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Unveiling the Intricacies of the Inner Ear Anatomy: Novel 3D-Printed Model for Detailed Visualization and Functional Demonstrations

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Main Article

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Abstract

Objectives. This research aimed to print realistically detailed and magnified three-dimensional models of the inner ear, specifically focusing on visualising its complex labyrinth structure and functioning simulation.

Methods. Temporal bone computed-tomography data were imported into Mimics software to construct an initial three-dimensional inner-ear model. Subsequently, the model was amplified and printed with precision using a three-dimensional printer. Five senior attending physicians evaluated the printed model using a Likert scale to gauge its morphological accuracy, clinical applicability and anatomical teaching value.

Results. The printed inner-ear model effectively demonstrated the intricate internal structure. All five physicians agreed that the model closely resembled the real inner ear in shape and structure, and simulated certain inner-ear functions. The model was considered highly valuable for understanding anatomical structure and disorders.

Conclusion. The three-dimensionally printed inner-ear model is highly simulated and provides a valuable visual tool for studying inner-ear anatomy and clinical teaching, benefiting otologists.

Introduction

The inner ear is a complex and delicate three-dimensional (3D) spatial structure located deep in the temporal bone. A microscope is needed to obtain a clear picture of the inner ear. It is particularly difficult to visualise the membranous labyrinth structure inside in this case. Thus, most physicians have little opportunity to see the real inner structure of the inner ear. Due to the lack of a highly simulated and internally visualised anatomical model of the inner ear, it takes medical learners a great deal of effort to understand the structure of the inner ear. Typically, they need to restore the anatomical structure of the inner ear by relying on two-dimensional anatomical maps and text descriptions of the inner ear in anatomical books, coupled with their spatial recognition ability, to understand the structure and mode of action of the inner ear. This is a difficult and time-consuming process for a learner with poor spatial imagination while not having a better learning effect.[1] Therefore, a highly simulated and internally visualised anatomical model of the inner ear is particularly important.

In recent years, there has been significant progress in 3D printing technology and its application in the medical field. This technology converts two-dimensional sectional anatomical images into 3D objects, providing more realistic and intuitive 3D spatial structures. In other words, 3D structures can simplify the study of inner-ear anatomy.[2–5] Nonetheless, printing a model of the inner-ear shape is relatively easy with current 3D printing technology, but printing a model of the inner ear with internal structure is still a significant challenge. In this study, we attempted to create an enlarged 3D-printed inner-ear labyrinth model. Using special modelling strategies and printing methods, we accurately simulated inner-ear shape with the model and visualised the inner-ear internal structure, which helps to clarify the structure and operation of the inner ear to beginners.

Materials and methods

Manufacturing of 3D models

This study was approved by the ethics committee of Quanzhou First Hospital. Computed tomography (CT) scanning was performed on a 128-slice spiral CT scanner (GE Medical Systems, Waukesha, WI, USA) with 0.625 mm slice thickness and 512 × 512 μm resolution. Data pertaining to the CT scan of the temporal bone base were captured from a healthy individual. The original CT data were imported directly into Mimics 21.0 (Materialise, Leuven, Belgium) directly in digital imaging and communications in medicine (.dcm file) format, and the inner-ear structure was separated using the threshold

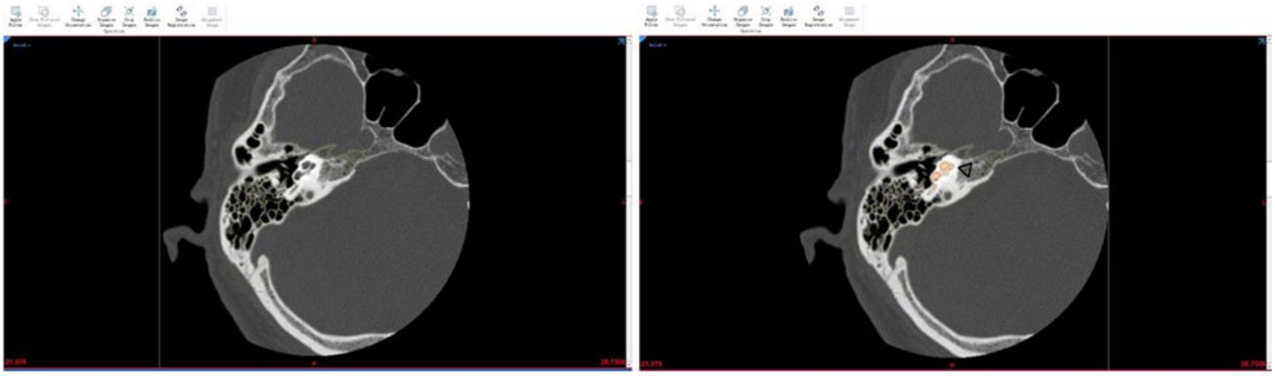

Figure 1. Inner ear CT data import and segmentation.

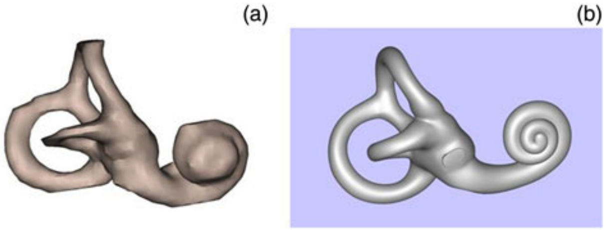

Figure 2. 3D modelling of the inner ear. **A.** CT reconstruction of the real appearance of the inner ear. **B.** Reconstruction of the inner ear in real form.

segmentation tool of the software. The segmentation result was saved as an object of Mimics, called a mask (Figure 1). Subsequently, the processed mask was reconstructed in three dimensions, and the optimized model was saved as a 3D-printed file in stereolithography (also known as standard triangle language or standard tessellation language) format following mild fairing optimization (Figure 2A). According to the reconstructed inner-ear shape, a complete enlarged inner-ear model was reconstructed using Zbrush version 2023.2 (Pixologic, California, USA), a 3D modelling software (Figure 2B). The internal membrane labyrinth structure was artificially 3D reconstructed (Figure 3). Afterwards, the model was entered into the rapid prototyping auxiliary software system of the Magics software, and after performing model inspection and repair, it was placed in a tilt direction, with the angle repeatedly adjusted to minimize the internal support of the model. For the remaining support structure, we fine-tuned the angle of the model's internal structure without compromising the authenticity of the inner-ear simulation to achieve a state without support (Figure 4). Subsequently, the model print file was uploaded on a 3D-printing website (www.3dworks.cn), and light-cured printing was selected, with a transparent photosensitive resin material.

Evaluation of the model

Five experienced senior attending doctors were invited to evaluate the model using a five-point Likert scale from the aspects of model simulation, accuracy, some of the model's demonstration features, and its advantages and teaching value.

Evaluation of teaching applications

Two groups of 10 fourth-year undergraduate students, each with approximately equal entrance grades and learning ability, were randomly selected from Fujian Medical University. One group was randomly assigned to 3D-printed model teaching and the other to conventional teaching, including anatomical identification and interpretation by looking at an atlas presented in PowerPoint format. After the lesson, a questionnaire was administered to explore the degree of learning distress, interest in learning, and recognition of teaching methods in the process of learning inner-ear anatomy and benign paroxysmal positional vertigo. The survey results were analysed statistically by independent t-test using GraphPad Prism 9 (GraphPad Software, Boston, MA). Meanwhile, the classroom expressions of the students, including classroom atmosphere and student interaction, were also recorded to evaluate the influence of 3D-printed model teaching on students' teaching classroom. A content knowledge test was conducted one year later without prior notice when the students returned to perform practice in the fifth year. The test evaluated the influence of the 3D printing model on students' knowledge retention and resulted in a total score of 10 points.

Results

The 3D-printed inner-ear model is realistic in shape as a whole and has an excellent look and feel (Figure 5A). It comprises

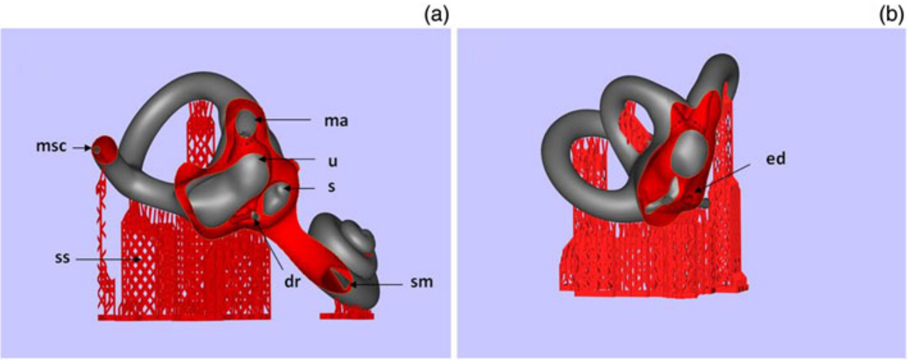

Figure 3. 3D reconstruction of the membranous labyrinth structure of the inner ear. **A.** X-axis cross-sectional view. **B.** Z-axis cross-sectional view. msc = membranous semicircular canals; ss = support structure; ma = membranous ampulla; u = utricle; s = saccule; dr = ductus reuniens; sm = scala media; ed = endolymphatic duct.

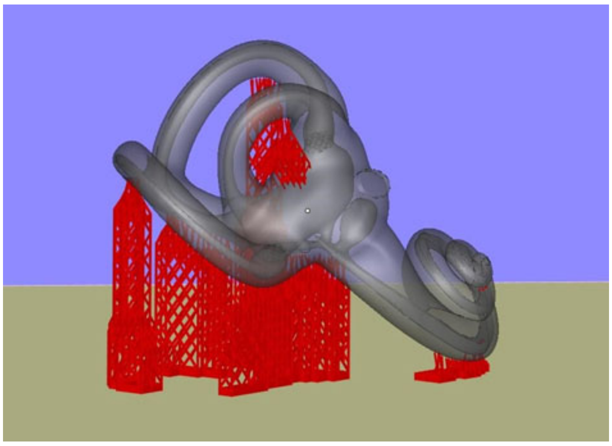

Figure 4. Print placement position of the inner ear model.

three semicircular canals, namely the total foot of the semicircular canal, ampulla of the semicircular canal, and vestibule and cochlea. A clear presentation of the internal membranous labyrinth, including membranous semicircular canal, membranous ampulla, elliptical sac and balloon, elliptical balloon tube, internal lymphatic vessel, vestibular window, commissure tube and cochlear duct (Figure 5B), can be achieved by injecting glycerine and blue dye into the model through a reserved tube. The injection of metal particles also makes it possible to imitate the flow of detached otolith particles in the semicircular canal and demonstrate the pathogenesis of benign paroxysmal positional vertigo in different semicircular canals (Figure 6).

After observing the model, the five attending doctors thought that its shape and anatomical structure were almost the same as those of the real inner ear, with a high degree of simulation and accurate score (4.4 ± 0.55). They readily recognized its application value in inner-ear anatomy learning and teaching, demonstration of membranous labyrinth diseases and clinical education. The evaluation results are presented in Table 1.

The questionnaire survey indicated that compared with the students assigned to conventional teaching, those assigned to 3D-printed model teaching were significantly more interested in the study of inner-ear anatomy and benign paroxysmal positional vertigo and had significantly higher recognition scores of the teaching methods. In addition, they were obviously less troubled by learning, with a statistically significant difference compared with the students that were assigned to the conventional teaching group. The relevant knowledge content assessment after one year demonstrated that the scores obtained by the 3D-printed model teaching group were significantly higher than those of the conventional teaching group (Figure 7).

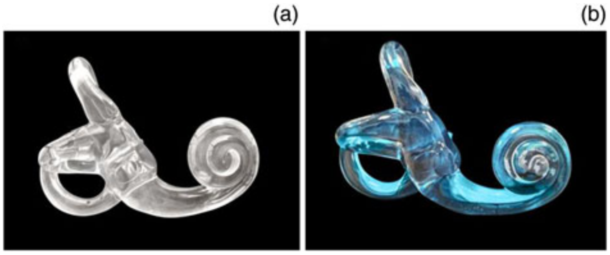

Figure 5. Printed inner ear model. **A.** Indicates the morphology just after printing without glycerol injection and dyeing. **B.** Indicates the morphology after injecting glycerol and dyeing, in which case the internal membranous labyrinth morphology can be clearly observed.

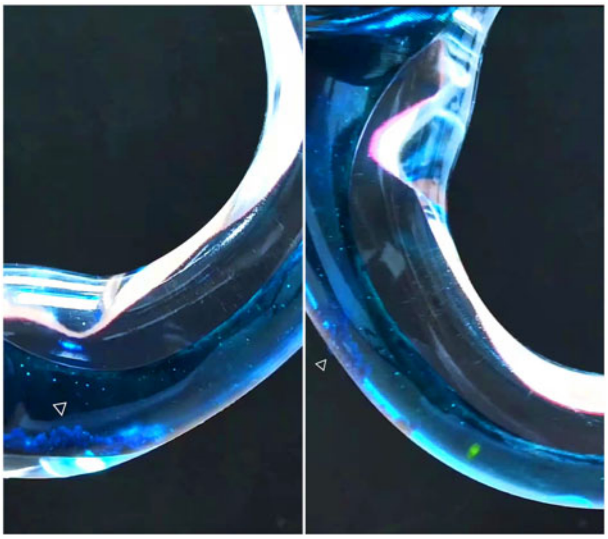

Figure 6. Otolith particles separated from the membranous semicircular canal. *Note*: The two arrows indicate Otolith particles.

Furthermore, in the conventional teaching group, the students had blank faces when degrading the anatomy of the inner ear, the classroom atmosphere was average, and few students asked questions. In contrast, in the 3D-printed model teaching group, the students were more active in the classroom, the classroom atmosphere was livelier, and some high-quality and interesting questions were frequently asked.

Discussion

Three-dimensional printing technology, one of the hottest and most revolutionary technologies in use, is advancing rapidly and increasingly is being used in the medical field. In particular, 3D printing technology is used in the manufacture of medical models for medical research and teaching.[6,7] Some complex anatomical structures, especially tiny and fine structures, are not directly observable by the naked eye under normal circumstances. Thus, the use of 3D printing technology helps obtain a clear picture of these structures and shows the positions we need to focus on through different modelling

Table 1. Evaluation table of the results of the 3D printing model

Evaluation items	Mean agreement ± SD*
The shape and anatomical structure of the model are roughly the same as those of the real one	4.4 ± 0.55
The internal structure of the model can accurately reflect the shape of the membranous labyrinth	4.6 ± 0.55
The model can accurately demonstrate the function of the inner ear	4.2 ± 0.45
The model is of great value in helping to learn the inner ear anatomy	4.8 ± 0.45
The model can well simulate the pathogenesis of benign paroxysmal positional vertigo	4.2 ± 0.45
The model has a good auxiliary function for learning the manual reduction treatment of benign paroxysmal positional vertigo	4.6 ± 0.55
The model should be included in the training props for junior otologists	4.8 ± 0.45
The model should be used for clinical education	5.0 ± 0.00

*SD = standard deviation; 1 = completely disagree, 5= completely agree

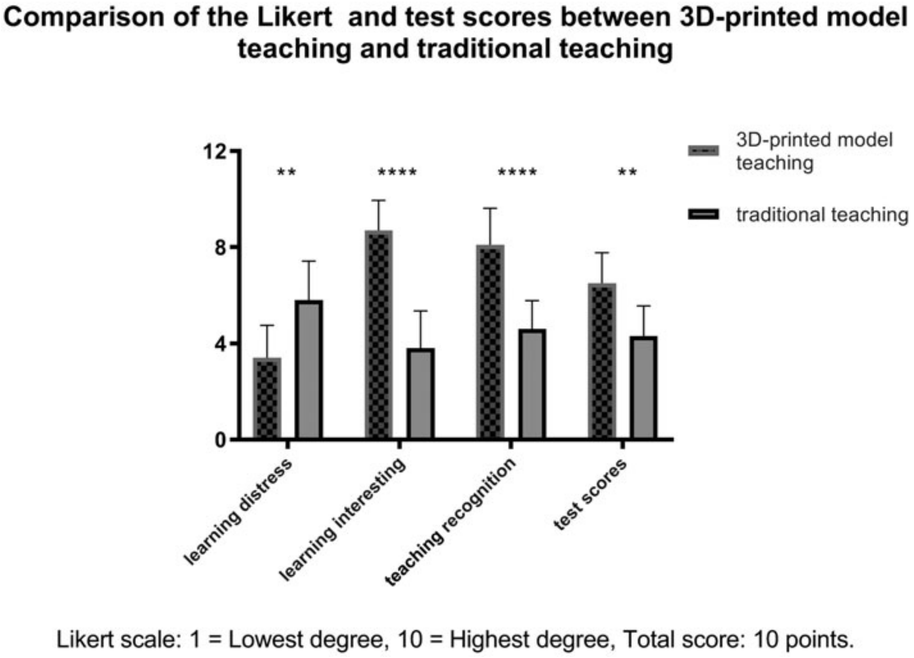

Figure 7. Comparison of the Likert-scale and test-score results 1 year later between 3D-printed model teaching and traditional teaching.
Note: Two asterisks indicate $p < 0.05$, four asterisks indicate $p < 0.0005$.

strategies, which improves the understanding of the structures and their functions.[8–10]

The inner ear is a small, precise, complex 3D structure located deep in the temporal bone. In view of the absence of a corresponding teaching model for the inner ear, the first step in learning it is usually to understand it from the schematic diagrams and textual descriptions in anatomy books. However, such a learning approach is prone to bias due to the complexity of the inner ear and makes it more difficult for young learners, who generally forget the structure of the inner ear and the names and relationships of the internal structures years later.

The inner ear model designed and printed in this study accurately simulates the shape of the real inner ear, which has been unanimously recognized by investigators. The internal structure of the inner ear can be observed clearly by using transparent printing materials and by injecting dye. Furthermore, with this model, the internal membranous labyrinth can be clearly seen, including the membranous semicircular canal, membranous ampulla, elliptic sac and balloon, elliptic balloon tube, internal lymphatic vessel, vestibular window, commissure tube and cochlear duct, as well as their spatial relationships (Figure 5). The 3D model has excellent visual and sensory replication, which helps us not only to learn and remember but also to understand inner-ear functions, such as the transmission process of listening, spatial arrangement of semicircular canals, and its operation mode in human acceleration. As confirmed in this demonstration of 3D-printed model teaching, students who received 3D-printed model teaching tended to not only feel that learning was much easier, but also had a good learning experience and a lasting memory. In this study, the students raised an interesting question. Why are the vestibule and cochlea together, given that one is for balancing and the other for hearing? By putting together two functionally disparate structures that are structurally connected rather than separated, wouldn't it be possible for a problem with one to affect the other? We can't help but wonder if this arrangement is to facilitate the delivery of nutrients, or is it just a coincidence, or is there some other reason we haven't discovered yet?

The printed inner-ear model can also help us learn about membranous labyrinth diseases, such as benign paroxysmal positional vertigo. By injecting glycerol, the endolymph in the semicircular canal can be simulated; metal particles can simulate the degenerated otolith in the semicircular canal and elliptic sac and the situation that the degenerated otolith in the elliptic sac falls off into the semicircular canal and flows in different semicircular canals. In this way, we can intuitively learn the attack process of benign paroxysmal positional vertigo and understand the ways of manual reduction of different semicircular canals from the otolith. Three-dimensionally printed model teaching is a livelier and more interesting process than the use of schematic diagrams and text explanations. In this study, all the participants judged that this model accurately represented the anatomical shape of the inner ear and recognized its high-quality restoration of the internal structure of the inner ear as the most accurate model they had seen so far. Furthermore, they recognized the potential applications and important value of this model in the study and teaching of inner-ear anatomy, demonstration of membranous labyrinth diseases and clinical education.

Model printing is no longer a difficult task. The popularity of 3D printing technology provides us with a variety of options to either print the model ourselves, have it printed by a 3D-printing company, or upload it to the web for cloud printing. The model in this study was uploaded to a website for cloud printing, which yielded very satisfying printing results. However, there is one limitation that cannot be avoided: because the existing 3D-printing technology requires additional support when printing in places with large inclinations, while the inner-ear model is a relatively closed space, the conventional placement position will add too many supports when printing the internal structure, which will be difficult to remove after printing. Therefore, we changed the model to a vertical position and fine-tuned its angle to minimize the support of its internal structure. Furthermore, because of the support problem, we printed the space inside the model as solid, except for the membranous labyrinth; therefore, the shape of the tympanic and vestibular steps cannot be obviously seen on the model, which is the model's biggest drawback. However, in the clinical application of 3D printing, it is possible to utilize specific modelling strategies and printing methods to overcome the limitations of 3D printing technology, and to achieve the requirements of certain clinical functions to the greatest extent possible.

Conclusion

The 3D-printed inner-ear labyrinth model in this study has an extremely accurate 3D spatial representation, faithfully representing the anatomical shape of the inner ear and the 3D spatial structure of its internal membranous labyrinth, which helps beginners recognize and understand the structure and function of the inner ear more intuitively. The model can be widely used for learning and teaching inner-ear anatomy, demonstrating membranous labyrinth diseases, and clinical education.

- Three-dimensional (3D) printing technology is widely used in medical research and education, particularly in the creation of medical models; however, it is challenging to accurately replicate complex internal structures, especially with regards to the inner ear
- The 3D-printed inner-ear model allows for clear visualization of the intricate and fine structures of the inner ear, enhancing understanding of its anatomy and function
- Teaching with the 3D-printed inner-ear model provides a more engaging and memorable learning experience, with heightened visual and sensory awareness
- Application of the inner-ear model extends beyond academic research, with significant potential in disease studies and clinical education, such as in the case of benign paroxysmal positional vertigo

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Competing interests. None declared.

Ethical approval. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional guidelines on human experimentation set forth by the Quanzhou First Hospital Affiliated to Fujian Medical University and Helsinki Declaration of 1975, as revised in 2008.

Author contributions. Shou-Wu Wu and Xiao-Dong Zhang contributed equally to this study.

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