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Design of a Virtual Reality Module for Learning Parotid Gland and Facial Nerve Anatomy

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Abstract

Introduction:

Otolaryngology trainees must master complex three-dimensional (3D) head and neck anatomy for safe surgical practice. Existing educational resources, including cadaveric dissection and 3D-printed models, are limited by cost and accessibility. Virtual reality (VR) has demonstrated efficacy for anatomy education, yet no published immersive VR module addresses the facial nerve and parotid gland, which are structures critical to otolaryngology training. We describe the design and development of a multimodal VR anatomy module targeting this gap.

Methods

CTA DICOM data were segmented in Mimics 23.0 and sculpted in ZBrush to generate high-fidelity 3D models. Models were optimized for the Meta Quest 3 standalone headset using the Unity game engine. A reusable, step-based architecture organized content into sequential, otolaryngologist-scripted narrated scenes featuring progressive anatomical disclosure and dynamic highlighting. Multimodal features include CT/MRI slice viewers, parotidectomy surgical video, and 2D anatomical diagrams. Development involved iterative build cycles, followed by informal usability testing with surgeons, residents, and medical students.

Results

The final module incorporated 65 anatomical structures, achieving a 96.4% polygon reduction (22.7 million to approximately 806,000 polygons) while preserving clinical fidelity. Most users navigated the environment independently. Feedback identified refinement needs including orientation aids, automated narrator pronunciation corrections, and expanded interaction capabilities.

Conclusions

This proof-of-concept demonstrates that optimized 3D models derived from clinical imaging can be successfully integrated with standalone educational assets in an immersive VR environment. This module addresses a key gap in otolaryngology education and provides a reusable technical and pedagogical framework adaptable to multiple anatomical regions and learner populations.

INTRODUCTION

Otolaryngology-Head and Neck Surgery (ENT) trainees must master complex head and neck anatomy for clinical practice and surgical planning. However, visualizing intricate muscles, nerves, vessels, and foramina through two-dimensional (2D) textbooks and illustrations can be difficult, which is why

cadaveric dissection has long been considered the gold standard for anatomical education.(1) However, cadaveric tissue is costly and not always readily available. Three-dimensional (3D) modeling has therefore gained attention in medical education, with well-documented benefits for anatomy learning across multiple specialties, including otolaryngology.(2–5) For instance, otolaryngology residents have preferred 3D models over 2D images when planning frontal sinus surgery.(6) Despite these advantages, 3D printed models require expensive equipment to create, generate waste, can be difficult to transport, and do not incorporate other important medical assets such as surgical videos, expert narration, and 2D illustrations into a single interactive environment, potentially limiting accessibility and learning efficacy outside the classroom.

Virtual reality (VR) and 3D printing offer an alternative to cadavers and has proven valuable for surgical training.(7) In fully immersive systems, users enter a complete virtual environment via head-mounted displays (HMDs), which are increasingly preferred for their portability, adjustability, and minimal space requirements. Core features of VR surgical anatomy platforms include 360-degree environments, stereoscopic visualization, and interactive 3D manipulation.(7) They can also integrate audiovisual and tactile feedback with dynamic case simulations in highly adaptable formats preferred by surgical trainees and medical students.(8, 9) VR has been shown to improve anatomy examination performance more effectively than other teaching methods, including textbooks/atlases, 3D plastic models, and augmented reality.(10–13) It was also a useful adjunct for teaching maxillofacial and dental procedures and facial aesthetic surgery in academic courses and workshops.(7, 14, 15) VR teaching environments have the potential to overcome many of the limitations imposed by relying on 3D printed models, allowing learners in various settings to access multimodal learning material in one immersive location.

Despite this promise, a standardized, reproducible pipeline for converting complex anatomical imaging data into high-fidelity immersive VR content and combining that with other educational assets has not been established. This limitation is especially relevant for facial soft tissue anatomy such as the facial nerve, which has a complex branching pattern within the parotid gland and remains underrepresented in VR anatomy education. A thorough understanding of the facial nerve is essential for parotidectomy planning and surgery for both benign and complex tumors, yet no VR anatomy modules for otolaryngology trainees and medical students have been described in the literature. In this paper, we present the development of a Facial Nerve and Parotid Gland VR module for otolaryngology residents and medical students based on our previously reported 3D digital anatomic models.(16) Using interactive 3D anatomy, video integration, and medical imaging, this work serves as both a proof-of-concept and a roadmap for translating 3D modeling data into immersive VR learning environments.

METHODS

Development and Team Overview

Development was conducted by an interdisciplinary team including an otolaryngologist, neuroradiologist, 3D medical illustrator, and an extended reality (XR) engineer. This composition reflects the concurrent

expertise required to translate clinical imaging data into an immersive educational environment, including otolaryngologist-provided clinical oversight and narration scripting as well as neuroradiologist-guided imaging interpretation, anatomic structures, and validated segmentation boundaries. The medical illustrator created, refined, and optimized all anatomical models, and the XR engineer designed and implemented the Unity-based environment, scene architecture, and interactive features.

3D Modeling of the Parotid Gland and Facial Nerve in ZBrush

De-identified computed-tomography angiography (CTA) Digital Imaging and Communications in Medicine (DICOM) images from a 29-year-old female patient were imported into Mimics 23.0 (Materialise, Leuven, Belgium), a 3D anatomical computer-aided design (CAD) software. Patient-specific anatomy from the soft palate, tongue/floor of mouth, larynx, pharynx, glands, muscles of mastication, central neck, lateral neck, infratemporal fossa, pterygopalatine fossa, parapharyngeal space, fascial layers, and posterior neck were segmented and exported as stereolithography (STL) files as described in previous work.(17–29) The 3D STL file meshes were optimized in 3-Matic (Materialise, Leuven Belgium) and then imported into a 3D modeling software, ZBrush (Pixologic, CA).

In ZBrush, the STL files were refined based on published anatomic literature to ensure accurate shape, volume, muscle origin/insertion, and spatial relationships of each structure. When more than one anatomical variant or pattern was encountered, the most common variant recorded in the literature was depicted in the model to represent the most accurate and typical head and neck anatomy. The anatomy was sculpted with multiple brushes in either the Dynamesh or ZRemesh modes. ZRemesh was used to create a clean and less dense base mesh. The Divide and Project functions were used to transfer high-detail geometry onto progressively higher-resolution meshes, enabling high-fidelity texture maps to be baked onto optimized lower-polygon models and exported as Filmbox (FBX) files suitable for real-time VR rendering.

VR Application Development and Scene Architecture

The module was developed in C# using the Unity game engine (version 2022.3.58f1, Unity San Francisco, CA) with the Universal Render Pipeline and deployed on the Meta Quest 3 standalone headset (Meta, Menlo Park, California). Extended Reality (XR) runtime layers were supported through the Unity XR Interaction Toolkit (version 3.0.3) and OpenXR plugin (version 1.14.3), the latter enabling cross-headset compatibility. The Unity VR Template, a starter project pre-configured with these packages, served as the foundation of the XR rig, teleportation system, spatial UI panel components, and video player, each of which were subsequently customized for this module.

Mesh Optimization for Real-Time VR Rendering

The original high-fidelity models contained polygon counts too large for real-time rendering at acceptable frame rates on the Meta Quest 3 headsets. Each model's polygon count, vertex count, and file

size was assessed to identify dense structures that required polygon reduction. Polygon reduction was performed iteratively by the XR engineer and medical illustrator to preserve clinically relevant anatomical detail while meeting headset performance thresholds. A target of fewer than 10,000 triangles per structure was established, with most structures reduced below this threshold.

Step-based Scene Architecture

To further optimize rendering, the module was designed to limit the number of structures visible at any given time. The anatomy of the parotid gland and facial nerve was organized into a series of sequential educational "steps" or scenes, each paired with otolaryngologist-authored text and narration scripts. Each step contained sub-steps controlling which anatomical structures were visible, highlighted, and narrated, so only relevant models were displayed at a given time. Highlighting was achieved through per-renderer material overrides with custom Shader Graph materials to emphasize structures during each sub-step and restore them afterward. This approach allowed us to use higher-fidelity models in scenes with fewer structures while reserving more aggressively optimized models for more dense views.

The underlying step-based system was originally developed to serve multiple VR anatomy projects within our institution's Anatomic Modeling Unit and was refined for the facial nerve and parotid module. The system was intentionally decoupled so that anatomical models and teaching sequences could be replaced or updated without modification to the underlying codebase, supporting an efficient iterative workflow between the members of the multidisciplinary teams.

Multimodal Learning Features in VR

The virtual environment was designed collaboratively; the XR engineer constructed the room geometry including walls, floor, ceiling, and lighting, while the medical illustrator provided the optimized 3D anatomical models and medical illustrations. Otolaryngologists narrated the surgical videos, and the neuroradiologist curated the cross-sectional imaging. The final virtual environment consisted of a room with a 3D anatomic head and neck model in the center flanked by a spatial UI panel displaying step-specific instructional text and synchronized voice-over narration (Fig. 1). Users remained stationary but could rotate 360 degrees to view a templated video player that displayed a parotidectomy video alongside de-identified computed tomography (CT) and magnetic resonance imaging (MRI) scans from a representative clinical case presented as an interactive slice viewer (Fig. 2). The imaging data were converted into sequential PNG images and uploaded into Unity, where a custom script displayed two viewing panels (one for CT and one for MRI) each controlled by a slider to scroll through the image slices. Labelled 2D radiographs and illustrations of the parotid gland were on the remaining walls. Together, these elements provided clinical correlation alongside the 3D anatomy, helping learners connect cross-sectional imaging with the spatial anatomy explored in VR.

User-Centered Design

The module was designed for accessibility, with the assumption that most users would have limited prior VR experience. To minimize the learning curve for first-time VR users, the interactive elements of the module were simplified: users remained stationary and interacted with spatial UI elements using a point-and-click controller trigger. Upon launching the application, users entered a brief introductory space explaining the controls before transitioning to the anatomy environment. Voice-over narration was incorporated throughout based on feedback from a prior VR development project at our institution, with the goal of enhancing immersion and comprehension beyond on-screen text alone.

RESULTS

The final developmental pipeline involved segmentation of CT DICOM data exported as STL files, importation of the STL files into ZBrush for editing, modeling of additional head and neck structures based on published anatomical literature, generation of low-resolution meshes with UV and texture maps of each structure, and exportation as FBX files for Unity integration. Of the 65 structures created across the pipeline, 55 were used in the final VR scene; the remainder were excluded based on rendering performance constraints or scope prioritization.

Mesh Optimization Outcomes

The original segmented mesh extracted from CT DICOM data exhibited dense, irregular topology with surface artifacts characteristic of automated segmentation (Fig. 3A). The medical illustrator refined this into a high-resolution sculpted mesh of approximately 22.7 million polygons with anatomically accurate proportions and clean topology (Fig. 3B). The final low-resolution model exported for real-time rendering in Unity was approximately 806,000 polygons, a reduction of 96.4% (Fig. 3C). Across the 55 structures deployed in the final scene, the combined triangle count was approximately 73,500, with the arterial vasculature representing the largest single structure at approximately 19,000 triangles.

Usability Testing

To evaluate functionality and navigability, the module was demonstrated at four medical education events. A total of 36 otolaryngology-head and neck surgeons, residents, and medical students volunteered to use the VR modules and provide informal feedback. Overall, the VR module functioned as intended. Most users navigated the module without prompting or additional guidance. A small number required assistance reorienting within the virtual space, likely due to limited prior immersive VR experience. These observations emphasized the importance of incorporating stepwise orientation instructions to support usability across varying experience levels.

Technical Challenges and Solutions

A major challenge during development was adapting the high-fidelity anatomical models for standalone VR rendering, which required an iterative process of testing and optimization. During scene authoring, frame rates were monitored in the Unity editor and tested directly on the headsets by the XR engineer.

Steps containing models that exceeded rendering thresholds produced lag or application failure. When performance issues were identified on a given step, the specific models were flagged for polygon reduction by the medical illustrator. After reduction, the updated models were reintegrated into the step system with care taken to preserve the sub-step configuration and interaction data linked to each anatomical structure. This cycle of build, test, flag, and replace continued throughout development, resulting in 34 total build iterations.

A key feature of the VR module was the ability to highlight specific anatomic structures on the 3D model during narration. A script was written in Unity to highlight single meshes in translucent purple. However, this proved more complex than initially anticipated due to the multiple mesh layers required for the facial nerve and skull bones. The facial nerve was created as a single mesh, requiring each of its 5 major branches to be separated into independent meshes to be individually highlighted (Fig. 4). This was successfully completed and integrated into the final module. Subdivision of the skull mesh into smaller components proved substantially more time-intensive than anticipated. Instead, because the Unity script could only highlight the entire skull mesh, separate texture maps were created in ZBrush where each target structure was colored purple. A material override feature was then coded into Unity to allow the plain skull texture map to be hidden while the purple highlighted texture maps were visible when indicated in the sub-step, thus creating the appearance of highlighting (Fig. 5).

DISCUSSION

This study provides a proof-of-concept that VR modules can effectively illustrate complex 3D head and neck anatomy and are among the few focused on soft-tissue structures such as the facial nerve and parotid gland. We successfully transferred anatomical data from prior 3D modeling projects into a VR platform and integrated adaptable step-by-step animations for future modification and expansion. To enhance its potential educational value, the virtual environment incorporated multimodal learning tools including audiovisual guidance from otolaryngology experts, surgical videos, medical imaging, and anatomy atlas diagrams.(30) By combining these approaches within an immersive platform, this module may improve academic performance, increase accessibility, and streamline future transitions from 3D models to VR.

The successful repurposing of pre-existing 3D anatomical models, originally created for static visualization and 3D printing, for real-time interactive VR rendering represents the technically significant contribution of this work because this conversion process is complex and incompletely described in the existing literature. The iterative polygon reduction workflow developed collaboratively by the XR engineer and medical illustrator proved essential for balancing anatomical fidelity against the rendering constraints of a mobile standalone headset. This process helped address concerns regarding realism and anatomical detail of VR-based learning models.(31) Similarly, Erolin et al. described the trade-offs between fidelity, interactivity, and platform constraints when developing 3D anatomy resources from photogrammetry, CT scans, and digital modeling.(32) Our experience supported these observations but demonstrated that close collaboration among XR engineers, medical illustrators, and subject matter

experts, coupled with systematic identification and correction of performance-limiting structures, can mitigate these limitations without compromising anatomic accuracy.

The step-based structure functioned as both a technical solution and authoring framework for transforming 3D anatomy and media assets into a VR learning environment. By rendering only the anatomical structures relevant to each step, the system maintained the performance and frame rates required for a standalone headset without uniform polygon reduction across all models, preserving higher anatomical fidelity where the educational content demanded it. This configuration-driven approach allowed educators to reorder instructional sequences or replace models without modifying the codebase or disrupting linked interaction data, supporting an efficient iterative workflow between the XR engineering and members of the team. This decoupled architecture positions the framework as a reusable foundation for future modules; anatomical content, teaching sequences, and interactive features can be reconfigured independently to accommodate different anatomical regions, clinical specialties, or learner populations, including radiology or radiation oncology trainees encountering the same anatomy in distinct clinical contexts.

In addition to its technical advantages, the step-based architecture may also serve as a pedagogical tool by presenting anatomy through guided, sequential steps with synchronized narration and visual highlighting. This progressive disclosure approach may manage learners' cognitive load by limiting the amount of new visual information presented at any one time.(30, 33) Supporting this design, a recent functional Near-Infrared Spectroscopy (fNIRS) study of medical students learning cardiac anatomy found that VR and 2D modalities can achieve comparable knowledge gains when cognitive load is appropriately managed, while also showing modality-related differences in neural processing dynamics.(34) Similarly, Schott et al. reported that a highly detailed environment increased extraneous cognitive load without improving learning, whereas coherent, contextually appropriate scenes supported deeper comprehension.(31) The focused scope of this facial nerve and parotid gland module built with selective rendering and progressive disclosure aligns with these findings and provides an efficient, evidence-based framework for adapting previously published 3D anatomy content to immersive VR platforms.

Throughout development, unexpected technical challenges emerged that required creative solutions. As noted previously, the facial nerve mesh was easily segmented into individual branches, allowing straightforward per-branch highlighting without additional texture work. In contrast, Unity's rendering pipeline does not natively support highlighting sub-regions within a single mesh, making selective highlighting of skull structures more complex. To address this, the team developed a material override system that used multiple texture maps, each isolating a specific anatomical structure and creating the illusion of highlighting. These solutions illustrate the type of asset-specific problem-solving required when adapting anatomical models not originally designed for interactive VR experiences.

Overall, our VR module addresses a well-documented gap in the ENT simulation literature, which predominantly focuses on bony anatomy and procedural training. In a scoping review of extended reality applications in this field, 29 (72.5%) of 40 studies were focused on temporal bone surgery.(35) Similarly,

Piromchai et al performed a Cochrane systematic review of VR training for ENT surgery and found that many areas of the specialty, including soft tissue or open surgery, remain underrepresented in virtual training environments despite evidence supporting VR simulation for functional endoscopic sinus surgery. Our innovation extended immersive VR anatomy education to a surgically critical soft-tissue region, incorporating several media assets such as CT and MRI cross-sectional imaging, surgical video, and surgically accurate 3D anatomy to teach facial nerve and parotid gland anatomy and clinical applications. While other approaches, such as a low-cost 3D-printed parotidectomy simulator using a copper-wire facial nerve and an augmented reality program for visualizing the extracranial facial nerve intraoperatively from MRI data, have improved soft-tissue learning, they lack the multimodal VR environment shown to optimize learning and retention.(35, 36)

Furthermore, existing simulators in this space were designed predominantly for procedural skill acquisition in endoscopic sinus surgery and temporal bone drilling, not anatomical education.(35, 36) Accordingly, these tools emphasized task performance metrics (e.g., instrument path, tissue removal, procedural time) rather than progressive anatomical education from basic anatomy to surgical/procedural anatomy. The parotidectomy simulator developed by Gabrysz-Forget et al. used a 3D-printed skeleton with silicone soft tissue and a copper-wire facial nerve demonstrated the ability to distinguish procedural skills performance between faculty and residents.(35) Although valuable for procedural training, such physical models cannot always provide guided anatomical instruction, allow unlimited repetition without consuming limited resources (e.g., silicone and copper wire), integrate clinical imaging, or be easily updated and distributed. The current VR module can complement these approaches by addressing the foundational anatomical knowledge that underpins safe parotidectomy performance: understanding the 3D spatial relationships of the facial nerve branches within the parotid gland and their proximity to major vessels and bony landmarks. The standalone headset-based VR module may also offer advantages over both cadaveric dissection and 3D-printed models because learners can access the content in any setting without specialized laboratory facilities, and the module can be updated, expanded, or redistributed digitally without material costs.

LIMITATIONS

Several limitations of this proof-of-concept study should be acknowledged. The polygon reduction required for real-time rendering on the headsets sacrificed some anatomical detail compared to the original high-fidelity models, and the degree to which this affects educational value should be minimal but is unknown. The module also only depicts the most common anatomical variant of the facial nerve branching pattern; incorporating additional variants would increase educational comprehensiveness but also development complexity. The text-to-speech narration, while functional, was noted to mispronounce some medical terminology, which can be addressed in future iterations with runtime pronunciation correction by human narration or phonemic transcription. Lastly, user feedback was collected informally across educational events rather than through validated usability instruments, limiting the ability to draw quantitative conclusions about navigability or educational effectiveness. Each of these limitations defines a concrete direction for future development and formal evaluation of the module.

CONCLUSION

This feasibility and development study demonstrates that high-fidelity 3D anatomical models derived from clinical imaging can be successfully optimized and integrated with multimodal educational assets into a standalone immersive VR environment, using the facial nerve and parotid gland as a representative and surgically critical anatomical target. The development pipeline described here, spanning DICOM segmentation, medical illustration refinement, mesh optimization, and Unity-based scene architecture, provides a reproducible technical roadmap accessible to academic medical centers without dedicated software engineering resources. The step-based framework addresses both the rendering constraints of standalone VR hardware and established principles of cognitive load management, functioning simultaneously as a technical solution and an evidence-based instructional platform. The module directly addresses a documented gap in head and neck surgery education, where soft-tissue anatomy remains substantially underrepresented in existing virtual learning platforms. Formal evaluation of learning outcomes and usability optimization remain priorities for subsequent investigation; however, this work establishes a reproducible foundation and transferable framework for immersive VR anatomy education with broad potential for adaptation across anatomical regions, clinical specialties, and learner populations.

Abbreviations

ENT
Otolaryngology–Head and Neck Surgery
VR
virtual reality
2D
two–dimensional
3D
three–dimensional
CT
computed tomography
MRI
magnetic resonance imaging
CTA
computed tomography angiography
DICOM
Digital Imaging and Communications in Medicine
HMD
head mounted displays
XR
extended reality
STL

stereolithography
FBX
filmbox
fNIRS
Functional Near–Infrared Spectroscopy

Declarations

Ethics approval and consent to participate:

This study was exempted from the Institutional Review Board and approved by the Office of Reasonable Conduct of Research.

Competing interests:

The authors declare that they have no competing interests

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Author Contribution

RA, JM, AE, CVW, and KVA wrote the main manuscript text. AE and LMO prepared the figures. All authors reviewed the manuscript.

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Availability of data and material

statement: Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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Figures

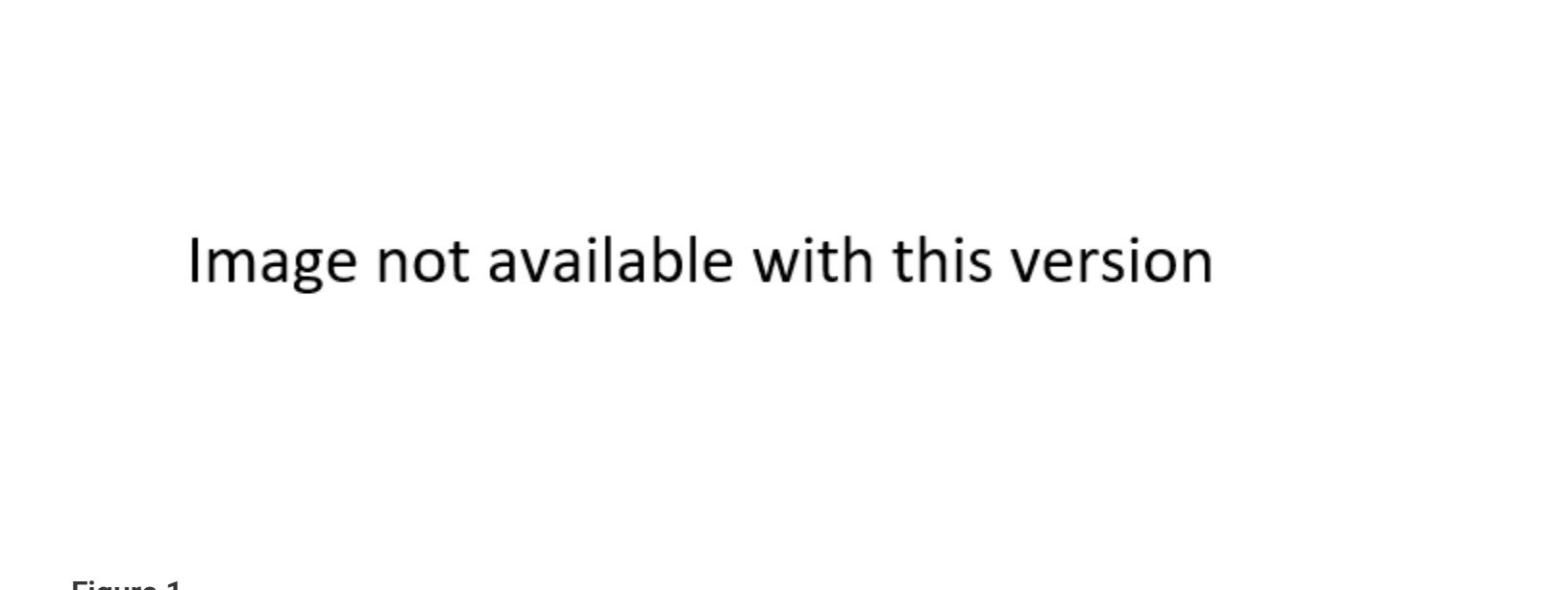


Figure 1

Step progression through the parotid gland and surrounding head and neck anatomy. Four sequential teaching steps from the VR module showing progressive anatomical disclosure: (A) parotid gland orientation, (B) spatial context with the mandible, (C) masseter muscle highlighting, and (D) full regional anatomy with vasculature and facial nerve. Each step pairs the 3D anatomical view with a narrated Step Info panel that contextualizes the displayed structures.

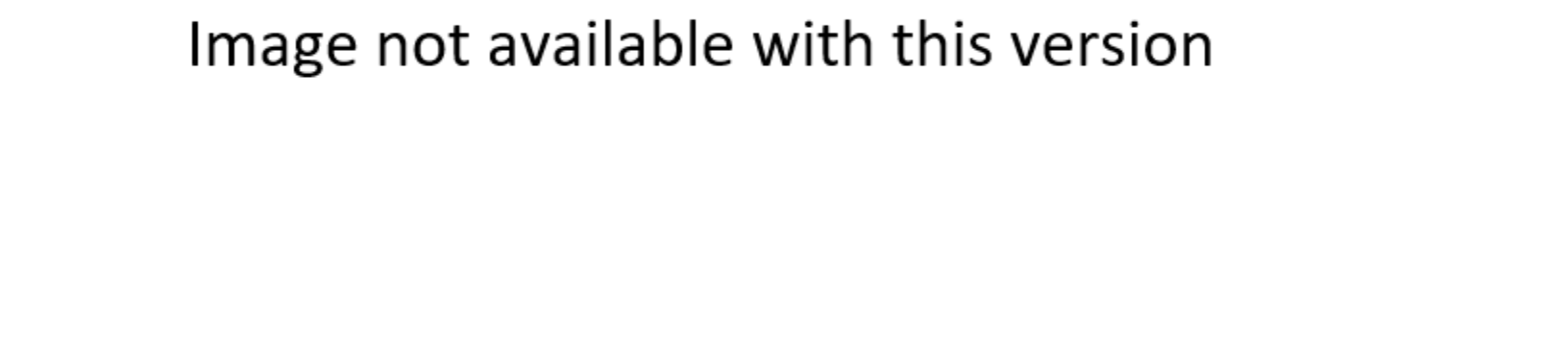


Figure 2

Multimedia learning wall in the VR environment. Screenshot showing the parotidectomy surgical video player (left) and the dual-panel CT/MRI slice viewer (right) mounted on the same wall. The slice viewer presents paired computed tomography (CT) and magnetic resonance imaging (MRI) series from a representative clinical case, controlled by an independent slider for scrolling through the image series. The adjacent placement allows learners to correlate surgical procedure with cross-sectional imaging without re-orienting in the environment.

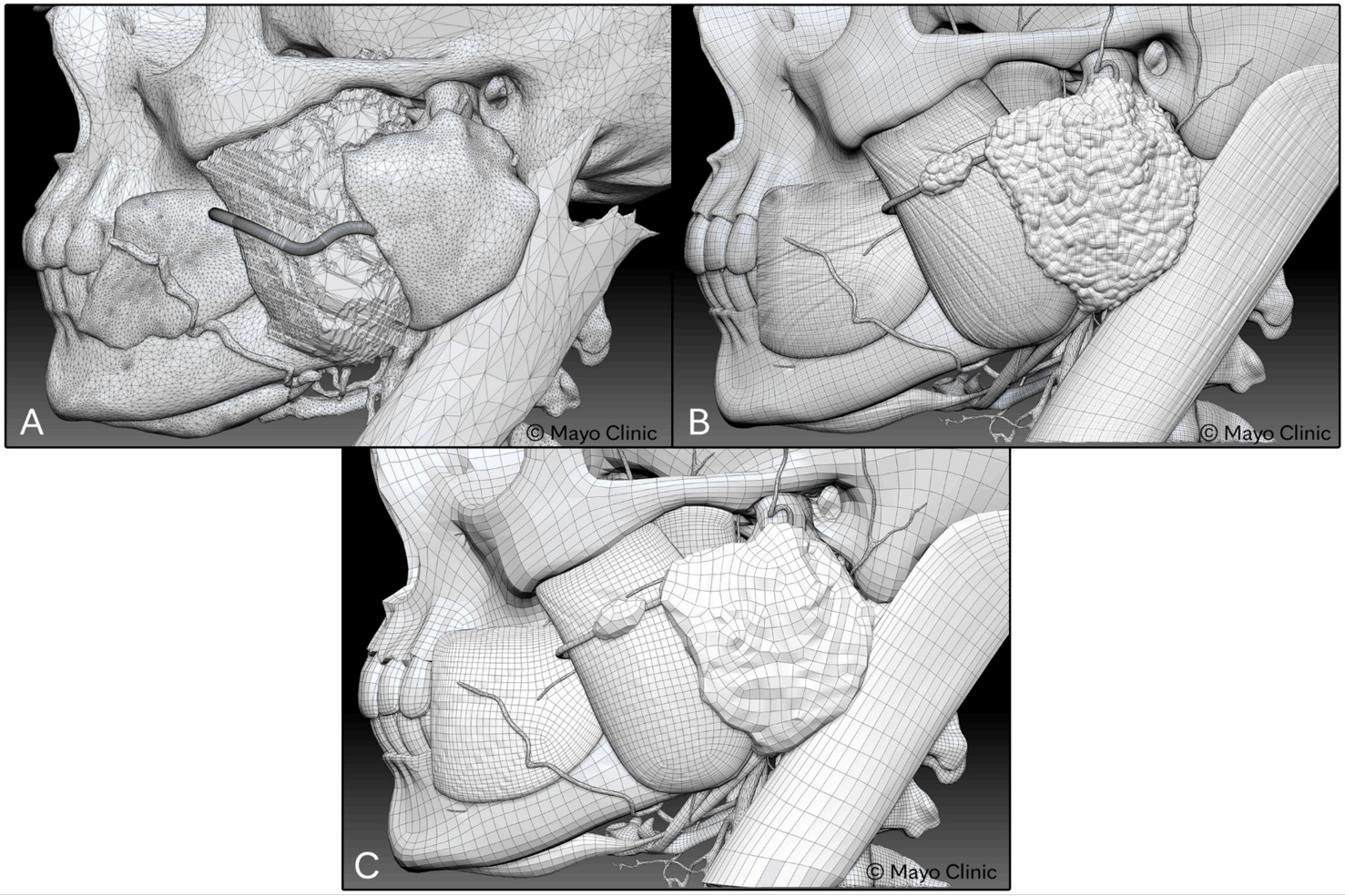


Figure 3

Model creation and refinement. The original mesh segmented in Mimics 23.0, imported to ZBrush (A). The original mesh edited and additional structures sculpted at high resolution in ZBrush (B). The model at low resolution, the mesh optimized for use in Unity (C).

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Figure 4

Interactive highlighting of the facial nerve. Screenshot from the VR module showing the highlight system applied to a terminal branch of the facial nerve, with the spatial UI step panel visible to the left. A translucent purple material override visually emphasizes the targeted anatomy as part of the step-based progression through the module.

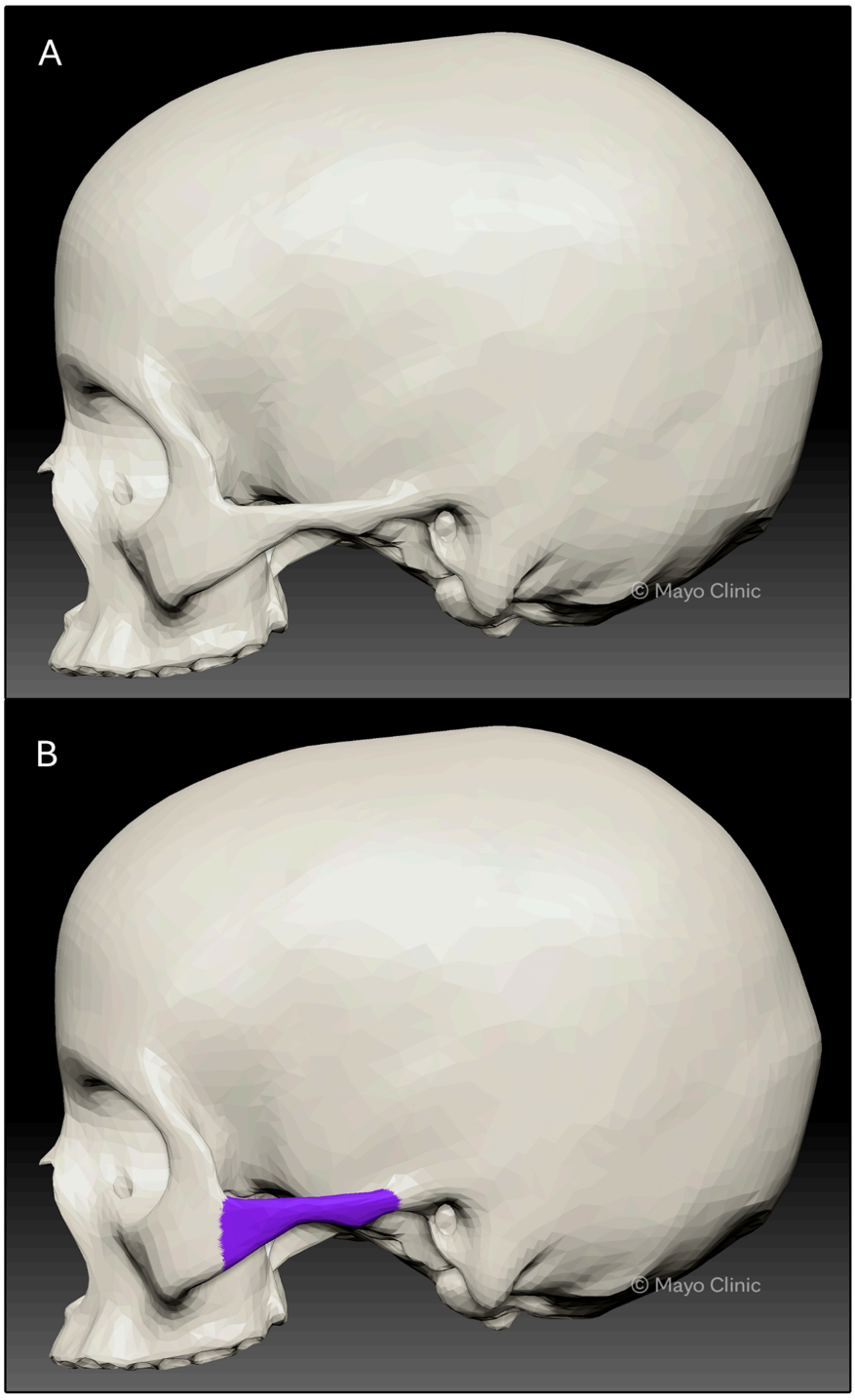


Figure 5

Skull texture maps. ZBrush render of the skull mesh showing the plain texture map (A) and the texture map with the zygomatic process painted purple to mimic the coded highlight feature in Unity (B).