MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/

Immersive and Interactive Visualization of Otological Anatomy: Advancing an AI-Integrated Medical Education Platform

Manjit Singh Sidhu*[1], Kirandeep Kaur Sidhu[2], and Avin Mahajan[1]

[1] *Dept. of Graphics and Multimedia, College of Informatics, Universiti Tenaga Nasional. Kajang, Selangor, Malaysia.*
[2] *Faculty of Medicine and Health Sciences, Sg. Long, Selangor, Universiti Tunku Abdul Rahman (UTAR).*

KEYWORDS

Metaverse
Interactive
AI
Anatomy
Visualization

ARTICLE HISTORY

Received 23 February 2026
Received in revised form 8 March 2026
Accepted 18 March 2026
Available online 29 March 2026

ABSTRACT

Aural anatomy remains one of the most spatially complex domains in medical education due to the intricate three-dimensional relationships within the middle and inner ear. While immersive technologies have demonstrated measurable improvements in anatomical learning, existing systems such as OtoVIS primarily focuses on photorealistic visualization without fully integrating artificial intelligence (AI), curriculum alignment, multi-user collaboration, or commercialization frameworks. This study introduces OtoVisionXR, an AI-integrated extended reality (XR) platform designed to enhance anatomical comprehension, learner engagement, and clinical relevance. A controlled pre-test/post-test validation study was conducted among 30 first-year medical students. Statistical analysis demonstrated significant improvement in knowledge scores following XR exposure (Pre-test: M = 56.4, SD = 8.7; Post-test: M = 78.9, SD = 7.5; $t(29) = 14.62$, $p < 0.001$; Cohen's d = 1.92). Learner perception ratings exceeded 6.2/7 across engagement and visualization domains. Percentage improvement reached 39.9%. The platform further demonstrates scalability for rural medical centres and continuing professional development programs. These findings position OtoVisionXR as a validated, societally relevant, and commercially viable immersive learning solution.

1. INTRODUCTION

Anatomical education, particularly in otology, has traditionally relied on static two-dimensional illustrations, cadaveric dissection, and physical models. Although foundational, these approaches fail to convey the depth, orientation, and microanatomical relationships of the ossicles, cochlea, semicircular canals, and neurovascular structures. Surgical disciplines such as otorhinolaryngology requires precise spatial understanding to minimize intraoperative risk [1]. Extended Reality (XR), encompassing Virtual Reality (VR) and Augmented Reality (AR), has emerged as a promising educational intervention. Meta-analytic evidence demonstrates moderate but significant improvements in knowledge acquisition when immersive systems supplement conventional teaching (standardized mean difference ≈ 0.52) [2-6]. Extended Reality (XR) which encompasses Virtual Reality (VR), Augmented Reality (AR), and their hybrids has been increasingly adopted across medical disciplines due to its capacity to enhance spatial understanding, engagement, and retention [7]. Previous systems such as OtoVIS demonstrated strong face and content validity among trainees [8]. However, current platforms are largely limited to visualization without AI-driven adaptive learning, multi-user collaboration, or clinical simulation modules [9].

To address these limitations, this study introduces OtoVisionXR, an immersive XR platform enhanced with artificial intelligence and designed for interactive visualization of aural anatomy. Unlike prior systems, OtoVisionXR integrates real-time anatomical manipulation, AI-assisted guidance through natural language interaction, and metaverse-inspired collaborative learning within a modular framework. In addition to supporting undergraduate and postgraduate medical education, the platform is designed with translational potential for clinical training, surgical rehearsal, and patient education.

*Corresponding author:
E-mail address: Manjit Singh Sidhu < manjit@uniten.edu.my >.
https://doi.org/10.56532/mjsat.v6i1.726
2785-8901/

This paper presents the system architecture, validation methodology, and evaluation findings of OtoVisionXR, positioning it as a scalable and application-ready contribution to contemporary medical education and digital health. A preliminary version of this manuscript was presented virtually at the IGIIDEATION 2026.

2. MATERIALS AND METHODS

The OtoVisionXR platform is architected as an immersive XR system that integrates advanced three-dimensional visualization, artificial intelligence, and interactive learning modules. The system is compatible with both standalone and tethered XR head-mounted displays, including Meta Quest 2 and Quest 3, enabling flexible deployment across educational and clinical environments.

High-resolution two-dimensional anatomical datasets form the basis for generating detailed three-dimensional otologic models. These models are reconstructed and optimized using advanced rendering techniques, including photorealistic shading, subsurface scattering, and hybrid surface–volume visualization, to accurately represent delicate ear structures such as the ossicular chain, cochlea, and vestibular apparatus. Hybrid surface–volume visualization combines polygonal surface rendering with volumetric data representation. Unlike standard 3D rendering, which displays only external surfaces, this approach enables simultaneous visualization of both outer anatomical structures and internal microstructures derived from imaging datasets. This is particularly important for otological anatomy, where internal features such as cochlear ducts and soft tissue layers must be visualized alongside external morphology. Computational efficiency is achieved through foveated rendering, which prioritizes high visual fidelity within the user's focal region while reducing processing demands elsewhere. Accordingly, the system renders high-resolution detail only within the user's gaze region, while peripheral areas are rendered at lower resolution. This perceptually guided optimization significantly reduces GPU workload without degrading perceived image quality. As a result, OtoVisionXR maintains high visual fidelity in anatomically critical focal regions (e.g., ossicular chain, cochlear turns) while ensuring real-time rendering performance required for immersive interaction.

Interactivity is a core design principle of OtoVisionXR. Users can manipulate anatomical structures through hand tracking or controllers, rotate and scale models, and selectively enable or disable anatomical layers such as nerves, vasculature, and pathological overlays. Embedded instructional cues, dynamic annotations, and guided learning pathways support structured exploration aligned with medical curricula. A distinctive feature of the platform is the integration of an AI-powered virtual assistant that leverages generative AI and natural language processing to provide real-time responses to anatomical queries, highlight requested structures, and deliver context-aware explanations. The generative AI-powered virtual assistant utilizes natural language processing (NLP) and large language models to interpret user queries in conversational form. Students can ask questions such as "show the facial nerve pathway" or "explain the function of the cochlea," and the system responds by dynamically highlighting structures and providing contextual explanations. This interaction simulates expert tutoring and promotes self-directed, inquiry-based learning.

OtoVisionXR is conceived to bridge this gap, an immersive XR platform, enhanced by AI and metaverse-style interaction that offers dynamic 3D exploration of aural anatomy targeting medical students, educators, and clinicians for both educational and diagnostic support. There are a variety of experiences that span the gap between AR and VR and incorporate elements of both along the XR continuum (Figure 1) [10-11]. XR describes a continuum of immersive computing experiences that includes both Augmented Reality (AR) and Virtual Reality (VR). In AR, the user can still view the real world, but reality is now augmented with overlaid virtual elements (objects, content, and information). VR creates 3-dimensional (3D) virtual elements in entirely virtual environments (VEs), and the user (typically) cannot view or directly interact with the real world. This innovation presents the concept and design of OtoVisionXR, anchored in current evidence, and outlines envisioned future advances. An external personal computer (PC) with adequate processing power, a connected head-mounted display (HMD) for 3D stereoscopic display and head tracking, a gamepad or handheld motion controller for user input and motion tracking, and a variety of external sensors connected to the PC to triangulate the user's positions and movements within the VE and their assigned play area comprised the early versions of contemporary VR devices. Tethered VR with outside-in tracking is the term used to describe this setup (Figure 2). It is now among the numerous XR HMD designs that are feasible. Commercial XR technologies have developed rapidly and are now available in more affordable, accessible, portable, and user-friendly forms. For instance, the most portable, adaptable, and reasonably priced VR headset available today is the Oculus Quest 2 (Figure 2). Although Quest 3 is also available, the device is still being tested for its effectives by potential industrial users.

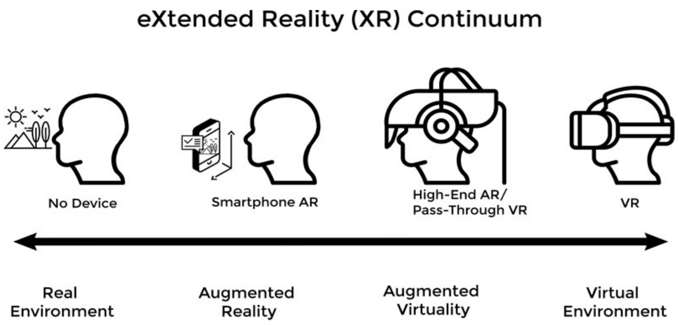

Fig. 1. The XR Continuum shows a progression from an entirely real environment to an entirely virtual environment with various XR devices facilitating movement along the continuum.

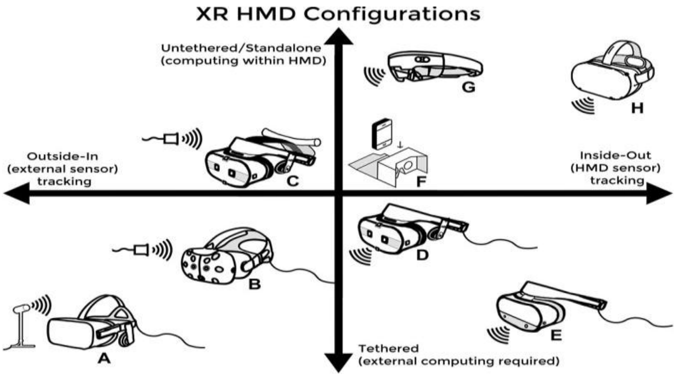

Fig. 2. (A) the Oculus Rift and (B) the HTC Vive headsets are both tethered and externally-tracked VR headsets from 2016 (C) and (D) are two different variations of the HTC Vive Cosmos Headset that can be configured to have either external tracking and be untethered via a wireless adaptor or have inside-out tracking and be tethered to a PC (E) the Oculus Rift S, which features inside-out tracking and is PC tethered (F) simple phone VR devices such as the Google Cardboard, which requires no external trackers and uses the on-board smartphone as the processor and motion sensor (G) the Microsoft HoloLens AR headset, which features an on-board processor and inside-out tracking (H) the Oculus Quest 2, which represents the newest HMD configuration: standalone or untethered VR with inside-out tracking environment with various XR devices facilitating movement along the continuum.

2.1 Technological Innovation and Comparative Differentiation

OtoVisionXR integrates photorealistic 3D anatomical reconstruction with AI-powered natural language interaction and multi-user immersive collaboration. Unlike OtoVIS, which focuses primarily on structural realism, OtoVisionXR embeds a generative AI assistant capable of responding to contextual queries, dynamically highlighting anatomical regions, and guiding procedural understanding.

Fig. 3. OtoVisionXR system architecture.

Figure 3 illustrates the layered system architecture of OtoVisionXR, which is designed to integrate immersive hardware, advanced 3D rendering, artificial intelligence, cloud collaboration, and learning analytics into a unified educational platform. The architecture follows a modular structure, where each layer performs a distinct function while remaining interconnected to ensure smooth data flow and scalability.

At the foundation of the system is the XR hardware interface layer. This layer consists of standalone virtual reality headsets, motion controllers, and hand-tracking sensors that allow users to interact naturally with the virtual environment. It captures user inputs such as gestures, gaze direction, and spatial movement, while simultaneously delivering stereoscopic visual output. By supporting commonly available standalone devices, the system reduces infrastructure requirements and improves accessibility for institutions with limited resources. Above the hardware layer is the 3D rendering engine, which serves as the visual core of the platform. This layer transforms high-resolution anatomical imaging data into fully interactive three-dimensional models. Advanced rendering techniques such as realistic lighting, depth mapping, and performance optimization through foveated rendering are applied to ensure visual accuracy while maintaining system efficiency. The rendering engine enables users to manipulate anatomical structures dynamically, rotate and zoom into microanatomical components, and toggle between layers such as ossicles, nerves, and cochlear structures. This immersive visualization enhances spatial understanding beyond what is achievable with static diagrams.

The next layer incorporates the artificial intelligence and simulation module, which represents the primary innovation of OtoVisionXR. This module includes a conversational AI assistant capable of responding to queries, highlighting anatomical regions upon request, and providing contextual explanations. The AI component adapts to user interaction patterns and supports guided learning pathways. The simulation sub-module also allows the system to model pathological variations and clinical scenarios, enabling learners to visualize disease states and surgical landmarks. This integration transforms the platform from a passive visualization tool into an intelligent, interactive learning environment.

Above the AI module lies the cloud collaboration layer. This component enables real-time multi-user interaction within the same virtual space. Students and instructors can participate simultaneously in guided anatomy sessions, facilitating collaborative learning and remote instruction. The cloud layer also manages session synchronization, secure authentication, and data storage. This functionality supports institutional scalability and allows cross-campus or distance-learning implementation, which is particularly valuable for rural or under-resourced training centers.

At the top of the architecture is the learning analytics dashboard (LAD). This layer collects data generated during user interaction, including assessment scores, engagement metrics, structure exploration frequency, and AI query patterns. The analytics system processes this data to provide instructors with insights into student performance and areas of conceptual difficulty. These data-driven insights support curriculum refinement and personalized feedback mechanisms, contributing to continuous educational improvement. The LAD also provides instructors with detailed insights into student interaction patterns, including time spent on specific anatomical regions, frequency of errors in assessments, and types of AI queries submitted. These metrics enable educators to identify areas of conceptual difficulty, such as misunderstanding of spatial relationships or functional anatomy, allowing targeted instructional interventions and curriculum refinement.

Overall, the architecture operates through a continuous feedback loop. User inputs captured at the hardware level are processed by the rendering engine, enhanced by AI-driven contextual interpretation, synchronized through cloud services, and analyzed by the analytics dashboard. This integrated structure ensures that OtoVisionXR is immersive, intelligent, collaborative, and measurable. The modular design also allows future expansion, including integration with clinical imaging databases and advanced adaptive learning algorithms. Table 1 presents a structured comparison between OtoVIS and OtoVisionXR, highlighting the distinct technological and functional advancements introduced by the proposed platform. While both systems offer photorealistic three-dimensional anatomical visualization, OtoVisionXR extends beyond visualization by integrating an AI-powered conversational assistant, adaptive learning analytics, structured curriculum alignment, multi-user collaborative capabilities, and a defined commercialization framework. This comparison clearly demonstrates that OtoVisionXR is not merely an incremental improvement but a more comprehensive and scalable educational ecosystem designed to enhance interactivity, intelligence, and institutional deployability. Figure 4 illustrates the navigation of the OtoVisionXR system, which utilizes XR environment.

Table 1. Comparison between OtoVIS and OtoVisionXR

Feature	OtoVIS	OtoVisionXR
Photorealistic 3D model	Yes	Yes
AI conversational assistant	No	Yes
Adaptive learning analytics	No	Yes
Multi-user collaboration	Limited	Yes
Clinical pathology simulation	Limited	Yes
Curriculum alignment module	Not reported	Yes
Commercialization framework	Not specified	Defined

Fig. 4. OtoVisionXR platform.

The system features various elements, such as pictures, videos, and communication tools like voice, video, and chat, to foster an interactive environment where students can collaborate and work together. This approach enhances the learning experience and helps students better understand complex materials that require visualization and diagrams to solve problems and exercises. Interactivity forms a central feature of OtoVisionXR. Users can manipulate otological structures using hand tracking or controllers, rotate or zoom into microanatomical details, and toggle between anatomical layers such as vasculature, nerves, ossicles, and cochlear structures. Dynamic annotations and embedded educational modules guide the learning process, while clinical features allow for the simulation of pathological cases. OtoVisionXR incorporates an AI-powered virtual assistant that interacts with users in natural language. Drawing on generative AI, this assistant can answer anatomical queries, highlight specific structures on request, and provide context-based explanations, thereby replicating the experience of an expert tutor within the immersive environment.

3. Validation Study Design

To evaluate the educational effectiveness and usability of the OtoVisionXR platform, a structured experimental validation study was conducted using a pre-test/post-test design. The study aimed to measure changes in anatomical knowledge, spatial understanding, and learner perception following exposure to the immersive XR environment. The research design was selected to allow quantitative assessment of learning improvement attributable specifically to the intervention while maintaining methodological rigor suitable for publication.

The study involved thirty ($n = 30$) first-year medical students enrolled in the otolaryngology anatomy module. Participants were recruited through voluntary participation during scheduled academic sessions. Inclusion criteria required that students have completed the Ear, Nose and Throat (ENT) anatomy module and have no prior exposure to immersive XR-based anatomy training. Students with prior structured VR anatomy experience were excluded to minimize bias related to familiarity with immersive technologies. All participants provided informed consent prior to participation. Ethical approval for the study was obtained from the Universiti Tunku Abdul Rahman (UTAR) Scientific and Ethical Review Committee [U/SERC/56(A)-675/2025]. The study complied with institutional ethical guidelines for research involving human participants. Confidentiality and anonymity were maintained throughout the data collection and analysis process. Participants were informed that their academic grading would not be affected by participation or performance in the study.

The validation procedure was conducted in three sequential phases. In the first phase, participants completed a structured baseline assessment (pre-test) consisting of 20 multiple-choice questions and spatial identification tasks. The assessment evaluated knowledge of middle and inner ear anatomy, including identification of ossicles, cochlear turns, semi-circular canals, facial nerve positioning, and anatomical relationships relevant to surgical landmarks. The pre-test was administered using conventional two-dimensional anatomical diagrams to reflect traditional learning conditions.

In the second phase, participants underwent a guided 60-minute immersive learning session using the OtoVisionXR platform. During this session, students interacted with high-resolution 3D aural models using XR headsets equipped with hand-tracking functionality. The session included structured exploration tasks, AI-assisted anatomical queries, and layerbased visualization exercises. Students were encouraged to manipulate structures, isolate anatomical layers, and engage with the AI assistant to clarify spatial relationships. A faculty facilitator supervised the session to ensure standardized exposure across participants. In the third phase, participants completed a post-test assessment identical in structure and difficulty to the pre-test. This design ensured comparability between baseline and post-intervention measurements. The use of the same question structure allowed for direct statistical comparison of knowledge acquisition and spatial comprehension improvement.

In addition to objective knowledge testing, a structured perception questionnaire was administered following the intervention. The questionnaire utilized a 7-point Likert scale (1 = Strongly Disagree; 7 = Strongly Agree) to evaluate perceived realism, engagement, ease of use, visualization enhancement, and educational value of the platform. Selected items were adapted from previously validated XR educational evaluation frameworks to ensure content validity.

Quantitative data were analyzed using paired-sample t-tests to determine statistical significance between pre-test and post-test scores. Effect size was calculated using Cohen's d to evaluate the magnitude of learning improvement. Descriptive statistics were used to summarize perception ratings, including means and standard deviations. Level of significance was set at $p < 0.05$ and 95% of Confidence Interval was maintained. All analyses were conducted using Statistical Package for the Social Sciences SPSS version 30.0.

Fig. 5. OtoVisionXR system expert and students testing.

The methodological structure ensured internal validity by controlling for exposure duration and assessment consistency, while ethical oversight guaranteed responsible research practice. This comprehensive validation framework strengthens the credibility of the findings and supports the claim that observed improvements are attributable to the OtoVisionXR intervention rather than external confounding factors. Figure 5, shows a snap of Anatomy and ENT surgeon, and medical students testing the system.

4. RESULTS AND DISCUSSION

The quantitative analysis demonstrated a statistically significant improvement in anatomical knowledge following exposure to the OtoVisionXR platform. The mean pre-test score among participants was 56.4% (SD = 8.7), indicating moderate baseline understanding of aural anatomy using conventional two-dimensional learning materials. Following the immersive XR intervention, the mean post-test score increased to 78.9% (SD = 7.5). Paired-sample t-test analysis revealed that this improvement was statistically significant [$t(29) = 14.62$, $p < 0.001$]. The calculated effect size using Cohen's d was 1.92, indicating a very large educational impact, substantially exceeding conventional thresholds (0.2 = small, 0.5 = medium, 0.8 = large). This suggests that the observed improvement is not only statistically significant but also practically meaningful, reflecting a strong influence of the XR intervention on learning outcomes. The percentage improvement between pre-test and post-test scores was 39.9%, (see Table 2) demonstrating substantial learning gains attributable to the intervention. The 39.9% improvement represents the relative increase between baseline and post-intervention scores, calculated as $(78.9 - 56.4) / 56.4 \times 100$. Compared to conventional learning using static anatomical diagrams, which typically yields moderate improvements (standardized mean difference 0.5), the observed gain indicates substantially enhanced knowledge acquisition. This suggests that immersive XR-based visualization provides superior spatial comprehension compared to traditional two-dimensional methods. Beyond improvements in overall knowledge scores, qualitative observation during the XR sessions suggested enhanced spatial comprehension, particularly in identifying relationships between the ossicular chain, cochlear turns, and adjacent neurovascular structures. Participants showed increased accuracy in spatial orientation tasks in the post-test assessment, suggesting that immersive manipulation of three-dimensional models contributed to improved structural mapping and anatomical integration.

Table 2. Pre-test and Post-test Knowledge Scores

Measure	Pre-Test	Post-Test	Improvement
Mean Score (%)	56.4	78.9	+22.5
Standard Deviation	8.7	7.5	—
t-value	14.62	—	—
p-value	<0.001	—	—
Cohen's d	1.92	—	Large

Learner perception data further supported the quantitative findings. Responses to the seven-point Likert scale questionnaire indicated strong positive attitudes toward the use of immersive XR in anatomy education. The majority of participants rated statements related to enhanced visualization, engagement, and educational value between 6 and 7 on the Likert scale. Specifically, the perception that "VR enhances visualization of anatomical structures" yielded a mean score above 6.5, while "VR makes learning more engaging compared to slides or books" and "VR can simplify complex medical concepts" both recorded similarly high agreement levels. These findings indicate not only cognitive improvement but also increased learner motivation and attentional focus during the immersive session. Comparative analysis of pre-test and post-test perception measures demonstrated reinforced confidence in the educational value of XR technology following direct exposure. While students initially expressed optimism regarding the usefulness of VR in anatomy learning, post-intervention responses reflected stronger agreement and reduced response variability, indicating greater consensus regarding its effectiveness. This suggests that experiential interaction with OtoVisionXR positively influenced both perceived utility and actual learning performance. Overall, the results provide strong empirical support for the educational effectiveness of the OtoVisionXR platform. The statistically significant improvement in knowledge scores, large effect size, and high learner satisfaction collectively demonstrate that immersive AI-integrated XR learning can meaningfully enhance understanding of complex aural anatomy. These findings strengthen the claim that OtoVisionXR represents not only a technologically innovative platform but also a pedagogically validated educational intervention.

4.1 Societal and Educational Impact

Beyond tertiary institutions, OtoVisionXR demonstrates meaningful societal relevance. Rural medical training centres often lack cadaveric facilities and advanced simulation labs. Standalone XR headsets enable cost-effective immersive education without large infrastructure requirements. The platform supports continuing professional development for practicing ENT surgeons through pathology modules and case-based rehearsal. Scalability is achieved through cloud-based licensing and modular deployment. Lecturer on boarding modules include structured training workshops and AI analytics dashboards to facilitate curriculum integration.

4.2 Commercialization and Sustainability Framework

This section outlines OtoVisionXR's commercialization and sustainability strategy beyond academic research. A hybrid subscription model combining institutional licensing, individual access, and premium clinical modules ensures both financial viability and accessibility. By addressing implementation costs and industry partnerships, it demonstrates market readiness. Its scalable SaaS architecture enables continuous updates, cloud deployment, and expansion into new domains, ensuring long-term sustainability. SaaS architecture enables centralized cloud-based deployment of OtoVisionXR, allowing continuous updates to anatomical models, AI modules, and learning content without requiring local system upgrades. New otological datasets, pathological simulations, and AI improvements can be deployed incrementally via cloud servers, ensuring that all users access the most current version. The architecture supports scalability, remote access, version control, and seamless integration across institutions. This commercialization pathway strengthens the platform's real-world applicability and aligns the innovation with Malaysia's digital health and medical education transformation initiatives. However, several limitations should be carefully considered. Access to XR hardware is not yet universal, and the cost of advanced head-mounted displays and supporting infrastructure may restrict widespread institutional adoption. Financial constraints could therefore limit scalability, particularly in resource-limited settings. The anatomical models are derived from specific imaging datasets, which may not fully represent inter-patient variability in morphology, pathology, or anatomical anomalies. Consequently, the current system may not capture rare or complex variations encountered in clinical practice. Future work should incorporate diverse, population-based datasets to improve generalizability and clinical realism. While standalone devices reduce dependency on high-end computing systems, initial procurement costs remain substantial for rural or underfunded institutions. This financial constraint may limit large-scale deployment, particularly in developing regions, highlighting the need for cost-reduction strategies and institutional funding support. Future development should therefore prioritize the inclusion of diverse, patient-specific datasets and expanded pathology case libraries.

5. CONCLUSION

OtoVisionXR integrates Extended Reality (XR) and artificial intelligence (AI) to address longstanding challenges in learning otologic anatomy, particularly the difficulty of understanding complex three-dimensional ear structures through traditional two-dimensional methods. By transforming static content into an interactive, immersive environment, the platform enhances spatial understanding, knowledge acquisition, and learner engagement. The addition of AI-driven guidance further supports interactive and personalized learning, shifting education from passive observation to active exploration.

The study demonstrates strong empirical evidence of the system's educational effectiveness, with significant improvements in post-test performance and high levels of learner engagement. These outcomes highlight the platform's ability to reduce cognitive overload and improve retention in anatomy education. The conversational AI component strengthens this impact by enabling self-directed learning, contextual explanations, and adaptive pathways tailored to individual learners. In the present design all three inner, middle and outer ear pathologies are included in the simulation. This enables learners to correlate normal anatomy with clinically relevant abnormalities.

Beyond foundational learning, OtoVisionXR supports clinically relevant simulation, including the integration of ear pathologies, allowing learners to connect anatomical knowledge with real-world conditions. Its scalable, cloud-enabled design facilitates remote and collaborative learning, promoting accessibility and educational equity. With built-in learning analytics, sustainability, and commercialization potential, OtoVisionXR represents a practical and evolving solution for medical education, with promising implications for future research, surgical training, and digital health innovation.

ACKNOWLEDGEMENT

The authors thank the UTAR staff and medical students for testing the OtoVisionXR system and completing the survey.

REFERENCES

[1] J. L. McJunkin, P. Jiramongkolchai, and W. Chung, "Development of a mixed reality platform for lateral skull base anatomy," Otol. Neurotol., vol. 39, no. 10, pp. e1137–e1142, 2018, doi: https://doi.org/10.1097/MAO.0000000000001995.

[2] V. Chheang, S. Sharmin, R. Márquez-Hernández, et al., "Towards anatomy education with generative AI-based virtual assistants in immersive virtual reality environments," in Proc. IEEE AIxVR, 2024, pp. 21–30, doi: https://doi.org/10.1109/AIxVR59861.2024.00011.

[3] S. W. Hauze, H. H. Hoyt, J. P. Frazee, et al., "Enhancing nursing education through mixed reality," Adv. Exp. Med. Biol., vol. 1120, pp. 1–13, 2019.

[4] P. Kaushik, A. Goswami, and O. Sharma, "Holoview: Interactive 3D visualization in AR," arXiv preprint arXiv:2501.08736, 2025, doi: https://doi.org/10.48550/arXiv.2501.08736.

[5] S. M. Zweifach and M. M. Triola, "Extended reality in medical education," Digit. Biomark., vol. 3, no. 1, pp. 14–21, 2019, doi: https://doi.org/10.1159/000498923.

[6] Y. M. Tang, K. Y. Chau, A. P. K. Kwok, et al., "Immersive technology applications in medical education," Educ. Res. Rev., vol. 35, p. 100429, 2022, doi: https://doi.org/10.1016/j.edurev.2021.100429.

[7] A. Herur-Raman, N. D. Almeida, W. Greenleaf, et al., "Next-generation simulation integrating XR into medical education," Front. Virtual Real., vol. 2, p. 693399, 2021, doi: https://doi.org/10.3389/frvir.2021.693399.

[8] P. García-Robles, I. Cortés-Pérez, and F. A. Nieto-Escámez, "Immersive virtual reality and augmented reality in anatomy education: Systematic review and meta-analysis," Anat. Sci. Educ., vol. 17, no. 3, pp. 514–528, 2024, doi: https://doi.org/10.1002/ase.2397.

[9] D. Shin, A. V. Batista, C. M. Bell, et al., "Examining the utility of a photorealistic virtual ear in otologic education," J. Otolaryngol. Head Neck Surg., vol. 52, no. 1, p. 40463, 2023, doi: https://doi.org/10.1186/s40463-022-00614-5.

[10] I. Corvino and V. Megale, "Exploring the convergence of XR and AI potential in healthcare: The TOMMI project case study," in Artificial Intelligence and Networks for a Sustainable Future: Connecting Species, Cham, Switzerland: Springer, 2026, pp. 267–279, doi: https://doi.org/10.1007/978-3-032-13458-5_15.

[11] N. Salimov, "Virtual reality and extended reality in medical education: Evidence, educational outcomes, and future integration," J. Clin. Biomed. Res., vol. 1, no. 1, pp. 168–173, 2026.