resources are detailed in Figure 1.

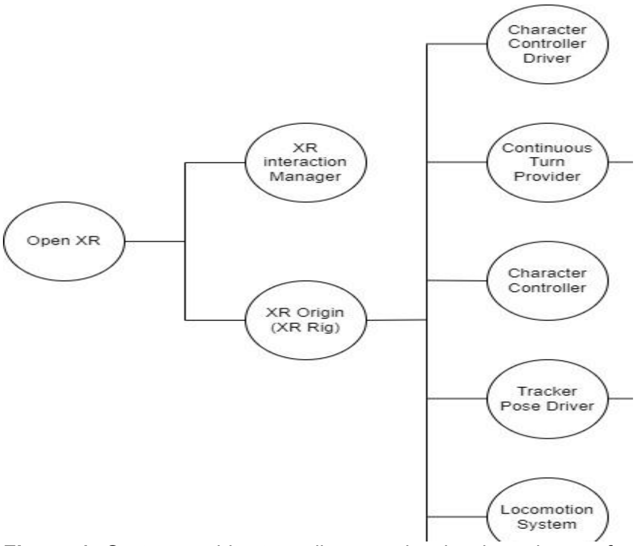

Figure 1. System architecture diagram showing key classes for implementing visualization and user interaction in the validation environment, using the Unity 3D game engine. Source: The author.

At the end, an analysis was conducted with all participants to assess the equipment's efficiency and the validity of the DS.

3. Results and Discussion

3.1. Introduction

In this initial stage, the 2 Coordinating Professors, after thanking the students for their volunteer work, explained how the DS would be carried out, the workload, and the objectives.

After this, the IRD specialist gave a lecture on fundamental concepts of Radioactivity, Radiological Protection, and National Legislation regarding the use of Ionizing Radiation in Medical Physics. The content presented was as follows:

- Historical aspects of the discovery of radioactivity;
- Definition and Types of Ionizing Radiation (alpha, beta, gamma, X-rays, and neutrons);
- Structure of Matter and Ionizing Radiation;
- Natural and Artificial Sources of Radiation;
- Radioactive Decay;
- Principles of Radiation Protection;
- Biological Effects;
- RDC No. 50 of the National Health Surveillance Agency (ANVISA) – that provides for the Technical Regulation of physical projects of health care establishments; and

. Use of X-ray Equipment

After this class, a group discussion was held to clarify doubts and carry out exercises.

3.2. Pedagogical Validation - Scenario Development

Different scenarios were established for Validation, including for pregnant patients and people with disabilities, based on the literature and specialists' knowledge. Some of these simulated scenarios were:

- Common examination: with the patient already lying down and in position, this scenario involves taking a chest X-ray; and
- Application of several X-rays: the purpose of this scenario is to show the user the risk presented to the operator when performing multiple examinations.

To this end, a sandbox environment was created, where the user can explore the validation's functionalities and behaviors, without there being any patients or any specific objectives. The step-by-step examination was as follows:

- Step 1: with the patient already lying down on the X-ray table, the operator must bring him/her the lead vest for the neck and pelvis;
- Step 2: the operator must position the emitting camera above the chest region.
- Step 3: the operator must leave the X-ray room for a separate room, from where he/she can activate the camera; and
- Step 4: the operator must activate the camera, taking care to correctly adjust the intensity of the beam, as well as the exposure time.

In addition, several interactive objects were added to the validation environment, including:

- Lead vest for the chest, thyroid and pelvis;
- Geiger meter;
- Radiation visualization control;
- X-ray machine control panel;
- X-ray machine

Within the player's field of vision there were several indicators such as a meter of radiation absorbed by both the operator's body and the patient's body, as well as the regions of the bodies that were most affected by the radiation. These values will always be compared with the maximum values recommended by the IRD.

A scenario for free exploration of the validation environment is also planned, allowing the creation of different configurations of the space and equipment and visualization of the propagation of ionizing radiation.

Figure 2 presents prototypes for evaluating object scales and distances of the validation environment. The top portion of the figure shows an initial test built with blocks, without texture and with neutral lighting, to evaluate the perceived distances and sizes of objects while using the Meta 3 device.

The bottom portion shows an improved prototype with furniture models, simplified models for the patient and radiological equipment, and text signs to display information for the user.

Figure 3 presents an initial prototype for visualizing ionizing radiation in the environment, using a computer graphics lighting algorithm.

In this version, a single point light with a red hue is configured at a position aligned with the radiological equipment.

It is worth noting that the representation of radiation is still approximate and graphical.

Figure 2. Volumetric prototype of the virtual environment, constructed for validation of scale and distances in 3D space. Top: first volumetric prototype, constructed with blocks and a gridded floor to validate size and distance perception. Bottom: second prototype, including 3D models of furniture, and simplified 3D models of patient and radiological equipment. Source: The author.

Objects that act as barriers to ionizing radiation are configured to block light from this source. This way, a simplified visualization of the propagation of ionizing radiation can be achieved, which can be further complemented by propagation simulation models in the future, such as calculating the amount of exposure to ionizing radiation based on the inverse-square law of distance and the parameters of the radiological equipment.

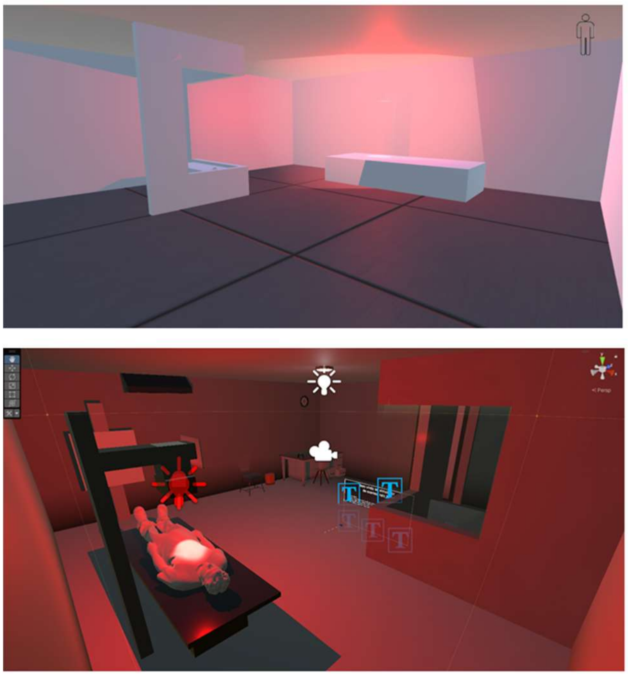

Figure 3. Prototype of visualization of ionizing radiation propagation by lighting algorithm. In this prototype, a point light source (red-hued) is used to show the propagation of ionizing radiation. Objects that act as radiation barriers are set up to block this light source. Top: initial proof of concept of the visualization. Bottom: light source positioned on the simplified radiological equipment, and visualization of areas of shadow produced by barriers. Source: The author.

3.3. Final Discussion

After the initial scenarios of the project were finalized, the 10 medical students from UNIFESP, were invited to evaluate the project.

The participants were allowed to interact individually with the system prototype freely, using a Meta Quest 3 device and its controls. After the interactive session, they filled an evaluation questionnaire on a digital platform.

A four-item TAM-style questionnaire (13) regarding ease of use and usefulness was applied, in which the students evaluated the project in terms of their perception of its ease of use and practical usefulness. Figure 4 illustrates a simple statistic of the questions presented and the answers obtained. The results were positive, demonstrating that the project has high potential.

The students' evaluation was as follows:

1) 60% completely and 40% partially agree with "It was simple to learn to use this software." In the opinion of some students, this 60% score is due to the fact that many of them are not familiar with the field of computing, but after a more detailed explanation, they would be able to operate the software on their own;

2) 20% completely and 60% partially agree with "Using this software would improve learning." Those who partially agreed attribute their response to not fully mastering the knowledge about Radiological Protection and not yet being familiar with the virtual environment;

3) 40% completely and 50% partially agree with "Using this software makes my learning more interesting." For students, despite not feeling familiar with the virtual environment, they believe that this practice stimulates learning, since it is a tool that helps in the complete visualization of the practice, and

4) 50% completely and 40% partially agree with "Software like this has the potential to be useful." For students, with the necessary adjustments and visual improvement, this VR activity can be useful for teaching and training in radiology. It is observed that participants, in the majority, agree that the use of VR for teaching X-ray can be considered a tool for teaching and learning in the medical field, with positive assessments of simplicity, appeal, and usefulness. If the scores are considered "Completely" + "Partially," it can be said that, on average, there was a 90% approval rate from the students.

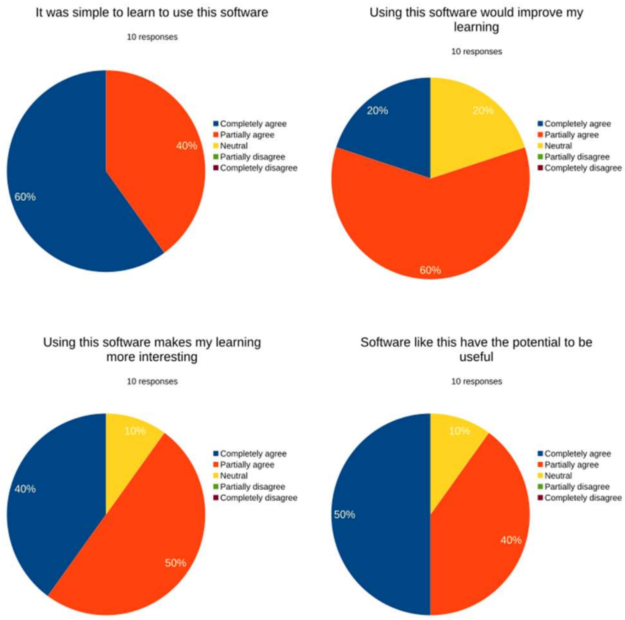

Figure 4. Summary of the responses given by medical students on their evaluations (n=10) on the perceived utility and perceived ease of use of the simulator prototype (Likert-like responses). Source: The author.

The results allow us to better understand participants' experiences with usability, engagement, and understanding of the activities, indicating that immersive virtual reality technology was more engaging, as participants felt immersed and engaged with the materials.

Thus, they were able to better understand how to handle radiation protection, how radiation is attenuated, and how shielding works. Finally, they showed interest in performing the exercises in new scenarios.

It is important to emphasize that the objective of this initial validation was to ensure that the simulator's features were meaningful for potential users.

This validation enables the continuation of the project, with further development and assessment of its educational effectiveness.

4. Conclusions

This paper describes the validation of Virtual Reality for X-ray training in a medical class. It is understood that medical education needs to keep pace with human development through teaching and new technologies.

The use of active methodologies, as a teaching and learning strategy, which places students at the center of the knowledge acquisition process, can bring medical education closer to the reality of young students.

This association has the potential to increase student interest, providing a positive impact on learning with the aim of training professionals equipped with differentiated techniques.

However, one barrier to overcome is the lack of knowledge about these technologies. This obstacle can be overcome by providing courses and training for teachers on the use of VR. Another barrier, specifically in Brazil, is still the high financial cost of the equipment used.

Using these technological tools can reduce the time needed for learning, allowing experiences to be modifiable and replicable until the educational objective is achieved.

Therefore, the use of techniques that adopt radiation protection as a basis is extremely relevant for application and training in Medical Physics.

At the moment, prototypes of the system are being implemented in accordance with the first expert validation. A new evaluation by experts and an evaluation by users are planned. The current project cycle is addressing X-ray examinations and, based on the results obtained, the system may be expanded to include other types of examinations.

This work is expected to assist in the training of operators of medical-hospital equipment that apply ionizing radiation, aiming at patient safety. As a future improvement, particle simulations could be added to this training system, in order to provide not only a visualization of areas exposed to radiation, but a measure of radiation intensity.

It is believed that this work could contribute to the development of a radiation attenuation model that allows simulating and visualizing the interaction of radiation particles with objects, users and dosimeter in the virtual laboratory during runtime using VR hardware.

Funding

Funding from "Fundo Patrimonial Amigos da Poli" was used for the acquisition of equipment used in this project, such as Meta Quest 2 and 3 head-mounted displays.

References

1. Da Conceição, G. O.; Renha, S.K.; Razuck, F.B. Ordinance 453/98: an analysis of its applicability in public and private hospitals of Rio de Janeiro after 20 years of its publication. Journal of Physics: Conference Series - IOP, 2021, 1826, 012051.
2. Brasil. CNEN. Resolução CNEN Nº 164. 2014.
3. Mota, T. A. A. Cartilha de orientação a pacientes e profissionais de saúde sobre física de radiações e exames de radiodiagnósticos (raio x e tomografia). Dissertação de Mestrado em Engenharia Biomédica, Publicação 100 A/2018, Programa de Pós-Graduação em Engenharia Biomédica, Faculdade Gama, Universidade de Brasília, Brasília, DF, 2018.
4. Nascimento, J. H. F.; Razuck F. B. Proposal for a professional qualification course in radiation protection to obtain the registration of Radiation Protection Supervisor to work at teaching and research laboratories. Brazilian Journal of Radiation Sciences, 2022, v. 10, n. 3B (Suppl.).
5. Stival, V. R. C.; Ribeiro, E. R.; GarbelinI, M. C. L. Augmented Reality and Virtual Reality as innovation in the medical course. Espac. Saúde, 2023, 24:e928.
6. Smith, J.; Nguyen, M.; Allison, N.; Carr, B.; Wood, K.; Uribe-Quevedo, A.; Perera, S.; Tokuhiro, A. Walle, E. Seeing the Invisible: A VR Approach to Radiation Attenuation Visualization for Nuclear Engineering. IEEE Transactions on Games, 2022, v. 14, no. 3.
7. Gonçalves, G. L.; Delgado, J. U.; Razuck, F.B. The use of Augmented Reality for the teaching of dosimetry and metrology of ionizing radiation at IRD. Journal of Physics: Conference Series – IOP, 2021, v. 1826, 1.
8. Gonçalves, G. L. De Sá, L. V.; Razuck, F. B. Use of Augmented Reality for demonstration of PET/CT and X-ray room to teaching Medical Physics in Nuclear Medicine. Revista Brasileira de Física Médica, 2020, 14.
9. Lewis, J. R. The System Usability Scale: Past, Present, and Future, International Journal of Human–Computer Interaction, 2018, 34(7)..
10. Pulijala, Y. et al. Effectiveness of Immersive Virtual Reality in Surgical Training—A Randomized Control Trial. J Oral Maxillofac Surg, 2017, 1-7.
11. Li, Q. et al. The use of metaverse in medical education: A systematic review. Clinical medicine, 2025, p. 100315.
12. Unity Technologies. Unity 3D. Disponível em: <https://unity.com/pt>. Acesso em 8 mar. 2025.
13. Silva, P.; Pimentel, V.; Soares, J. A utilização do computador na educação: aplicando o Technology Acceptance Model (TAM). Biblionline. Edição especial 2012. João Pessoa: Departamento de Ciência da Informação da Universidade Federal da Paraíba, 2012.

Contact:

Fernando Razuck
Coordination for the Improvement of Higher Education Personnel (CAPES).
Adress: Setor Bancário Norte (SBN), Quadra 2, Bloco L, Lote 06, Edifício CAPES, Brasília, DF, Brazil.
razuckdabrasilia@hotmail.com