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Development of a Mixed Reality Platform for Lateral Skull Base Anatomy

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Introduction

The lateral skull base anatomy is complex and rich with essential neurovascular structures. Surgical dissection in the lateral skull base requires a firm understanding of the anatomical relationships to ensure optimal outcomes. Dissection requires careful identification of known landmarks to generate a mental image of the relative location of these structures. Safety and efficiency of dissection increases with experience as the surgeon's 3D mental map of the anatomy improves. Technology that improves visualization of anatomic structures and their spatial relationship would significantly improve the surgeon's operative experience.

Extended reality (ExR) describes the spectrum, or "virtuality continuum" of technology from Virtual Reality (VR) where the user is immersed in the digital world to Augmented Reality (AR)¹, which allows the user to overlay digital data or images over their environment. Recent technology advancements² have allowed for ExR Head Mounted Display (HMD) devices. These wearable devices make application of ExR much more accessible and applicable to everyday uses including architecture³, healthcare⁴, simulation⁵ and education⁶. Current headsets produced by Oculus, HTC, Sony and Google create fully immersive VR environments. In contrast, Google Glass is an example of an AR headset that can be used to display pertinent healthcare data during a medical encounter⁶. Mixed Reality (MR) refers to interactive digital data displayed over the native environment.

A MR HMD that projects images onto a transparent lens over the user's visual field. The MR HMD has 3 key features ideal for image-guided navigation: 1) MR view, 2) spatial mapping, and 3) interactive hands-free interface.

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Conflicts of Interest:

None

Mixed Reality:

The MR headset projects images onto a transparent lens overlying the user's visual field utilizing stereoscopy to create the perception of depth for 3D models. Due to the transparency, the user maintains view of the external environment with a holographic overlay, allowing the user to maintain focus on the actual field by displaying data in a head-up manner. Current intraoperative navigation systems require the surgeon to fix their attention on a separate screen to check the relative position of a probe or instrument placed onto a point of interest. With the HMD display, the surgeon does not need to break view of the actual surgical field.

Spatial Mapping

The MR HMD employs spatial mapping technology to allow images to be anchored to specific points in the environment. The headset contains an infrared projector and camera that map the user's 3D environment when first turned on. 3D images displayed in the headset stay fixed relative to the mapped physical space while the user moves. In an operative setting, a 3D image-based model could be tethered to the patient while allowing the surgeon freedom of movement. Current intraoperative surgical navigation systems rely on co-registration of 3D data points generated from radiographic data and physical data points on the patient⁷. The system then co-registers these two data sets and aligns them to allow navigation. MR allows visual registration and adjustment of the 3D model as physical structures are identified.

Interactive hands-free interface

The MR headset features a multidimensional, hands-free interface ideal for use in a surgical setting. The MR headset contains a motion detection camera, gyrometer and microphone. Thus, the user can control the headset by gesture, gaze and voice commands. Application windows appear as holographs in the user's field of view similar to that of a personal computing desktop. A dot in the center of the screen acts as a cursor that can be moved around the holographic environment with head movement and gaze. Hand gestures can be used to "click" on objects. The headset also responds to voice commands after a voice prompt.

The objectives of this study are 1) to develop an MR platform for visualization of temporal bone structures 2) to measure the accuracy of the platform as an image guidance system.

Materials and Methods

The Human Research Protection Office at the study institution reviewed this study and determined that the study was exempt from Institutional Review Board review.

Image acquisition and 3D hologram generation

Fig. 1 demonstrates our workflow for image acquisition and 3D holographic generation. First, 0.6 mm slice thickness, high resolution, two-dimensional computed tomography (CT) scans (Siemens Biograph, Siemens Healthcare, Erlangen, Germany) of cadaveric temporal bones and heads were obtained. Digital imaging and communications in medicine (DICOM)

data generated from the CT scans were imported into an open-source software ITK-SNAP⁸, where a combination of semi-automatic and manual segmentation was employed to generate three-dimensional (3D) reconstruction images. Stereolithography (STL) files of the 3D reconstructed images were then imported into an open-source system, MeshLab⁹. Depending upon the complexity of the model, STL files can be comprised of thousands of raw, triangular meshes that can require substantial processing time in 3D platforms. In addition, the processing power of the headset limits the number of displayed triangular meshes. Meshlab allows for the simplification of triangular meshes while preserving geometrical detail and surface contouring. Furthermore, STL files can be converted to OBJ files in Meshlab, the latter of which is readily displayed with the MR platform described below.

Development of mixed reality (MR) platform

To view and interact with 3D images on the Microsoft HoloLens (Washington, Seattle), an MR platform must be built to allow for image release into the headset in the form of a Visual Studio project (Version 15.6; Microsoft, 2017). We developed a MR platform specific to our use in Unity® (Version 3.1; Unity, 2017), a gaming platform for 3D animation and hologram manipulation. C# scripts were used to generate interactive OBJ files that could be manipulated in the *xyz* dimensions. The images generated in Unity were then visualized in the HMD. Using C# programming in Unity and Visual Studio, code was written to allow for user-friendly voice, gaze, and gesture commands.

Surface registration and accuracy measurements

Prior to image deployment, the HMD was calibrated each time for each specific user's interpupillary distance. Once the 3D holographic image was displayed in the HMD, soft-tissue surface anatomy was used to align the holographic images over the physical objects. A combination of voice and hand gestures were employed to manipulate the holographic images in space to overlay the physical objects.

To verify the accuracy of our system, target registration error (TRE) was measured. TRE is defined as the displacement between an image (is) and physical space (ps) location of a specific point, and is calculated using the following formula: $([X_{is} - X_{ps}]^2 + [Y_{is} - Y_{ps}]^2 + [Z_{is} - Z_{ps}]^2)^{1/2}$. We used a 3D holographic image of a cadaveric skull overlaid on a 3D printed model of the same specimen to perform our accuracy measurements. 7 landmarks, 5 external and 2 internal structures, were chosen.

Our approach to error measurement is shown in Fig 2. First, a rigid four-ball passive probe was registered with an Optitrack camera bar (NaturalPoint, Coravllis, Oregon). Using infrared (IR) cameras, the Optitrack bar allows for tracking of marked rigid bodies. We reassigned the registration point on the passive probe from its center of mass to the tip to facilitate TRE measurement. Motive, an open-source Unity plug-in made available through Optitrack, allowed positional data of the location of the passive probe to be streamed real-time into Unity, allowing us to simultaneously record *x*, *y*, and *z* coordinates.

Results

3D hologram generation and registration for the MR HMD

Using our novel MR platform, we were able to successfully display interactive holograms of soft tissue, bony anatomy, and internal ear structures onto cadaveric and 3D printed models.

For cadaveric skull and temporal bones, the following structures were generated as interactive holograms: skin, bone, and inner ear anatomy including the facial nerve, cochlea, semicircular canals, sigmoid sinus, and internal carotid artery. We were able to successfully use voice, gesture, and gaze commands to align our holograms onto our physical objects using surface registration (Fig. 3).

C# scripts allowed the MR headset to recognize different voice, gesture, and gaze commands. Gaze commands allowed for placement of the object in 2 dimensions. Gesture commands were used to allow holographic images to move and rotate in all three *xyz* coordinate directions. Voice commands e.g. “lock”, “unlock” allowed for stability of object placement in relation to its surrounding, and also disabled simultaneous manipulation by gesture or gaze commands. Our C# scripts also created a pseudo-state for each object depending on the command. For example, an image can initially start off in its movable state, where manipulation of the image and overlay onto a physical object can take place. However, when the command for “lock” is performed, the image then shifts to its locked state. This pseudo-state allows for more refined control of the holographic image as the user has specific commands for each state.

These results were reproducible in both the cadaveric head and temporal bone models as well as the 3D-printed skull model.

Accuracy measurements

3 different observers performed triplicate measurements of 7 pre-specified landmarks on the 3D holographic skull and 3D-printed skull. The left earlobe, left lateral canthus, midpoint of the maxillary central incisors, right lateral canthus, and right earlobe were chosen as external landmarks, and the right and left internal auditory canal (IAC) for internal landmarks. We first used surface registration as described above to align the hologram and 3D skull model. We were then able to use voice commands to remove the external surface of our hologram revealing just the internal landmarks to perform TRE of the right and left IAC.

For the 3 observers, the average TRE ($\pm$ sem) was 6.46 mm $\pm$ 0.37, 4.69 mm $\pm$ 0.10, and 6.14 mm $\pm$ 0.14, respectively (Table 1). The overall average TRE between the 3 observers was 5.76 mm $\pm$ 0.54.

Discussion

One of the key surgical principles taught to surgical trainees is to obtain adequate exposure. Safe surgical dissection requires knowledge of relevant anatomy. With experience, surgeons build a mental 3D map of the surgical anatomy and are able to navigate more efficiently with

less exposure. An accurate surgical navigation system, using ExR, can potentially enhance a surgeon's operative experience, by enabling more efficient and safe dissection.

Image guided surgery (IGS) utilizing ExR, follows several basic principles: 1) target anatomy 3D model generation, 2) visual display, 3) registration and tracking, and 4) accuracy measurement.

Target anatomy 3D models are typically derived from either CT or MRI images. Modern CT scanners have accuracy to less than 0.234 mm¹⁰. The DICOM data is segmented using one of several available software programs to generate 3D reconstructions. In our study, we used semiautomatic segmentation for skin and bone surfaces and manual segmentation for individual anatomic structures of interest. Lateral skull base anatomy is well suited for image guidance application as the relevant structures are fixed in bone. The manual segmentation process can be time-consuming¹¹ and efforts have been made by others to automate this process for temporal bone structures¹². ExR IGS has been described in multiple fields including neurosurgery, maxillofacial, orthopedic, cardiac and laparoscopic surgery¹³. In otolaryngology, AR has been applied in sentinel lymph node biopsy¹⁴, endoscopic sinus and skull base surgery^{15,16}, and cochlear implantation¹⁷.

Visual display of digital models in ExR has been achieved in multiple ways for IGS. A computer generated (CG) image can be superimposed on real-world imagery and displayed on a monitor, which has most often been described in laparoscopic and endoscopic surgery¹⁸. Several groups have described using a surgical microscope with digital images projected into the eyepieces stereoscopically to allow for depth perception^{19,20}. The MR headset projects digital images onto a transparent lens on a HMD. The headset is wireless and allows the user freedom of motion. We were able to visualize and maneuver our digital 3D anatomic images in the headset to overlay the physical specimens (Fig. 3).

Registration and tracking in IGS are essential for reliable navigation. Registration is the process of alignment of the image space with the physical space.⁷ Current commercial IGS systems use either fiducial marker points²¹ or surface anatomy maps²² for registration. Fiducials can be affixed to the skin or bone of the patient before obtaining CT or MRI. In the operating room, the physical location of the fiducials is then defined with a tracking probe. Tracking is accomplished with either optical (infrared) or electromagnetic field systems. The IGS system then aligns the image space points with the physical space points as closely as possible. In our project, we visually registered a holographic image reconstruction to its physical model using the HMD. The conceptual shift when comparing the MR headset to current IGS systems is that the registration and tracking components are contained within the headset. Our next objective was to measure the accuracy of the HMD after registration.

Accuracy in IGS is most commonly measured using TRE, which refers to the distance between a physical space point and the corresponding point as located by an IGS system. Our study found TRE to be an average of 5.76 mm using the MR headset to locate points on a 3D-printed model. Prior studies comparing accuracy using different registration methods have found bone-anchored fiducials to be the most accurate. Metzger²³ reported TREs of 1.13 mm with bone-anchored fiducials, 2.03 mm with skin fiducials, 3.17 mm with bony

landmarks and 3.79 mm with a splint during maxillofacial surgery. Mascott²⁴ found TREs of 1.7 mm using bone-anchored fiducials and 4.4 mm when using surface map registration.

There are various limitations to our research and the MR HMD. When measuring the TRE, we used a 3D-printed model in place of the original cadaveric head. In addition, to view our models in the MR headset, the number of triangular meshes in our 3D reconstructions was reduced to permit image viewing at a smooth and stable frame rate. This reduction smooths the edges of the reconstruction and could affect model accuracy in the sub-millimeter range. We found that around 30,000 triangles frame rate and spatial mapping accuracy significantly decreased, causing the model to shift as the observer moves and increasing TRE. Higher resolution reconstructions can have >200,000 surfaces, and thus are not tractable for this type of display without some refinement. As computational power is continually improving with lower power draws, newer MR headset models will have increased computing power that should help with this issue. However, given that the improvement needed is more than an order of magnitude, we will likely need to produce models that have more surfaces in areas/structures of interest while decreasing resolution elsewhere. We perceive the majority of the inaccuracy is due to image distortion and difficulty with accurate depth perception. The MR HMD creates the perception of depth by presenting images stereoscopically- a separate image to each eye on the lens. Visualizing the location of a probe in 3 planes is difficult without moving to different perspectives. The user can experience discomfort trying to localize points in space for extended periods. Inattentional blindness- missing abnormal events when the user's attention is focused elsewhere- is a concern with AR surgery²⁵. It is difficult to describe the user experience in static format as in the figures and we would encourage the reader to view this video (<https://wustl.box.com/s/38o05xoygr50hmbf3ou4nj7w6lk1yhel>). We attempted to capture the utility of this platform with objective measurements(TRE), but the potential application is more readily apparent with headset demonstration.

Despite the limitations identified with the MR HMD as an IGS tool, we believe that this technology is promising and warrants further development. We plan to improve our surface registration method by improving the user interface to make fine adjustments of the hologram easier. Autoregistration will require defining the region of physical space where our image model will be anchored to be better mapped by the headset.

Conclusion

The MR HMD is capable of providing 'x-ray' vision of human anatomy. The logistics of registration, navigation and accuracy warrant improvement before it is ready to be used for image guided surgery. We are currently working to improve each of these areas. The device has several key features that make it ideal for IGS. The technology has significant promise to improve surgical navigation by helping the surgical trainee more efficiently develop a mental 3D anatomical map. Future iterations of the MR headsets may well be capable of reliable registration and better accuracy for intraoperative surgical guidance to improve surgical outcomes and improve physician training.

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Figure 1. Work flow demonstrating generation of 3D interactive hologram and projection onto cadaveric specimen as seen through the Microsoft HoloLens.

Figure 2. Demonstration of measurement of target localization error (TLE). Panel A) Observer using 4-point passive probe (blue arrow) to measure TLE of selected landmarks with Optitrack camera bar (red arrow); Panel B) View through the HoloLens during measurement.

Figure 3.
3D interactive holograms superimposed on cadaveric temporal bone as seen through the HoloLens. Panel A) Skin and bone; Panel B) Bone only; Panel C) Internal Ear structures including jugular bulb (blue), carotid (red), facial nerve (yellow).

Table 1.

Average Target Localization Error (TLE) of external and internal landmarks as measured by 3 different observers.

Measurement Points	Average TLE (mm) $\pm$ SEM		
	Observer 1	Observer 2	Observer 3
Left earlobe	4.32 $\pm$ 0.25	5.69 $\pm$ 0.10	4.89 $\pm$ 0.11
Left lateral canthus	6.18 $\pm$ 0.36	1.65 $\pm$ 0.015	4.70 $\pm$ 0.17
Midpoint maxillary central incisors	9.23 $\pm$ 0.53	2.31 $\pm$ 0.05	5.98 $\pm$ 0.04
Midpoint maxillary central incisors	1.72 $\pm$ 0.10	2.04 $\pm$ 0.03	4.19 $\pm$ 0.17
Right earlobe	8.22 $\pm$ 0.47	4.13 $\pm$ 0.11	3.89 $\pm$ 0.19
Left IAC	7.65 $\pm$ 0.44	7.50 $\pm$ 0.06	7.04 $\pm$ 0.13
Right IAC	7.87 $\pm$ 0.45	9.50 $\pm$ 34	12.3 $\pm$ 0.15
Total Average	6.46 $\pm$ 0.37	4.69 $\pm$ 0.10	6.14 $\pm$ 0.14