Temporal bone 3D models – an innovative approach in otologic surgical training

Original Article

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Abstract

Introduction: Temporal bone surgery requires high precision due to the complexity of its anatomy. Traditional surgical training with cadavers presents limitations such as scarcity of material, anatomical variability, and high costs. This study explores the use of personalized 3D models of the temporal bone from patients scheduled for otologic surgery as an innovative training tool.
Materials and Methods: Personalized 3D models were created from high-resolution CT scans of each patient's ear and printed in resin (White V4, Formlabs 3+ printer). Surgical training was performed prior to the in vivo procedure. Subsequently, surgeons completed a questionnaire adapted from the Michigan Standard Simulation Experience Scale (MiSSES) to assess the model's usefulness for surgical training.
Results: Eight models were used, covering procedures such as cochlear implantation, canalplasty, and tympanomastoidectomy. All respondents found the training useful, reporting increased surgical confidence and a potential reduction in complication rates. They also highlighted the realism of drilling and the usefulness of the model for hand–eye coordination training.
Conclusion: 3D temporal bone models represent a promising educational tool for otologic surgical training.
Keywords: otology; surgical training; additive manufacturing; 3D printing; 3D models; temporal bone; surgical simulation; surgical planning;

Introduction

Otologic surgery requires a high degree of precision and detailed anatomical knowledge due to the complexity of the region and proximity to critical structures such as the facial nerve, labyrinth, *tegmen tympani*, and sigmoid sinus[1]. Surgical training in otology has traditionally relied on the dissection of cadaveric temporal bones, considered the gold standard because it provides an authentic anatomical and tactile experience[2].

However, this training model has significant limitations, including the increasing scarcity of specimens, biological risk associated with handling human tissue, substantial logistical and laboratory costs, progressive tissue degradation, and anatomical variability (including the absence of otologic pathology and challenges of pediatric training). These factors reduce the breadth of the training experience[3,4].

The use of three-dimensional (3D) models in the teaching of surgical techniques has gained prominence across medical specialties[4–7]. The progressive incorporation of simulators and 3D-printed models as a complement to traditional training has accelerated the learning curve and improved surgical skills among trainees[4], leading to better intraoperative performance and potentially fewer errors[8].

Surgical otology, particularly mastoidectomy, has a steep learning curve due to the region's complex anatomy and potential morbidity risk, such as facial nerve injury[9,10], labyrinthine hearing loss[11], and meningitis[12].

Virtual reality-based simulation has demonstrated effectiveness in improving manual dexterity and trainee confidence, but it remains limited by the lack of haptic feedback (tactile sensitivity) and insufficient anatomical realism[13]. In this context, physical 3D models of the temporal bone have emerged as a promising alternative. They faithfully reproduce the bone anatomy and critical structures[14], are accessible, carry no biological risk, and allow repeated practice without sterilization requirements or risk to patients[3,15–21].

Several studies have reported a high acceptance rate for 3D models among trainees and trainers[15,18,19,22], although robust evidence regarding their impact on real surgical performance remains limited[14]. Nevertheless, both cadaveric bones and commercial 3D models share a key limitation: they are not patient-specific and therefore do not account for individual anatomical variants or changes caused by pathology or previous surgery.

Although costs vary considerably depending on the materials and printers used, Frithioff et al.[19] estimated an approximate cost of USD 15.4 per printed model, compared with USD 400–700 for a cadaveric temporal bone used for surgical training[3]. In addition to the low cost of the models themselves, their use requires significantly lower laboratory expenses (appropriate facilities, specimen preservation with formalin or freezing, sterilization protocols, and biological safety procedures). Furthermore, 3D models can be easily stored or discarded without requiring specific post-use handling[3,4,6,19].

Accordingly, this study analyzed the practical utility of surgical training using personalized 3D models generated from the patients' computed tomography (CT) scans, which enables customization to the individual anatomy and planned surgical procedure.

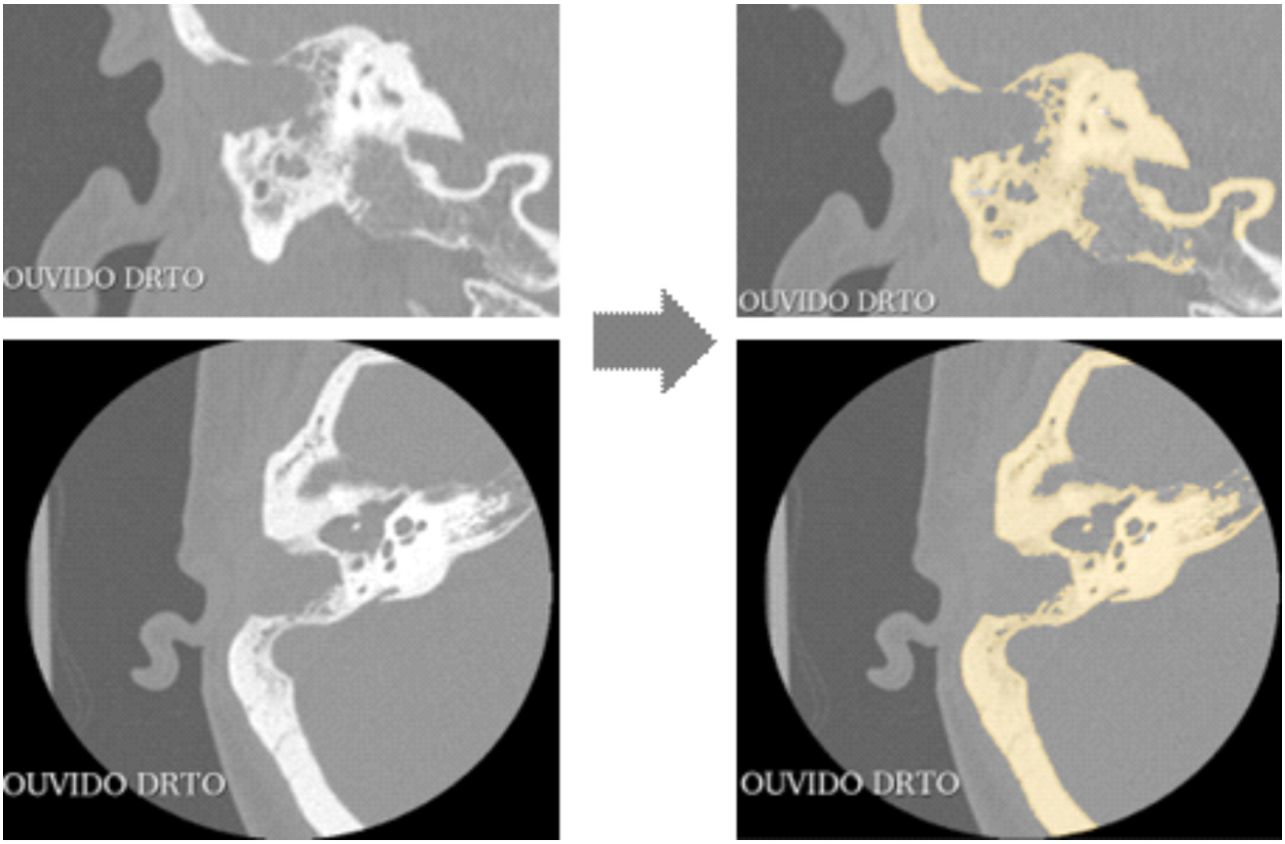
Materials and methods

High-resolution temporal bone CT scans previously obtained in routine clinical practice were used. These scans had been requested by otolaryngologists during the evaluation of patients scheduled for otologic surgery. Virtual 3D models were generated from these images through segmentation using the 3D Slicer software (version 5.8.1).

The modeling and printing phases of the study were conducted with the collaboration of the Operational Experimentation Unit for Unmanned Vehicles (CEOV) of the Portuguese Navy. Model refinement was performed using the AutoDesk Fusion 360 software. After testing different materials, White V4 resin was selected for coloration and realistic drilling behavior. Printing was performed on a Formlabs 3+ printer with a 0.050-mm layer resolution. The printed models initially contained thin supports that can be easily removed with a cerumen hook or similar instrument, as shown in Figures 2 and 3.

The models were subsequently used for surgical training in the dissection laboratory of the Otorhinolaryngology Department of the Almada-Seixal local health unit. Each model was used to replicate the surgical technique

Figure 1
Segmentation process



planned for the corresponding patient. Training took place during the same week as the *in vivo* surgery and always conducted before the procedure. Training sessions were conducted at the attending surgeon's convenience and used a standard otologic microscope, drill handpiece, cutting and

Figure 2
Printed 3D model prior to support removal

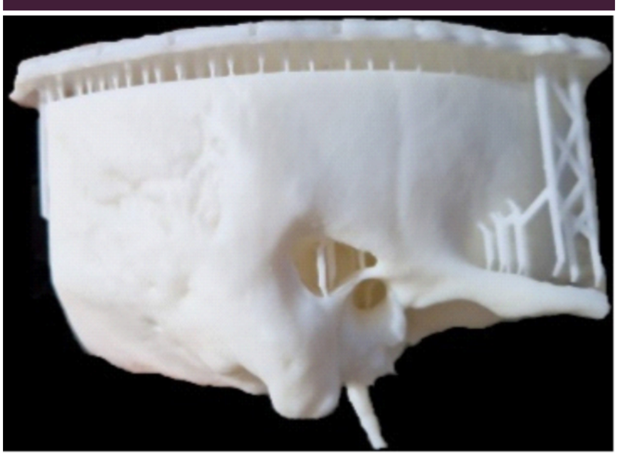
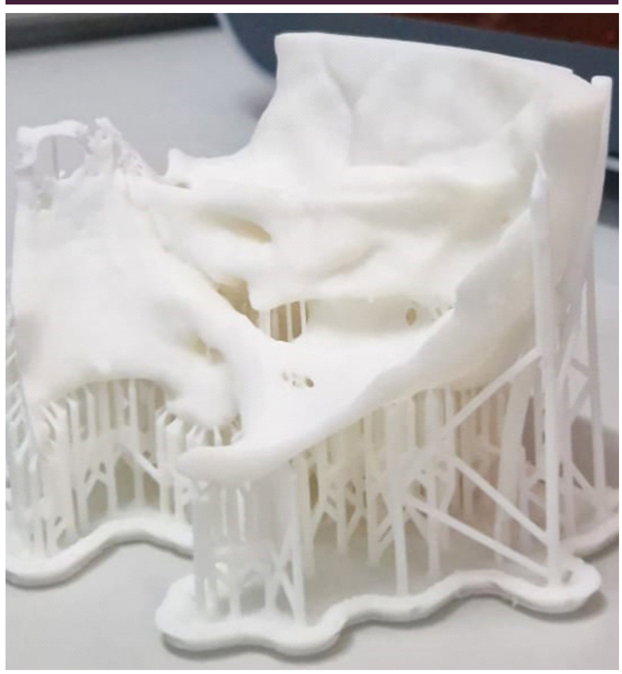


Figure 3
Printed 3D model prior to support removal



diamond burrs of various sizes (4 mm, 3 mm, 2 mm), and microsurgical instruments routinely used in the operating room.

To assess the utility of the 3D models for surgical training, a questionnaire was developed based on an adapted version of the Michigan Standard Simulation Experience Scale (MiSSES)[23]. Surgeons completed the questionnaire after training and performing the actual surgical procedure. Statistical analysis was conducted using the IBM SPSS® Software version 29.0.0.0.

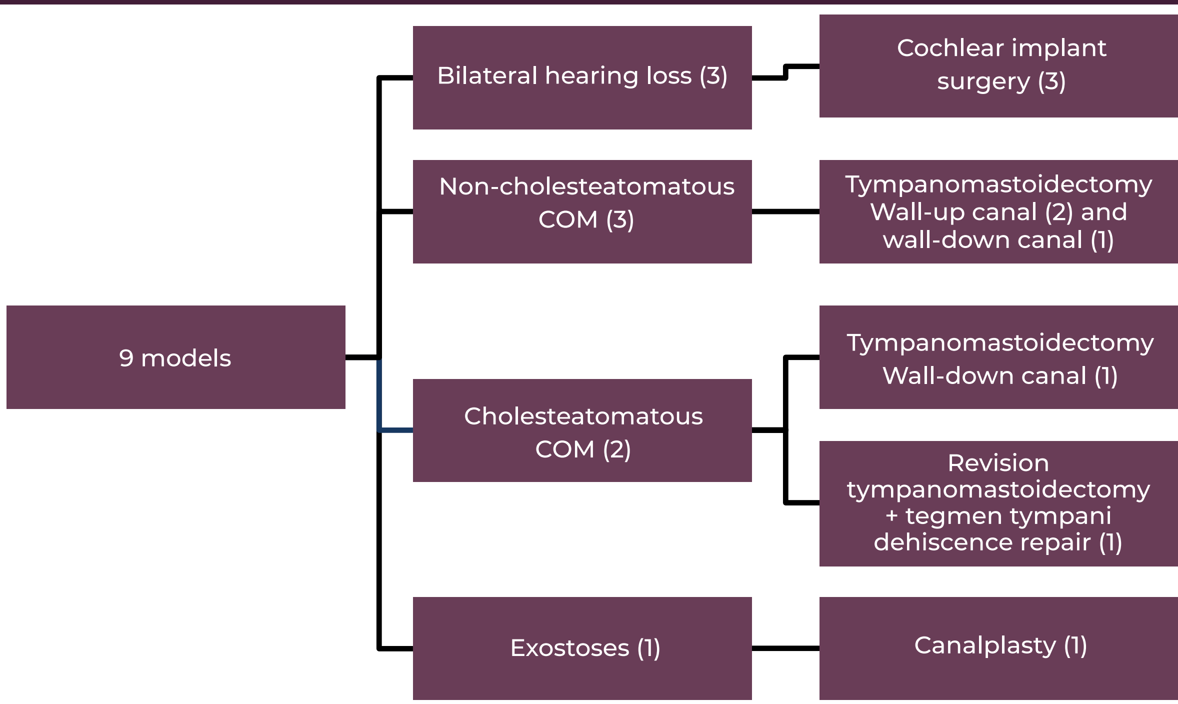
Results

Nine personalized 3D temporal bone models were created from high-resolution CT scans of patients scheduled for otologic surgery. Surgical training was conducted using eight of these models; one was excluded before surgery due to loss of the surgical indication.

Among the included patients, three had bilateral hearing loss and were selected for cochlear implantation. Training was conducted on two of these patients' models (one patient lost the indication for surgery). Three patients had non-cholesteatomatous chronic otitis media (COM); two were proposed for canal wall-up tympanomastoidectomy and one for canal wall-down tympanomastoidectomy. Two patients had cholesteatomatous COM; one was undergoing primary surgery and one was a revision case requiring additional repair of tegmen tympani dehiscence. Finally, one patient had external auditory canal exostoses requiring canalplasty. Model distribution by the pathology and proposed surgery is shown in Figure 4.

Training was conducted in the dissection laboratory of the Almada-Seixal Local Health Unit, using the models to replicate the planned surgical technique for each patient, without the need for aseptic precautions. Procedures were performed by the same surgeons responsible for the *in vivo* intervention, using the same microsurgical instruments and surgical microscope employed in the operating room. Drilling was performed using 4-mm, 3-mm, and 2-mm burrs depending on the stage of dissection and proximity to critical structures. Training occurred immediately before the real surgery, allowing surgeons to become familiar with the specific anatomy of each case.

Figure 4
Clinical indications and proposed surgical procedures. COM, chronic otitis media



All patients (excluding the one patient who lost the surgical indication) subsequently underwent the planned otologic procedure, performed by the same surgeon who had trained using the corresponding model.

After surgery, surgeons completed the questionnaire based on the adapted MiSSES, supplemented with the demographic data. The objective was to evaluate the perceived utility of the personalized 3D models in terms of anatomical realism, practical applicability, usefulness for surgical planning, and impact on the surgeon's confidence.

A total of eight surgeons participated in this study, with ages ranging from 27–64 years; 75% were women and 25% were men. Among them, five were specialized otorhinolaryngologists, including one with formal subspecialty training in otology, and three were residents (one each from years 2, 3, and 5). Each surgeon trained with only one model and completed the questionnaire once. Previous experience with the corresponding surgical technique varied widely, ranging from fewer than five procedures to more than one hundred.

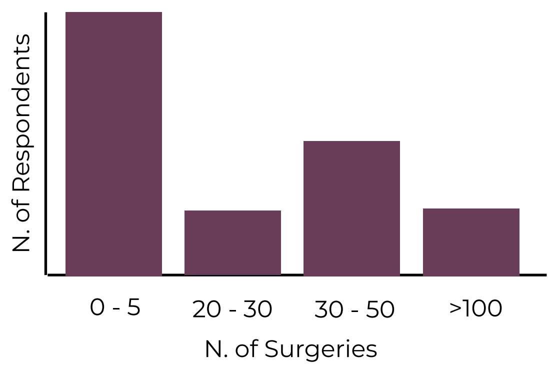
To assess overall satisfaction, responses to five key questionnaire items were analyzed, including whether the participants would recommend the model to other professionals and comparisons with traditional cadaveric training.

All participants stated that they would recommend 3D model training to other surgeons or trainees, reflecting high satisfaction and confidence in its educational value. Similarly, the mean scores for increased confidence in performing surgical procedures (4.5) and the need to incorporate 3D-model training into the otorhinolaryngology residency curriculum (4.5) were high, with low variability. Regarding skill transfer to the operating room, the mean score was 4.25, suggesting that most surgeons thought that 3D-model training had a positive impact on real surgical practice. However, direct comparison with traditional cadaveric training revealed a more moderate mean score (3.375) with greater variability. This indicates that although the 3D model was highly valued, surgeons acknowledge specific advantages of cadaveric training over 3D model training or consider 3D-model training to serve best as a complementary tool. A strong negative correlation was found between prior surgical

Figure 5
Surgical training on the model

Figure 6
Mastoidectomy training on the model

Figure 7
Surgical experience of the participants



Surgical experience with the surveyed technique

experience and satisfaction with the 3D model (r = -0.82, p = 0.04, Pearson correlation), indicating that greater surgical experience was associated with lower satisfaction. This relationship was statistically significant, despite the small number of responses.

Recommendation of the model received the highest score (mean 5.0 with no variation), indicating unanimous agreement. Confidence improvement, curriculum integration, and skill transfer to the operating room also scored highly (means 4.25–4.5, with low standard deviations).

Comparison with cadaveric bone dissection had the lowest mean score (3.38) and the highest standard deviation (1.51), reflecting more divergent opinions.

These findings suggest that the positive impact of 3D models is most pronounced among early-stage learners, whereas more experienced surgeons may derive less added benefit, likely due to their prior mastery of the techniques. All respondents (100%) would recommend the model to other surgeons, reinforcing the value of 3D models as a training tool, particularly for early-career professionals.

Overall, a decreasing trend in satisfaction was observed as item specificity increased (from general recommendation to direct comparison with cadaveric bone), accompanied by growing standard deviations, indicating greater divergence in response to more detailed questions. Comparison with cadaveric training showed the greatest variability, suggesting the need for technical improvement of these models to narrow the gap between 3D-model training, cadaver dissection, and real-patient surgery.

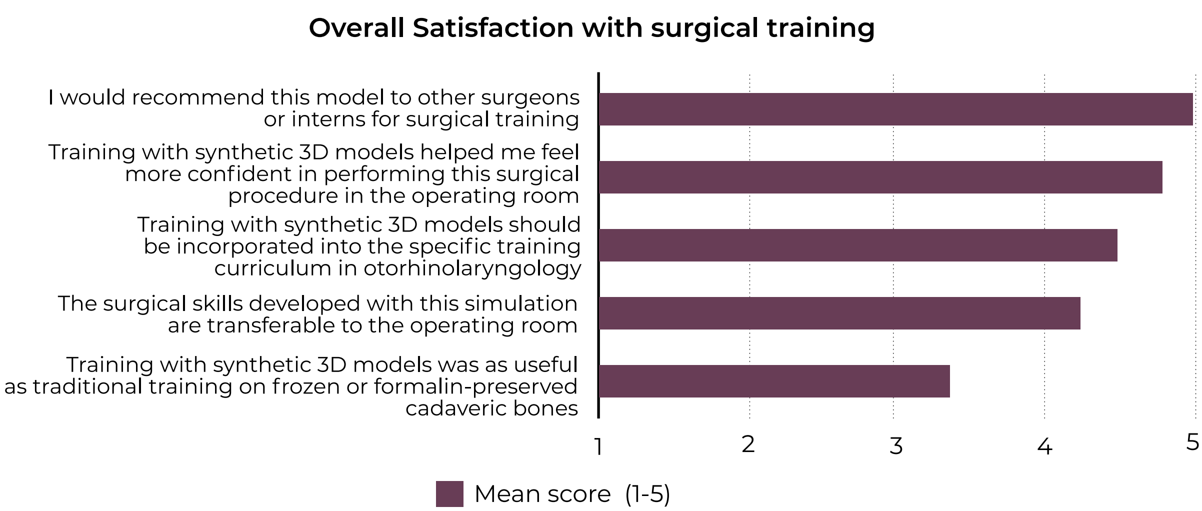
Suggestions for improvement included enhancing the definition of the ossicular chain and the round and oval windows (limited by difficulty in isolating these structures on standard temporal bone CT), adding and differentiating soft tissues (structures and pathology), and improving the color contrast and differentiation.

Discussion

This study demonstrates that patient-specific 3D-printed temporal bone models generated from CT scans are feasible, well accepted by surgeons, and useful as preoperative surgical training tools. The results demonstrated high perceived utility, particularly among residents, and increased confidence in performing otologic procedures, suggesting a meaningful role for these models in specialized medical training.

These findings align with those of previous studies that reported strong acceptance of 3D models in otologic practice and recognition of their educational value[3,15,18,24]. The observed

Figure 8
Mean agreement with statements related to overall satisfaction on the MiSSES (1 = strongly disagree; 5 = strongly agree). MiSSES, Michigan Standard Simulation Experience Scale



trend toward greater benefit among early-stage learners is consistent with the reports by Frithioff et al.[24] and Lannella et al.[15] indicating that 3D-printed models have a more significant impact on trainees with limited prior experience. Although more experienced surgeons assigned lower satisfaction scores, all recommended the models to other professionals, reinforcing their value in training.

One of the major strengths of this study is the personalized nature of the models, tailored to each patient's anatomy and the planned surgical technique. This represents an advancement over most previous studies, which relied on generic or cadaver-derived models. The integration of model-based training with subsequent surgery on the same patient also strengthens the evaluation of the perceived impact.

Nevertheless, this study has some limitations, including the small number of participants and absence of a control group, which prevented comparison of 3D-model training with cadaveric training or no training. Additionally, the evaluation was based on subjective measures of satisfaction and confidence, and did not include objective surgical performance metrics. Technical limitations of the models were also noted, including insufficient definition of the ossicular chain and the oval and round windows.

The quality of the source imaging (high-resolution CT) determines the anatomical definition, particularly for fine structures such as the ossicular chain or the round and oval windows[14,16]. Model creation involves a steep technical learning curve and is susceptible to human error, particularly during segmentation and model refinement[14]. The choice of printing material directly affects tactile realism, as overly rigid or brittle resins may compromise drilling simulation[19]. Most printers allow only the use of a single material per print, preventing differentiation between hard and soft tissues. The absence of biomechanical feedback and inability to simulate physiological properties such as variable resistance or bleeding limit sensory training[22]. Printing costs, the need for specialized software, and post-printing manual assembly for multicomponent models may also hinder widespread adoption.

Despite these limitations, our findings suggest that personalized 3D models hold substantial educational potential in otologic training. Integrating them into the otorhinolaryngology curricula, especially during early training stages, may contribute to safer, more efficient, and patient-centered surgical preparation. Future studies should include larger samples, control groups, and objective performance assessments to validate the true impact of these models on surgical outcomes. Advances in materials and printing technologies, as well as integration with augmented reality and haptic feedback, represent promising paths for improving this approach.

Conclusion

The use of patient-specific 3D-printed temporal bone models represents a promising innovation in otologic surgical training. These models enable realistic preoperative practice tailored to each patient's individual anatomy, with a positive impact on the surgeons' confidence and surgical performance. Although technical limitations related to model creation and printing materials persist, the models were well accepted by surgeons, particularly those in early stages of training. Their progressive integration into structured training curricula may represent an important step forward in surgical education, contributing to safer, more efficient, and more personalized practice. Further studies with larger samples and objective performance evaluation are needed to validate their impact in clinical practice.

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Conflict of interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data confidentiality

The authors declare having followed the protocols used at their working center regarding patient data publication.

Protection of humans and animals

The authors declare that the procedures were followed according to the regulations established by the Clinical Research and Ethics Committee and the 2013 Helsinki Declaration of The World Medical Association.

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Availability of scientific data

There are no datasets available, or publicity related to this work.

Declaration on the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT 4.0 for text summarization, improvement of language and readability, and reduction of citations to include only the 25 permitted. After using this tool/service, the author(s) reviewed and edited the content as necessary and assume(s) full responsibility for the content of the publication.

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