Augmented Reality for Otology: A Review of Applications, Benefits, and Limitations

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Abstract

Augmented reality has become an increasingly useful tool in medicine. For our sponsor, the Biomechanics of Hearing research group at Universitätsspital Zürich, we provided an overview of how augmented reality could be applied in otology. We performed a literature review of medical augmented reality applications and conducted interviews with expert otologic surgeons and researchers. We determined that augmented reality may have valuable navigational and educational applications but requires more development before seeing clinical use in otology.

Authorship Table

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Yashas Honnavalli also provided valuable work in creating references, linking citations, and creating transcripts for interviews.

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1.0 Introduction

Augmented reality (AR) is a technology which blends the user's perception of the real world with computer-generated information, and which shows great promise in applications including entertainment, education, business, and medicine. Though proposed as early as the 1960s, driven by technological developments that have allowed for vastly improved processing power, precision, and lightweight design, visual AR alone has evolved as a technology to the point where its diversity of applications is attracting investment in the billions of dollars (Gilbert, 2021; Wong et al., 2018). In particular, AR is finding use in a wide array of fields from space exploration, military and defense, leisure and recreation, education, and medicine especially, where it is offering new approaches to both operational workflow, medical training, and even limited use in treatment interventions ("Augmented Reality in Education," 2021). Despite this, some fields of medicine are seeing little in the way of AR.

While there have been some advances in applying AR to otology, a branch of medicine that deals with the anatomy, pathology, and physiology of the ear, as well as hearing research, wider adoption in the field has been limited. As a result, even though many medical fields, including otolaryngology, are increasingly making use of AR technologies, there remain few examples of AR systems developed for use in otology (Wong et al., 2018). Still, the sophistication of otologic procedures, implants, and surgeries has only been rising. Due to this, otology holds many unexplored areas of potential improvement.

To understand how AR might be able to help solve problems in otology, it is necessary to understand how it sees success in other medical contexts. Across various approaches, AR can improve surgical outcomes, has applications in treatment and diagnosis, and may also be useful in surgical training and medical education (Wong et al., 2018). Largely, AR aids surgery either preoperatively, where it helps surgeons visualize anatomy and plan out their approach, or intraoperatively, where it superimposes visual instructions or images on the operator's field of view or provides auditory or tactile feedback to guide their operation (Wong et al., 2018). In otolaryngological surgery, neurosurgery, and plastic surgery, AR has also shown reductions in operation time, mental and physical demand, and frustration, while increasing surgeon confidence and precision (Li et al., 2016; Wong et al., 2018). AR is also seeing increasing use in spinal surgery, where it competes with traditional approaches in accuracy and demonstrates improvements in workflow (Burström et al., 2021; von Atzigen et al., 2022). AR is still in its infancy, however, and not without its drawbacks: it still lacks the precision that is so crucial for especially delicate surgical operations, and faces many other novel logistic, operational, and technological hurdles (Hussain et al., 2020c). Despite this, given the benefits AR can provide today, otologic practice may have much to gain from the recent development and advancement of AR technologies.

At Universitätsspital Zürich (USZ), the lack of a well-defined problem space in otology and solution space in AR impedes progress in applying AR technologies to otology. It is believed that AR may be able to help with improvement and standardization of preoperative planning, guidance during surgical access to the middle and inner ear, and active monitoring and warning during insertion of prosthesis, among other areas. However, without a complete understanding of the available AR technologies, their capabilities, and their limitations, it is difficult to determine anything specific within otology that could be improved with AR. Therefore, USZ's ENT department and Biomechanics of Hearing research team could benefit from a better understanding of the available AR tools and how they could be applied to their current and future research, as well as existing clinical procedures.

The goal of this project was to provide a high-level overview of medical AR, determine benefits and limitations of medical AR applications, and to draw connections between AR solutions and problems in otology. To do so, we strove to answer four primary questions:

- What medical AR technologies are currently in use or under development?
- What are the benefits of medical AR?
- What are the limitations of medical AR?
- What connections can be drawn between these technologies and the problems that clinical otologists and hearing researchers face?

To achieve this, we first carried out an initial literature review to find current and developing applications of augmented reality in otology and other relevant fields. We then met with various hospitals, related industries, and academic institutions throughout Switzerland to interview expert clinicians, engineers, and researchers on the current state-of-the-art in AR and its potential applications for otology, using information gathered in our literature review to inform our process. Finally, we summarized our findings, drew connections between various AR solutions and problems within otology, and suggested where we believe AR to be most readily applicable. We hope that this report helps USZ better understand the relationship between AR and otology and offers researchers and clinicians possible directions of inquiry for further research into AR in otology.

2.0 Background

In this chapter, we begin with a holistic overview of augmented reality (AR), including recent technological developments that have enabled its existence, capital investment in AR, and examples of some novel uses of AR. Narrowing the scope, we focus on how those developments have impacted augmented reality's growth within medicine. Then, we introduce otology, and give a brief overview of some of the challenges still faced within the field. From this we establish an understanding of why AR is being investigated for use in otology.

2.1 Augmented Reality: Definitions, Recent Developments, and Reasons for Interest

Augmented reality (AR) is a classification of technology that augments the user's perception of their real-world environment in real time with computer-generated information. Unlike its cousin, virtual reality (VR), where computer-generated scenes completely replace the user's perception with a virtual scene, AR uses computer-generated stimuli to enhance the user's natural perception of the environment (Gilbert, 2022). In this report, AR can also refer to technologies that provide real-time mechanical or robotic assistance to the user. Recently, AR has seen an explosion in growth due to technological advancements and significant capital investment.

Visual AR alone spans a wide range of applications: AR has been used in phones, dedicated hardware devices (e.g., "mixed reality" glasses), and can even project onto surfaces in the real-world (Gilbert, 2022). In newer phone models, some camera apps can utilize AR to help the user capture a better photo. Gridlines appear overlaid on the environment to help line up the photo, and 'head finders' display boxes to help center the image on the head(s) of the subject(s). Additional filters can be overlaid on the photo to display virtual objects that adapt in real time. Another popular use of AR is in smartphone games such as Pokemon Go and Ingress Prime where the real world, viewed through the phone's camera, is 'augmented' with virtual monsters and objects. Big business is also adopting AR, as companies like Microsoft develop dedicated AR devices such as the Microsoft HoloLens™, which uses AR to visualize a product or process for marketing, sales, and safety and operational training (Gilbert, 2022). Additionally, there exist AR systems, particularly in the medical field, that project images into the real world, either by static or head-mounted projectors, in order to enhance the amount of information visible to the operator (Wong et al., 2018).

Recent technological advancements, particularly the refinement of new computing technologies, have accelerated the development and capabilities of AR. In particular, increases in the processing power of computer chips coupled with a decrease in their size has been key in opening the market to the world of mobile AR applications (Hussain et al., 2020b; Xiong et al., 2021). The advancement of machine learning and image recognition and tracking techniques, such as Simultaneous Location and Mapping (SLAM), and computer vision libraries like OpenCV, although developed outside an AR context, have also been instrumental to the creation of motion-tracking and feature detection AR software (Hussain et al., 2020c). Additionally, an increase in the sophistication of sensor design, like cameras, accelerometers, gyroscopes, and more specialized sensors, coupled with improvements in commercial embedded system capability, enables dedicated AR systems to function smoothly (Xiong et al., 2021). Advancements in high-speed communication also enable more sophisticated augmented reality devices by allowing for the offloading of computation to an external device (Xiong et al., 2021).

However, even with these significant technological advancements, AR still faces an array of challenges and limitations—particularly regarding fine-grain precision and set-up time (Hussain et al., 2020c). Moreover, even when there is meaningful data to present, there remains the issue of how to combine, integrate, and present information to the user in an effective manner—without a seamless integration, AR can wind up being confusing, overwhelming, or useless.

Despite these challenges, the technology sector is investing heavily into AR development. Large technology companies such as Microsoft, Google, Apple, and Meta, as well as numerous smaller companies, continue to invest large amounts of capital into augmented reality research and development. Among tech giants, Apple provides the largest platform for AR development and is developing its own AR glasses, Microsoft is pioneering its own dedicated AR devices, and Meta is already planning to invest over $10 billion a year in AR/VR (Heath, 2022; Kastrenakes, 2021). Additionally, Sundar Pichai, CEO of Alphabet, has said that AR will be “a major area of investment” for them in the near term (Heath, 2022). Over the past several years, the two largest individual venture capital investments in AR were in companies with strong ties to medicine: Magic Leap, which makes AR systems for use in medicine and other areas, closed a deal totaling $500 million, and SenseTime, an AI company with ties to medical imaging, raised even more than this (Metinko, 2022). Additionally, medical AR is, by some projections, expected to grow to an over $4 billion industry by 2025 at an annual growth rate of over 30% (TBRC Business Research PVT LTD, 2021). Accordingly, medicine is increasingly adopting AR.

2.2 Augmented Reality Within Medicine

Along with its mainstream commercial uses, augmented reality is being applied in medicine to positive effect, and research and development in medical AR is a growing field of interest. Augmented reality already sees experimental use in numerous different areas of medicine, though primarily in orthopedic, neurologic, hepatobiliary, and pancreatic surgery (Hussain et al., 2020c). AR helps surgery run smoothly in two primary ways: preoperatively, where it helps operators visualize and plan their surgery, and intraoperatively, where it helps guide the surgeon during operation (Wong et al., 2018). Intraoperative AR has the primary benefit that it enables doctors to keep their focus on the surgery table (Wong et al., 2018). With traditional intraoperative navigation (IN) systems, surgeons must switch their gaze between the patient and external monitors where information is displayed. Because AR allows for informational overlays, it overcomes this limitation. Intraoperative AR is also used in conjunction with other image-guided therapies, allowing doctors to see organs and tissues that are normally hidden (Zhao et al., 2021). AR has also been shown to improve outcomes by highlighting critical structures and other various pathologies (Bernhardt et al., 2017; Hussain et al., 2020c).

Enterprise-scale AR products designed for potential use in a medical setting, such as Magic Leap and HoloLens, are also undergoing experimental use, with promising results. Both of these products are AR glasses purported to be able to help display information during surgery. Additionally, start-ups such as Endosight and Incremed are focused on providing other medical AR solutions. Researchers developing an AR system to “visualize the cochlear axis in intraoperative videos” showed that “[AR] can particularly be useful in highlighting critical structures, pathologies and risk regions in an intuitive manner” (Hussain et al., 2020c, p. 2094). Furthermore, it was demonstrated that “AR also has the potential to facilitate minimally invasive procedures by allowing the surgeons to visualize structures without exposing them” (Bernhardt et al., 2017; Hussain et al., 2020c, p. 2094). In addition, AR navigation has been found to be “superior to conventional navigation systems with regard to mental demand, physical demand, effort, and frustration,” particularly for less experienced surgeons (Li et al., 2016; Wong et al., 2018, p. 963). Perhaps most crucially, there is also research that demonstrates that AR can, in some cases, reduce operational time and surgical error (Duarte et al., 2020; Hussain et al., 2020c;

Wong et al., 2018; Zhao et al., 2021). As a result, AR may be able to help address key problems within otology.

2.3 Defining a Problem Space for Otological Medicine and Research

Otology is the study of the ear's anatomy and diseases, which encompasses both surgery of the ear, and research on procedures, implants, education, and mechanical research relating to the study of the ear. The ear's anatomy is composed of many complicated structures contained within a very tiny area. These structures are also located very close to major nerves controlling hearing and facial movement, as well as major blood vessels like the jugular vein and carotid artery (Ying et al., 2013). As a result, otologic surgeries often require complex navigational techniques to access and operate on these structures. Through interviews with doctors and researchers, it was highlighted how current otological practice has multiple areas which could be improved upon. Specific examples include the process of installing cochlear implants and the removal of vestibular schwannoma (VS) tumors, as both of these procedures are complex and extremely delicate.

2.3.1 Accuracy and Guidance

The primary issue identified in our research was that of accuracy and guidance. Otologic surgery requires a high degree of accuracy due to the complexity and small size of the ear. When performing the surgery for a cochlear implant, a hole is drilled in the cranial base. This hole is located very close to a major nerve which controls the face and a major artery which supplies blood to the brain (Ying et al., 2013). Surgeries removing vestibular schwannoma require a high degree of accuracy, as these tumors are located on and around the facial nerve, the main nerve in the inner ear, and near major blood vessels. These tumors also tend to shift the nerves they grow on and around as they expand. This makes it difficult to navigate around the nerves and blood vessels when removing the tumor, as every patient's case will be different. In addition, current image guidance systems that could be used for guiding otologic surgery have "limited use due to their insufficient precision and poor ergonomics" (Hussain et al., 2020a, p. 1). Improving these systems and finding effective methods of intraoperative navigation would be highly beneficial in reducing surgical error and improving the success rate of surgery.

2.3.2 Lack of Visual information During Operations

Another common issue that we identified through our interviews was a lack of visual information. Multiple researchers and surgeons informed us during interviews that the current procedures for cochlear implant surgery rely on surgeons knowing where key structures are through experience, as well as muscle memory and force feedback while inserting the electrode. Although misplacement of the electrode during cochlear implant surgery is rare, reducing the risk of the implant malfunctioning and the risk of damaging delicate nerves and arteries nearby, or at least reducing the time it takes to perform these procedures, was deemed very important by otologic surgeons (Ying et al., 2013).

3.0 Methodology

The goal of this project was to provide a high-level overview of medical AR, determine benefits and limitations of medical AR applications, and to draw connections between AR solutions and problems in otology. To do so, strove to achieve three primary objectives:

1. Provide a high level overview of medical AR
2. Outline and characterize a portion of the problems within otology
3. Draw connections between medical AR and the problems we observed within otology

In this chapter, we describe how we conducted academic research and expert interviews to gather relevant information. We also briefly explain how our analytical techniques helped us draw a clearer picture of medical AR's potential within otology. However, our approach faced limitations with regards to time and our technical understanding of the material.

3.1 Objective 1: Provide a High Level Overview of Medical AR

To determine what kinds of AR could have potential within otology, we first sought to acquire a high-level understanding of what medical AR technology currently exists. To do so, we attempted to answer three guiding questions:

- What medical AR technologies exist?
- Which AR technologies have potential within the field of otology?
- What limitations do those technologies still face?

3.1.1 Medical Literature Review and Expert Interviews

Our knowledge of existing medical AR came primarily from medical and academic literature. We reviewed both primary and secondary sources from academic and research databases to identify existing and current medical AR technology. We utilized the WPI Gordon Library Databases to access many high-quality primary and secondary sources such as PubMed, Scopus, and the National Library of Medicine. We also utilized our primary contact at USZ, Dr. Ivo Dobrev, and his team as a resource to gain access to resources specific to otology. The results of our interviews from Objective 2 also had a large influence on how we guided our research, as these interviews gave us a better understanding of the specific needs of both otological clinicians and researchers and gave us direction for further research. This knowledge helped us pinpoint AR technologies that would be the best suited to assist with these issues.

In addition to our literature review, we conducted interviews with researchers in the field of AR. Prior to these interviews, we did background research on our interviewees and prepared several questions and topics of interest based on that research. These questions varied between interviews, but in general we sought to find out:

- Specific research or AR technology the interviewee worked on
- Specific software and hardware used
- Limitations of these technologies
- Learning curve for utilizing this technology (if applicable)

To find interview candidates, we were given an initial contact list by our sponsor which we expanded upon as we conducted research. We also employed the ‘snowballing approach’ by asking interviewees if they knew or could identify any other potential groups or experts in AR that may be willing to speak with us.

3.1.2 Analyzing Gathered Information

Through our research we constructed a broad list of the medical AR technologies that exist, both experimental and those already undergoing limited use or clinical testing. We also took note of the limitations and issues faced by these technologies, such as accuracy and usability issues, as well as problems in specific applications. Our research also helped us form more targeted questions for our interviews with AR experts and interviews with otologists within Objective 2.

Interviews with AR experts presented an excellent opportunity to ask specific questions about AR technology that we were not able to answer through our literature review. These interview results both helped us better understand both the capabilities and specific limitations of current AR. The information gained from our interviews also furthered our literature review as it allowed us to better understand the technical specifics of AR development and helped narrow the technologies that were capable of meeting the needs of otology.

3.1.3 Limitations With Literature Review and Interviews

The main limitation for our literature review was our lack of specialized medical and technical knowledge needed to properly understand the material we read, which means we may have missed some finer details that could be important to our research. Another limitation was that our problem scope was not very well defined until later on in our project, which caused problems with effectively directing our research. Our access to sources was also a limitation, as WPI provides extensive—but non-universal—access to research sources. We also had to account for bias in our literature sources, as we may have been presented with a less critical view of AR's actual applicability since researchers may not be as likely to take a negative stance on their own work. Finally, due to time constraints, we were unable to thoroughly investigate preoperative AR.

With interviews, the main limitation we faced was the limited time of interviewees. Since we spoke to experts, clinicians, and other professionals, our interview candidates had very busy schedules. As a result, in most cases meetings had to be scheduled at least 2-3 weeks in advance. Relatedly, the snowballing approach we utilized was somewhat ineffective due to the limited availability of prospective interviewees—many of the people we were recommended to speak to were not available within the time frame of this project, or were on vacation. Additionally, we did not always have the required technical knowledge to fully understand the complexities of the technologies and research discussed. Regardless, we are very appreciative of the time interviewees spent out of their busy days to help us.

3.2 Objective 2: Outline and Characterize Problems Within Otology

In order to narrow our search for AR technologies that may have use within otology, we wanted to better understand the problems faced by otologic surgeons and clinicians. We wanted to answer four primary guiding questions:

- What information do they use during surgery?
- How is this information displayed?
- What missing information would they like to have access to during surgery?
- What are the biggest challenges with performing otological procedures?

3.2.1 Interviewing ENT Surgeons and Clinicians

We gathered our data through semi-structured interviews with several experts in the field of otology. We capitalized on our relationship with USZ to contact otologic surgeons and clinicians to schedule interviews. Prior to these interviews, we performed background research on the interviewee and then created a list of interview questions based on that research. Our interviews, aside from a few exceptions, were fully recorded to allow for full transcription and analysis. Our literature review from Objective 1 also helped us to formulate questions, as we were able to pinpoint exact areas of interest for our questions.

3.2.2 Analyzing Interview Results

The main purpose of the interview results was to both develop our understanding of otology and to further guide our literature review. Utilizing the interview transcripts, we extracted information relevant to our research questions. We analyzed trends between all of our interviews, looking for similar problems. We also noted any similarities and differences in the responses to similar questions between interviews. As in Objective 1, these interviews assisted us with guiding our literature review. The trends we identified helped us narrow down specific AR technologies that have potential in solving problems in otology.

3.2.3 Limitations With Interviews

The main limitation we faced was that we did not have the required medical knowledge or expertise to fully understand the complexities of the issues we are dealing with. Because of this, we may have missed some nuanced issues within otology that could be important to our research. In addition, we were not able to gain a full and comprehensive understanding of the problems within otology because of time constraints for our project. On top of this, our interview pool was fairly small and we mainly conducted interviews with otologists from USZ, which may add bias to our results. Finally, the snowballing approach we utilized was mostly ineffective due to the limited availability of our interviewees and the fact that some of our interviewees recommended people we already knew. Regardless, we are again very appreciative of the time interviewees spent out of their busy days to help us.

3.3 Objective 3: Draw Connections Between Medical AR and Problems Within Otology

To pinpoint key areas where medical AR could assist within otology, we compared the state-of-the-art in medical AR from our literature review with the problems in otology gathered from our interviews. We synthesized the results from both Objective 1 and Objective 2 and specified which areas of otology would benefit the most from the application of medical AR. We then documented the results of this synthesis within our report.

4.0 Findings and Discussion

In this section, we first present an overview of medical AR and break its applications into two categories: informational AR and mechanical AR. In informational AR, we introduce our definition of visual overlay augmented reality and describe the two primary techniques it employs. The benefits of these applications are discussed, including reducing operation times, increasing surgical accuracy, and improving anatomical education and surgical training. Next, we discuss how, despite its potential benefits, AR still struggles with achieving the level of precision that otology requires, and how it faces many difficult design choices in presenting information in a useful, intuitive manner.

4.1 Applications of Augmented Reality In Medicine

At a high level, medical AR involves the merging (registration) of two or more different modalities of information (e.g., computed tomography (CT) scan and optical video) to achieve an augmented function. This merging does not exist in isolation, and in fact the medical AR pipeline can largely be broken into three phases: information gathering, merging of modalities, and acting upon the newly merged information set. All of these phases are inextricably linked to one another and the broader concept of medical AR, and medical AR devices need not be restricted to just the merging phase. Many AR solutions combine different facets of each of these stages, leading to AR devices that both augment the collection and display of information, AR devices that help surgeons contextualize information and robotically act upon it, and even AR devices that automatically perform certain procedures.

Broadly, we split medical AR applications into two categories: tools that present extant information in a more consolidated, intuitive, or useful manner, and tools that allow for new procedural approaches by changing the way the user interacts with their subject through mechanical augmentation, automation, or robotic aid. We refer to this first group of tools, which we focus on in this report, as *Informational Augmented Reality*, and the second group of tools as *Mechanical Augmented Reality*. The line between these categories is not solid, and in fact these two classes of tools tend to synergize well when applied together. However, this delineation allows for a clearer discussion of the benefits, limitations, relationships between, and underpinning design philosophies of these technologies.

4.1.1 Informational Augmented Reality

When planning and performing surgery, it is necessary to consider many different kinds of information. Magnetic resonance imaging (MRI) scans, computed tomography (CT) scans, cone beam computed tomography (CBCT) scans, optical coherence tomography (OCT), endoscopic camera feeds, and microscopes—to name a few—are all vital parts of many procedures, and each provide their own unique form of information that must be considered in relation to each other. Even still, new methods of acquiring even more information, such as real-time vibrational data of inner ear structures, and impedance measurements of cochlear implants that may potentially help determine their placement, are only continuing to be developed (Haaije, 2022; Sijgers et al., 2022). As a result, methods of effectively merging these different modalities of information are becoming increasingly important. It is the goal of informational AR to address this problem.

Perhaps the most recognizable form of informational AR, and the type of AR that this report makes its primary focus, is *visual overlay augmented reality* (*VOAR*). We define VOAR as a class of devices that augment the user's visual perception of their environment by overlaying system-generated images, text, or objects onto their field of view. The majority of the examples covered in our report that fall into this category utilize head-mounted displays in the form of glasses or headsets, but there also exist systems that physically project information onto a surface (e.g., projecting subdermal anatomical information onto an operational area) (Wong et al., 2018).

Compared to other intraoperative navigation (IN) systems, intraoperative VOAR has the principle advantage of enabling doctors to keep their focus on the surgery table (Wong et al., 2018). With traditional IN systems, surgeons must switch their gaze between the patient and external monitors where information is displayed, but VOAR overcomes this limitation by merging the operational view with other important information. For instance, when used in conjunction with other image-guided therapies, VOAR can allow doctors to see organs and tissues that are normally hidden (Zhao et al., 2021). In other implementations, VOAR has also been used to highlight critical structures like nerves and infected regions (Bernhardt et al., 2017; Hussain et al., 2020c). In some cases, VOAR can also be used to maneuver instruments obstructed from view, view endoscope or microscope camera feeds, and consult other forms of live information normally displayed externally (Hussain et al., 2020c; Yoon et al., 2018). VOAR can also simply be used to display static information, e.g. CT images of a patient taken preoperatively, in a more convenient location (Hussain et al., 2020c; Yoon et al., 2018). While the exact nature of the information that must get merged varies drastically depending on the surgical procedure, we find that there are broadly two different approaches that are taken in otological VOAR: anatomy overlays and navigational guides.

The first primary use of VOAR we observed was in overlaying visualizations of patient anatomy onto the surgical area. This involves superimposing models of risk regions such as delicate nerves or blood vessels, critical areas such as the structures targeted for operation, or pathologies such as infected regions or tumors, onto their location on the body. These models are usually generated from MRI, CT, or other scans conducted pre-operatively (Hussain et al., 2020c; Vávra et al., 2017; Wong et al., 2018). An example of how anatomy overlays were used by Liu et al. in a 2014 cadaveric otologic surgery is shown in Figure 1. Image A shows a coronal slice of critical ear structures from a preoperative CBCT scan of the cadaver. The cochlea, oval window, and facial nerve are highlighted in this scan. During operation, these structures are overlaid on the surgeon's field of view through a head-mounted display, which is shown in Image B. This allows the surgeon to see previously hidden anatomy, enabling real-time guidance and target avoidance that adapts to the surgeon's perspective (Hussain et al., 2020c; Wong et al., 2018).

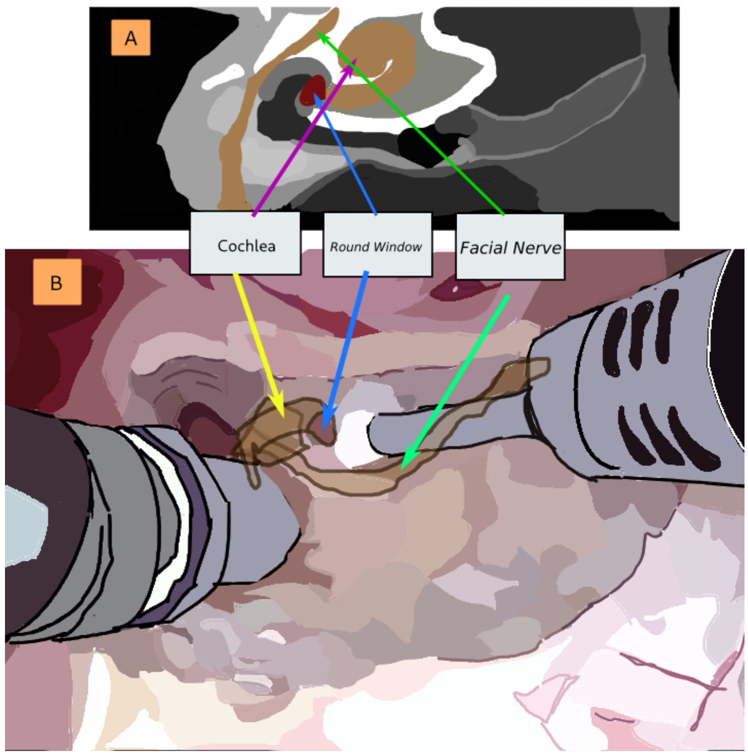

Figure 1: Example of Anatomy Visualization on the Surgical View
This figure is based heavily on a figure from Liu et al., 2014.

Navigational guides were the other primary VOAR technique we observed in our research. In this technique, guiding images are overlaid on the surgeon's view of the operating space in order to direct the surgeon on the correct positioning, orientation, and (in the case of inserting prostheses) shape and size of tools. This guidance generally combines preoperative planning with live computation in order to adaptively display the planned approach and better tailor operational procedures to the patient's particular anatomy. Researchers from the Research in Orthopedic Computer Science team at Balgrist University Hospital have found success in using this technique to augment spinal correction surgery. After screws are inserted into precise locations in the spine, they are held together by a precisely bent metal rod (von Atzigen et al., 2022; Wanivenhaus et al., 2019). To facilitate this process, the VOAR headset shows precisely what length and size of metal rod is necessary. Navigational guides were also a key part of a proposal for transmodiolar cochlear implantation. Alignment guides were overlaid on the view of the surgeon in order to correctly align the surgical instruments at the right location and angle for surgery, as shown in Figure 2 (Guigou et al., 2022). The line indicates the modiolar axis, with the red section indicating the section to drill. Semicircular lines are displayed perpendicularly to the axis in order to guide the surgeon's angle of approach, and markers (black dots) can be compared to similarly spaced markers on the drill in order to validate proper alignment.

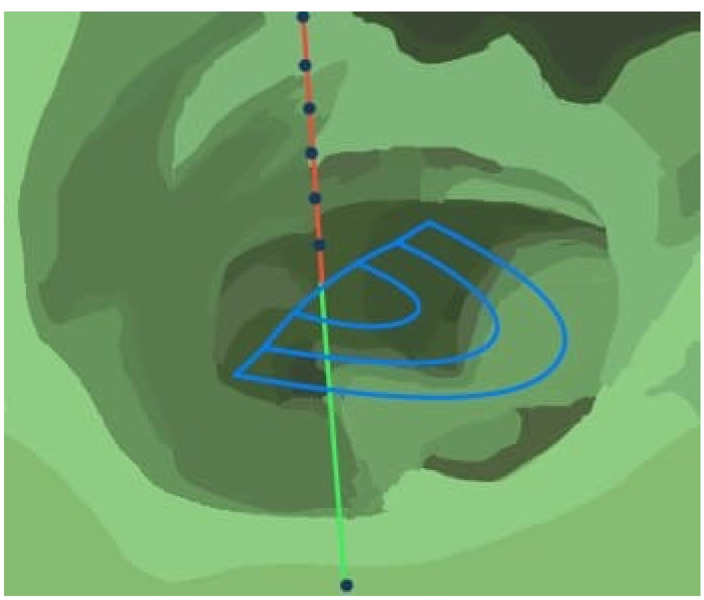

Figure 2: Example of Navigational Guidance on the Surgical View
This figure is based heavily on a figure from Guigou et al.

While informational AR need not be restricted only to the visual domain, we found very few applications of non-visual informational AR. One surgeon we interviewed noted that there exists a sound-based warning system for avoiding contact with the facial nerve during some otologic surgeries. By monitoring the facial nerve's electrical impulses, the system plays a warning sound if it detects that a surgical implement is approaching the nerve. However, the surgeon noted that this system is a last-resort failsafe at best: once the warning system detects an issue, the nerve has likely been at least partially damaged, and at least temporary facial paralysis is likely. Additionally, potential AR applications in the sonification of force sensing were raised to us, though we were unable to find any research on this in fields relevant to otolaryngology. This possibility, along with haptic (touch) feedback, seems best fitted for situations where there is no natural feedback on how much force you are applying (e.g. when using robots), or in extremely delicate scenarios (e.g. cochlear implant insertion).

VR is closely related to informational AR, though it serves to accomplish a different purpose. Since VR replaces the user's perception of their surroundings with a virtual scene, it cannot be used to aid intraoperative procedures as surgeons would completely lose sight of their operational area. Instead, it may be useful in preoperative planning, though research into preoperative informational AR appears to be limited. Informational AR may present opportunities for integration with cutting-edge artificial intelligence systems in the preoperative phase, though many of these applications remain tentative and fall outside the scope of our research (Chawdhary et al., 2021). More frequently, VR is used in education.

Interestingly, the most clinically promising use of VR that we encountered was not visual, but auditory. At USZ, there exists a soundscape room with the ability to accurately simulate all manner of sonic environments, from a quiet coffee shop, to crowded streets, to the inside of a grand church. In interviews with the researcher primarily responsible for the implementation of this room, it was discussed that though this room is used for research on patients with cochlear implants, its potential applications in early detection, diagnosis, and treatment of problems with cochlear implants are largely unexplored. However, the soundscape room comes with many drawbacks in its current form. Firstly, it requires a high degree of technical expertise to operate and can be time-consuming to set up. Additionally, high-quality data collection for the soundscape room requires high fidelity microphone arrays, potentially with over 100 channels. These are costly to acquire and restricts the ability to add new simulation environments. It was also noted that complications with cochlear implants limit the usefulness of simulations of sounds above 1500kHz. As a result, additional testing and an increase in the ease of use of the system is likely required before it can be readily applied in otology.

4.1.2 Mechanical Augmented Reality

In this study, tools that mechanically augment the surgical or hearing research experience largely fall under the domain of medical robotics. These systems exist in a wide array of forms in research and clinical practice, and applications range from performing measurements, precisely positioning instruments, being manually guided by a surgeon to perform operations, to even automatically executing certain parts of a surgery (Tamaki et al., 2020). In discussions with hearing mechanics researchers, we found that in hearing mechanics research, robotics is generally constrained to the use of a general-purpose robotic arm. This robotic arm can either be manually guided to a specific point in space in order to facilitate measurements from different angles or distances, or be attached with a sensor and programmed to automatically perform measurements that would otherwise be difficult, time-consuming, or imprecise if performed by a human (e.g., scanning precisely across the entire surface of an ear structure). While this does augment the process of conducting research, we find that these applications are mostly unrelated to the larger discussion of AR. However, in a surgical setting, there is more room for AR to be integrated into procedures.

While medical robotics presently sees limited use in otology, a number of different experimental setups are being evaluated for future use. Due to the high precision requirements of working with the middle ear and the minimally invasive nature of ear surgeries, the da Vinci robot was the most common choice we encountered in experimental research (Liu et al., 2014; Liu et al., 2015; Qian et al., 2018; Tamaki et al., 2020; Tarabichi et al., 2021). The da Vinci robot, intended for minimally invasive surgery, consists of several robotic arms that can be equipped with various surgical implements controlled by the surgeon from a console (Intuitive Surgical, n.d.). Many applications of the da Vinci system in otological procedures focused on increasing surgical accuracy, though Guigou et al. also propose a novel otologic surgery that these systems may facilitate when combined with VOAR, and Qian et al. look into using AR to support the first assistant in robotically-assisted surgery. In a few cases, custom setups were established, including a (highly experimental) joystick-controlled micromanipulator intended for very precisely measuring distances in the middle ear (Maier et al., 2011).

Other commercial robotics systems aimed at achieving a different purpose are being experimented with. One such system is the RoboticScope, which aims to achieve a very high degree of microscope maneuverability. The RoboticScope is, in essence, a surgical microscope attached to a robotic arm. The view from the microscope is projected to a headset that the operator wears, which also controls the positioning and orientation of the microscope by following the motion of the surgeon's head (BHS-Technologies, n.d.). This allows the surgeon to quickly make tiny changes to the perspective of the microscope. A different commercial system still undergoing experimental validation proposes augmenting the normally lengthy process of drilling through bone in order to access inner ear structures. It does so by using a powerful laser to precisely and automatically drill according to a planned trajectory (Advanced Osteotomy Tools, n.d.).

These systems all present opportunities for integration with other kinds of AR, and in fact much of the research on using these systems within otology makes use of VOAR to augment the operator's interaction with the robot. In most implementations where VOAR was used, video feeds on the surgical console were augmented with anatomical or guidance information, allowing the operator to better contextualize the location of the robotic implements (Yoon et al., 2018; Qian et al., 2020). This augmentation was added in part to make up for the haptic feedback that these robotic systems lack. This is because a surgeon's ability to determine the toughness and 'give' of certain parts of the body, as well as simply being able to tell with how much force they are pressing with, can be a major guiding factor for them (Tamaki et al., 2020). As a result, augmenting robotic systems with haptic feedback has been outlined as a major possible improvement of these systems (Tamaki et al., 2020). Additionally, in interviews with AR engineers, it was suggested that VOAR could be used to unify the surgeon and robot view by showing the surgeon "what the robot sees," potentially increasing surgeon confidence in and understanding of the robot. This is particularly relevant for automated systems, since surgeons must put their trust in the system to perform without any harm to the patient despite having incomplete knowledge of how the robot works. Accordingly, while medical robotics has seen great advancements, it still has many potential areas of improvement through the incorporation of other AR techniques.

4.2 Benefits of Augmented Reality

When applied to medicine, AR has a multitude of benefits that may make it preferable over conventional approaches. Although many systems are still experimental and face several limitations, we have identified three key areas where AR poses a significant advantage over traditional methods. Firstly, AR can both reduce the time costs and the cognitive load of surgeries by unifying the information surgeons require for procedures, minimizing surgeons' reliance on external monitors and the amount they switch their gaze. Second, AR can improve surgical accuracy through the utilization of both navigational guidance and anatomical overlays. Finally, AR can benefit education training and surgical confidence through interactive visualizations, semi-realistic surgical simulations, and the recording of surgical procedures for retrospective analysis.

4.2.1 VOAR: Consolidating Information and Reducing Time Cost

Though a lot of VOAR research focuses on using the technology to increase surgical accuracy, we believe that, partly due to AR's struggles with precision, VOAR's primary surgical benefit is in unifying information and reducing time cost. By intuitively combining information into one field of view, VOAR is able to reduce cognitive load required for surgical operation, which can make surgeries both faster and easier (Alexander et al., 2020; Hussain et al., 2020c; Wong et al., 2018; Zhao et al., 2021). Depending on the surgical operation, this can come to play in three primary ways. Firstly, it helps surgeons translate the two dimensional images they see externally into actual patient anatomy. With VOAR, surgeons have a reduced need to mentally rotate and combine different axes of the information they are given, which has the added benefit that surgeons do not have to perform complex motions while faced away from their hands because they are looking at an external screen (Zhao et al., 2021; Hussain et al., 2020c).

Secondly, VOAR reduces the need for the surgeon to switch their gaze back and forth between the patient and external monitors, which saves time and lessens the mental overhead surgeons spend remembering detailed information (Sahovaler et al., 2021; Zhao et al., 2021). For instance, in a study by Sahovaler et al., a combined AR plus conventional IN system reduced the percentage of operational time spent looking at a screen from 78.5% to 61.8% compared to a conventional IN system alone. Finally, by highlighting critical areas, VOAR increases surgeon confidence and reduces mental load (Li et al., 2016; Liu et al., 2014). This effect is more pronounced in less experienced surgeons compared to senior surgeons, which additionally suggests a role for AR in education and training (Wong et al., 2018; Hussain et al., 2020c). As a result of these factors, if a VOAR system has a short calibration and registration time, it may be able to reduce total operational time.

In interviews with researchers at Balgrist University Hospital working on VOAR, the time savings and intuitive nature of those systems was emphasized to us even more so than their potential to improve surgical outcomes. At Balgrist, AR researchers utilize the Microsoft HoloLens, a VOAR headset. The VOAR systems in research there have been developed with ease of use as one of the primary considerations, which means that VOAR solutions with the HoloLens tend to rely on relatively few external tools. As a direct result of this, calibration and registration can take as few as five minutes, though twenty minutes is usually allocated for set-up time even if most of that time usually goes unused. Though this time is added over top of the normal pipeline, it may ultimately end up saving time by reducing the amount of time spent in operation. Typical reductions in time were observed to be in the 20% range (Wanivenhaus et al., 2019). However, this reduction in time does not come automatically with the incorporation of VOAR. Designing useful ways of combining and presenting information to clinicians is not easy, and as the researchers explained, it requires a long, iterative back-and-forth process between engineers and clinicians for this to be achieved. Though some surgeons were notably faster at adapting to and using novel VOAR devices than others, VOAR solutions need to be designed to be usable by every surgeon. Ease of use is thus central to the design principle of VOAR, and it is for this reason that we believe that VOAR's main benefit is in consolidating information into a more useful, intuitive format, reducing the cognitive load of operators, the need for gaze-switching between the patient and external monitors, and—as a result—the time spent during operation, too.

4.2.2 Increasing Surgical Accuracy

In some cases, AR can improve surgical accuracy, though this is largely only in surgical specialties where accuracy requirements are not as strict as in otology. However, it is important to analyze situations where AR does benefit surgical accuracy, both to see what problems AR is best at addressing, and to see how it may be applied to otology in the future once AR becomes more precise. Improvements to surgical accuracy have been demonstrated using both primary techniques within VOAR, navigational guides and anatomical overlays.

Navigational guides have demonstrated the ability to increase surgical accuracy. In one notable example, researchers in orthopedic computer science at Balgrist were able to increase the accuracy of a corrective surgery of the spine utilizing navigational guides (von Atzigen et al., 2022). Surgical accuracy was increased by using 3D image overlays to inform the surgeon on the correct shape and length of the rod to be inserted into the spine. Normally, surgeons must estimate the length and proper bending motion, but the AR system the researchers developed provides the operating surgeon with a quantitative shape to base the rod off. As a result, the amount of trials where the rod lengths were correct improved from 4/18 trials to 15/18 trials (Wanivenhaus et al., 2019).

When combined with navigational guides, anatomical overlays have also shown promising results. Liu et al., 2015 demonstrated how an AR and CT guidance system for transoral robotic surgery improved accuracy of resection margins on mock tumors compared to alternative image guidance methods. The AR system utilized spherical guides concentric to a tumor to show the ideal margin for resection and also displayed overlays of critical structures, such as tumors and surface fiducials (Liu et al., 2015). Since the AR system was able to overlay the ideal margin in the surgical view, the margin achieved by surgeons was much closer to the ideal margin compared to alternative methods (Liu et al., 2015).

4.2.3 Education, Training, and New Surgeon Confidence

Hearing research often requires the visualization of complex anatomical and physiological information for the benefit of education and training, such as in teaching settings, communication, surgical training, and when sharing, reviewing, and recreating research data. Since VOAR and VR both have the capability to interactively visualize complex 3D structures, they hold potential to help in these areas. In particular, we believe that VOAR and VR may be able to help in anatomical education and surgical training by helping learners visualize concepts more interactively, by providing a safe and effective method of practicing operations, and by serving as an intraoperative data collection method.

By allowing for a more interactive visualization experience, VOAR and VR are able to help medical students learn anatomy. The ability to interact with structures in 3D space, a capability that VOAR and VR can provide students, has by itself been shown to be conducive to better learning (Dalgarno & Lee, 2010). Being able to intuitively highlight, remove, and play around with the many complex 3D structures in the middle ear may thus be especially useful in teaching middle ear anatomy and the working principle of different organs. Kugelmann et al.

demonstrated in a study of 880 first-year medical students that incorporating AR into a traditional anatomy course "not only increased motivation and engagement but also enhanced student understanding of anatomy" (Wong et al., 2018, p. 964). Among other examples, Gnanasegaram et al. also observed this in a study teaching undergraduate medical students ear anatomy through either a lecture, a 3D computer model, or a holographic (VOAR) model. Even though quantitative improvements in educational outcomes were similar, students felt they were much better able to grasp spatial relationships with the holographic model and reported much higher levels of interest and engagement (Gnanasegaram et al., 2020). Additionally, when AR is used in conjunction with physical models, students can benefit from improved visual input while retaining the tactile feedback that traditional models afford (Uppot et al., 2019; Wong et al., 2018). By allowing students to interactively visualize and manipulate different structures of the human body in three dimensions, AR's benefits mirror those of anatomical dissection while being easier to set up and not coming with the cost of procuring dissection material. Accordingly, simulations are already seeing increasing use in otolaryngology, especially for simulating surgery (Wiet et al., 2011).

AR allows surgical students to practice operations in semi-realistic simulations without the risks or costs normally associated with live environments or cadaveric simulations, and students doing this were able to retain more information compared to a classroom lecture setting (Duarte et al., 2020). In virtual simulations, students are able to practice in a risk-free environment and repeat sections they have trouble with, which is much more difficult to do with conventional methods (Wiet et al., 2011; Parsons & MacCallum, 2021). VOAR in particular appears to work best when combined with physical models, as this combination allows for the development and practice of practical skills in a physical, spatial context (Parsons & MacCallum, 2021). Additionally, when used in the operating room, AR can also serve as "training wheels" for residents by highlighting nearby critical structures, increasing their confidence (Wong et al., 2018, p. 963). AR has shown to be more effective for less experienced surgeons, bringing their accuracy and operational speed closer to experienced surgeons, which further implies a role for AR in teaching and training (Hussain et al., 2020c; Li et al., 2016). Positive education findings in otolaryngology AR are consistent with observations from studies in other surgical specialties, which again suggests that there may be a role for AR in otologic surgical training (Wong et al., 2018). In particular, one interviewee brought up the possibility of using AR to soften the learning curve for inexperienced surgeons or residents learning otological endoscopy and microscopy skills.

Finally, surgical VOAR may be able to unobtrusively record and collect data from surgical procedures for the benefit of retrospective analysis and education. Research into this appears to be limited, but Balgrist researchers noted to us that the university hospital is experimenting with this idea, and we found mention of this approach in one North American hospital (McGill University Health Centre, 2017). The Balgrist researchers informed us that since high-quality videos of surgery are generally limited, an increase in the availability of this kind of educational material could be valuable, especially for residents or medical students. They also mentioned that these videos could be combined with existing VOAR techniques for automated tracking of surgical phase, pose-tracking, implement positioning, and other relevant information to further enhance the usefulness of the material. Many VOAR implementations already have the ability to record video without impacting their augmentative capabilities, so these videos could be recorded with minimal disturbance to the operating surgeon.

4.3 Limitations and Challenges in Augmented Reality

Despite AR's many potential benefits, medical AR still faces many concerns when applied to otology. AR struggles with achieving submillimetric precision, a requirement for working within otology. On top of this, AR also faces tough questions in displaying information in a user-friendly and non-intrusive way that complements a surgeon's existing knowledge.

4.3.1 Accuracy and Precision

Currently, most AR systems struggle to meet the precision and accuracy requirements of procedures in otology. Given the small scale of otological procedures and the highly delicate nature of middle ear structures, AR devices must be accurate within a sub-millimetric range (Hussain et al., 2020c). Many AR devices fall short of this requirement (Hussain et al., 2020c). There are some promising results in overcoming this challenge: in recent papers on the topic, researchers have been able to create AR systems with sub-millimetric registration errors—but these systems are specialized, largely in their preliminary stage, and far from widespread implementation (Hussain et al., 2020a; Hussain et al., 2022; Marroquin et al., 2018; Guigou et at., 2022). AR's struggles with precision and accuracy come primarily from complications in registration, image tracking, a lack of high-quality machine learning training data, and time and ease-of-use constraints.

Error within calibration and registration is the first—and most important—problem that AR faces. Any error in this step propagates throughout the entire process, so it is critical that error here is kept to an absolute minimum (Hussain et al., 2020c). However, this presents a number of challenges. First, to register the device, some kind of spatial correspondence must be established between the different modalities of information that the AR device is combining (Hussain et al., 2020c; Wong et al., 2018). In some cases, this can be accomplished by identifying anatomical landmarks, but this faces the issue that the landmarks might deform or become obscured by blood or surgical implements mid-operation, though there exist algorithms to partially account for this (Guigou et al., 2022; Hussain et al., 2020c; Negrillo-Cárdenas et al., 2020). Additionally, given the complexity of the inner ear and the variation of individual patient anatomy, these landmarks are not always apparent and may be infeasible to consistently select across otologic surgeries (Hussain et al., 2020c). To overcome this, AR systems often use fiducial markers, small objects or markings placed in or on the patient's body in view of an imaging system for the AR device to use as a point of reference (Hussain et al., 2020c; Marroquin et al., 2018). However, finding the space to place fiducials at critical locations within the ear can be difficult in some scenarios (Hussain et al., 2020c). With head-mounted displays, other issues concerning the calibration of the device to the particular user also exist, as images must be displayed according to the particular user's eyesight and eye position (Azimi et al., 2017).

Image drift also poses an issue to AR systems. Image drift occurs when an AR device's internal representation of it or its target's position within space becomes misaligned, causing the images displayed on the AR device to drift from their calibrated positions (Zhou et al., 2022). This can happen because of a multitude of reasons, including miscalibration or movements of tracked landmarks (Hussain et al., 2020c). For example, patients often move slightly during procedures, or tissues deform slightly, and the system must be able to account for those changes or risk drifting (Hussain et al., 2020c; Zhou et al., 2022). Well-placed fiducials help combat image drift, but they face the same issues as in the registration phase. Furthermore, since operators move around during operation, AR devices must be able to accurately self-position in relation to the patient and tools from a number of different positions and orientations. If this tracking is out of sync, the image displayed on the AR device will not align correctly with the patient's anatomy. Even if a small amount of drift is not properly accounted for, tracking error will compound and the AR system will continually become less accurate as the operation progresses (Zhou et al., 2022).

Many implementations of AR rely on machine learning algorithms in some form for registration and image processing (Sahovaler et al., 2021; Moawad et al., 2020). While immensely powerful, machine learning tools come with their own drawbacks. These techniques typically require high computational power in order to run in real time (Hussain et al., 2020c; Xiong et al., 2021). Additionally, machine learning algorithms require a very large data set to train off of in order to become useful. This becomes a limiting factor when trying to apply machine learning to specific surgical domains, as adequate datasets may not exist for that specific application. Furthermore, as Balgrist AR researchers stated to us, gathering this data can be difficult. Both surgical and computer science experience are necessary to properly label data for use in training sets since computer science researchers typically know why things need to be labeled and what makes a good label, whereas clinicians know what needs to be labeled and can discern when a label is or isn't applicable. Balgrist researchers also noted that machine learning techniques also tend to struggle with pathological data as their characteristics can vary large amounts at a patient-specific level. These kinds of variations are usually not logistically possible to capture well in training sets. As noted in interviews and our literature review, this variance is particularly evident for areas in and surrounding the ear, exacerbating machine learning's problems within otology (Hussain et al., 2020c).

One potential method of mitigating these issues is to simply add additional registration, calibration, tracking, and other external devices to the AR system (Hussain et.al, 2020c). This, however, makes the system in its entirety more cumbersome, time-consuming, and expensive to set up and use, since each piece of additional equipment that is added must also be set up, calibrated, and integrated into the procedure. Given that one of the main draws of using AR systems is to make operations easier and more efficient, this would be counterproductive—AR systems must keep time and effort to a minimum in order to be worthwhile to use over conventional methods. To this end, commercial VOAR systems tend to come with a wide array of sensors incorporated natively in order to minimize reliance on external systems (Kerman et al., 2015). This purpose is entirely defeated if expensive, gold-standard advanced camera systems and infrared reflective spheres are added over top of these sensors. Indeed, Balgrist researched noted that many of AR's problems can be addressed by incorporating other external systems, but the more this is done, the more AR becomes "just an expensive display."

4.3.2 Difficulties in Displaying Information in a User-Friendly Manner

Even once all forms of information have been accurately collected, merged, and processed, there still remains the question of how that information should be displayed to the surgeon. By merging the different modalities of information into one cohesive view, AR seeks to solve problems associated with displaying information on separate interfaces. However, this presents numerous difficulties of its own. Different kinds of information are relevant at different stages in operation, so AR systems must be designed to show only the most pertinent information and must provide an intuitive method of switching between different information sets. Surgeons must also retain clear sight of their operation, which means overlays should be unobtrusive. Further, questions about how to clearly visually represent different modalities of information must also be addressed. Additionally, since surgeons are often not the ones directly designing and programming AR systems, AR designers usually do not have the requisite experience to intuitively grasp what kind of guidance or information would be most useful to display by themselves. As a result, displaying information in a user-friendly manner is intricately challenging.

To be useful, AR must present a workflow that complements the intuition surgeons have developed through years of experience. As a part of this, AR devices must display only useful and pertinent information while retaining a minimalistic control scheme so as not to distract the surgeon (Wong et al., 2018). Surgeons already have well-tuned intuitive feelings for the operations they perform, so AR should not seek to replace this intuition, but rather to enhance it. As a result, Balgrist researchers highlighted to us that more (or more granular) guidance is not always useful since surgeons already have an intimate understanding of the operations they carry out. AR systems must also take into account inattentional blindness, a phenomenon where objects that are clearly in one's field of vision go unnoticed because concentration is focused on a separate object or task (Dixon et al., 2014; Marcus et al., 2015). This poses additional design challenges for AR, as inattentional blindness must be avoided in order to facilitate safe surgeries (Marcus et al., 2015; Wong et al., 2018).

Since AR devices must combine disparate modalities of information into a unified view, it is not always apparent how to best display this information in an intuitive manner. For instance, while it might seem like it is best to present as much detailed anatomical information as possible, it was highlighted to us in interviews that the complexity of the inner ear means this approach is largely unhelpful. The inner ear is too complex to be able to quickly isolate important features from a full visualization, so cross-sectional slices are usually analyzed instead—even when full 3D information is available. Accordingly, it is not immediately apparent how to reconcile the many interconnected sections of the inner ear into one single view. Questions of how to display non-visual information, such as vibrational data, also arise. Furthermore, compromises between accuracy and communicative value may need to be made, such as when displaying tumors or infected regions in a visually distinct but still representative manner. Though we observed little research on the topic, some interviewees also believed that it is important to communicate the AR device's uncertainty in some form. Rarely do machines have absolute certainty in the placement of objects in space, rather, they have areas of higher and lower confidence. Without proper communication of these intervals, AR devices may convey a misleading sense of certainty. Besides this, other challenges still present themselves: for example, if the operative field and the virtual objects are not aligned along the same plane, the user's eyes tend to struggle to bring both information sets into focus simultaneously (Hussain et al., 2020c).

At Balgrist, these issues are remediated only by a close, iterative process between AR engineers and clinicians. Researchers there perform frequent usability studies not only to test the accuracy of the system, but also to gather surgeon feedback. This allows them to determine what forms of information are most useful to display, when they need to be displayed, and how best to avoid distracting the surgeon. With this feedback, they make improvements to the AR system and put it back to surgeons to again receive more feedback, repeating the cycle. While this adds time to the development process, it is necessary to preserve the ease-of-use benefits that AR can provide.

5.0 Conclusions and Recommendations

This chapter discusses the current applications, benefits, and limitations that we identified in medical AR. We then give analysis and discussion on what we've determined to be the most and least promising area of application for AR technology, along with important trends that we identified. Finally, we give future recommendations based on our findings and limitations found in our method.

5.1 Summary of Key Findings

Broadly, we categorized AR applications into two sections: informational AR and mechanical AR. Informational AR augments the user's perception with system-generated information. These techniques assist the surgeon through anatomy overlays, which are images of the internal anatomy and structure, and navigational guides, which indicate correct positioning and orientation of important surgical implements. Mechanical AR augments the surgical experience by means of robotic assistance. Current commercial medical applications identified in this category include the da Vinci system, the RoboticScope, and a laser drilling device still being validated for use in otology. These systems are able to increase precision and reduce complications in procedures, though they often add complexity to setup and come with a cost to time.

Due to time constraints, our team focused primarily on researching VOAR, a subcategory of informational AR. We determined VOAR's primary benefit to be in consolidating important surgical information for the user, which has the effect of reducing cognitive load and decreasing operational time. In some cases, AR was able to increase surgical accuracy. VOAR can also be used to positive effect in educational settings, training, and new surgeon confidence.

Despite its potential benefits, AR has two key limitations. Firstly, we observed that, outside of time-consuming specialized AR systems, AR applications are not accurate to a sub-millimetric level. Sub-millimetric precision is required in otology due to the small, delicate anatomy of the middle ear. However, AR is largely unable to achieve this due to error within calibration, errors with image tracking due to anatomy deformations, and image drift. The second challenge was with displaying information in a user-friendly way, as assistance should enhance, rather than replace, the intuition of the surgeon. Additionally, methods of effectively combining and displaying different modalities of information in an intuitive fashion are not obvious.

5.2 Analysis and Discussion

We believe that, with regards to otology, AR is most applicable in medical education. AR simulations of anatomy allow for a more interactive experience compared to traditional models, which can benefit education on the complex anatomy of the ear. This method of teaching has been shown to increase student motivation, engagement, and understanding. AR also shows promise in surgical training, where its benefits mirror cadaverous operations without the drawback of needing to obtain cadavers. It may also be valuable in collecting recordings of surgical operations for retrospective analysis and education. Finally, AR's limitations in accuracy and precision means that an educational application will be more viable than a clinical one, as classrooms represent a much lower risk environment compared to an operating room. Additionally, educational environments can serve as a testing ground for new AR applications, and hospitals that are affiliated with education institutions, like USZ, may be able to utilize this to their advantage.

In the future, as the precision and accuracy of informational AR devices increase, they may become valuable in clinical otology. In particular, we believe that VOAR shows promise in revealing the facial nerve through an anatomical overlay. In interviews, surgeons consistently described the facial nerve as one of their main concerns when performing procedures, as it is in very close proximity to drilling paths, not always visible, and major issues arise if it is even slightly damaged. Additionally, there are established tractography methods for locating and constructing a 3D model of the facial nerve, though no method of precisely overlaying it directly onto the surgical field (Epprecht et al., 2021). Because of this, if VOAR becomes able to match the precision of experienced surgeons, it may be readily applicable in otology. However, given current technological limitations, informational AR is not yet suited for clinical otology.

In discussing current medical technologies, we observed that there is a philosophical issue at play: companies are engineering driven, and so software and user integration often comes as an afterthought. As a result, we observed a lack of standardization among user interfaces, leading to impressive systems being held back by complicated, clunky designs. Because of this, researchers noted that many new devices require significant training (that is not often adequately provided) to be used effectively. On top of this, researchers and clinicians noted that it is not unusual to encounter bugs and user interface issues among newly acquired medical devices. However, AR may offer a path towards improvement. Informational AR has at its core a design philosophy that is centered around improving user experience, and so developments in informational AR may steadily improve and standardize methods of effectively communicating new forms of information and interfacing with new operational technologies.

5.3 Recommendations For Future Work and IQP Teams

In future works regarding this topic, we recommend further researching the benefits and limitations of mechanical AR systems, as well as the possibilities in using AR in preoperative planning. Due to the time constraint of our project, our group focused mainly on the benefits of VOAR, and how that specific implementation of AR could be applied to otology.

We also recommend a study on the use of AR in otology education, perhaps involving prototyping AR learning material for otology. AR presents enticing but unexplored possibilities for the interactive visualization of the inner ear's uniquely complex structures. As we highlight education as the first candidate for AR in otology, we believe this will be the most fruitful line of further inquiry.

We recommend that any future IQP teams plan and arrange for interviews during their preliminary literature review. This would solve issues we experienced where many doctors, researchers, and other individuals we were interested in interviewing were too busy to meet with us during the time frame of the project.

The results of this report implies that AR can be applicable and beneficial to not just otology. This may warrant a follow-up study in other fields, possibly ones with less stringent precision requirements than otology, that do not see the use of AR. This report was created with the Biomechanics of Hearing research group at USZ in mind, however, AR may be found applicable to other hospitals otology departments, as well as other branches of medicine experimenting with AR. We encourage USZ to use this report as a starting point in gaining a firm understanding of medical AR applications, and to use that to explore AR applications in other universities, research, and medical fields.

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Appendices

Appendix A: Table of Preliminary Questions for Interviews

This section contains a table of preliminary focus areas for use during interviews, and sample codings to be used when transcribing interviews.

Table 2: Table of Sample Codings For Transcriptions

Name	**Code**	**Description**
Negative outlook on AR	NAR	Opinion expressing negative outlook on AR/medical AR
Positive outlook on AR	PAR	Opinion expressing positive outlook on AR/medical AR
Medical AR research	MAR	Talked about their own or their institution's medical AR research
Research description	RED	Data that fits the scope of the research
Source Suggestion	SS	Suggested an additional source to interview
Tech Reference	TF	Reference to AR technology that could be applied to otology
AR Limitation	ARL	Describes limitation of AR, either in general or when applied to otology

IN System Description	IND	Describes existing intraoperative navigation system
Otology Challenge	OC	Discusses challenge(s) faced in otology (that AR may be able to help with)

Sample Questions and Introduction

Hello,

We are the Augmented Reality in Otology team consisting of Jack Brazer, Yashas Honnavalli, Noah Plasse, and Duncan Soiffer. Our interacting qualifying project in A term of 2022 focuses on investigating how augmented reality can be used in otology. An interview with you will help us gain a better understanding of our project. With your permission we would like an audio and written transcription of the interview, you may withdraw anytime. We will omit any personal information including your name unless otherwise stated. If you are uncomfortable you do not have to answer the questions. Would you like to continue?

For AR researchers and engineers:

1. What is your current involvement with AR?
2. What are the current technical challenges with AR?
3. What kinds of software are you using in your AR developments?
4. What kinds of hardware are you using in your AR developments?
5. How much does it cost to buy the hardware used in AR?
6. How are your AR products being used in hospitals?

7. What are the current limitations in AR?
8. What kinds of problems does AR work well to address? What problems does it struggle with?

For doctors and clinicians:

1. Is AR being used in your hospital?
2. What is your experience with AR in the hospital?
3. How are intraoperative navigation systems in your current procedures?
4. How are robotic systems being used in your current procedures?
5. What are some difficulties you have when doing surgeries?
6. What are the biggest areas of challenge in otology?
7. Where do you see the need for better precision (for example, when drilling in preparation for later phases of middle ear surgery)?

Appendix B: Informed Consent Agreement for Participation in a Research Study

Investigators: Jack Brazer, Yashas Honnavalli, Noah Plasse, Duncan Soiffer
Contact Information: You may contact us at any time for questions or follow-ups at gr-zuricha22-augmented-reality@wpi.edu

Title of Research Study: Augmented Reality for Use in Otology

Sponsor: UniversitätsSpital Zürich

Introduction
You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study: The goal of this project is to investigate the current and potential applications of augmented reality in clinical otology, otologic procedures and surgeries, research and development, and medical applications to assist UniversitätsSpital Züric in the development of augmented reality technologies to further the field of otology.

Procedures to be followed: We will perform interviews of approximately 1 hour in length, discussing AR in otology. We will not ask personal questions besides your name and occupation and will avoid recording personal information wherever possible.

Risks to study participants: We do not anticipate that this interview will put you at any risk. However, you should consider if you believe that you may face retribution from your employer for opinions you express, and you should avoid breaches of confidentiality or copyright. You may ask us at any time to exclude certain details of the conversation, and we will oblige to the best of our ability.

Benefits to research participants and others: You will not directly benefit from this interview or be compensated for participating. Our research is aimed at helping UniversitätsSpital Zürich begin research into medical AR for use in otology.

Record keeping and confidentiality: We will ask your consent to record your name for possible publication and attribution. You may ask us to omit your name. We will also ask to record your occupation and affiliated institution. Additionally, we will ask for your consent to record the interview and transcribe it. You may ask us to redact any (or all parts) of the transcript or recording, or ask us not to record it in the first place. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you. You do not give up any of your legal rights by signing this statement.

Compensation or treatment in the event of injury: No injury or harm of any kind is expected as a result of these interviews. You agree to not hold us liable for harm, except for harm resulting from deceitful practices or mismanagement of your information. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: any of the addresses listed at the top of the first page (gr-zuricha22-augmented-reality@wpi.edu). Additionally, you may contact the IRB Manager (Ruth McKeogh, Tel. 508 831-6699, Email: irb@wpi.edu) and the Human Protection Administrator (Gabriel Johnson, Tel. 508-831-4989, Email: gjohnson@wpi.edu).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____________________________ Date: ____________________

Study Participant Signature

____

Study Participant Name (Please print)

_____________________________________ Date: ____________________

Signature of Person who explained this study

Appendix C: List of Interviews and Interviewee Institutions

Table 1 presents a chronological list of the interviews we conducted, as well as the institution of the interviewee. We would like to extend our thanks to everyone who agreed to meet with us and who provided valuable answers to our inquiries.

Table 2: Chronological List of Interviews and Interviewee Institutions

Name	Institution	Date of Interview
Dr. Jae Hoon Sim	Universitätsspital Zürich	9/13/2022
Dr. Flruin Pfiffner	Universitätsspital Zürich	9/13/2022
Florentin Liebmann	Balgrist University Hospital	9/19/2022
Marco von Atzigen	Balgrist University Hospital	9/19/2022
Matthias Seibold	Balgrist University Hospital	9/19/2022
Prof. Dr. Christof Roosli	Universitätsspital Zürich	9/22/2022
Dr. Fabio Carrillo	Balgrist University Hospital	9/30/2022
Dr. Lorenz Epprecht	Universitätsspital Zürich	10/3/2022
Sören Kottner	Institute of Forensic Medicine	10/6/2022
Dominic Gascho	Institute of Forensic Medicine	10/6/2022
Dr. Laurent Simon	Sonova (previously Universitätsspital Zürich)	10/7/2022

Dr. Ivo Dobrev	Universitätsspital Zürich	(multiple days of interaction, no structured interview)
Merlin Schär	Universitätsspital Zürich	(multiple days of interaction, no structured interview)

Appendix D: Switzerland's Medical Culture and Our Sponsor

Switzerland is a well-renowned medical hub with world-class research and some of the highest healthcare quality in the world (Roy, 2021). Notably, 2.6% of Switzerland's GDP comes from its medical technology sector (Brussels Research Group, 2021). The country also spends the most money on pharmaceutical research per capita in the entire world (Roy, 2021). The Universitätsspital Zürich is both a medical and a research institution with access to unique resources that allow it to be a force in medical research. USZ has a particular interest in staying on top of both current research and technological breakthroughs. Our sponsor, the Biomechanics of Hearing research group based at the Universitätsspital Zürich, does projects researching hearing and, from that research, develops diagnostics, therapy, and prostheses for correcting disorders of the ear. They have sponsored several other IQP projects, the most recent ones being "The Role of the "Internet of Things" in Hearing Research and Clinical Otology" in 2021 and "Use of AI in Otology" in 2020. AR is currently rising in popularity as technological development enables more powerful AR applications. However, within the domain of otology, there is little to no AR technology being applied. Our sponsor wants us to know how AR can be applied in an otologic setting, whether that is in surgery or research.

Appendix E: Table of Relevant Terms

Table 3: Table of Abbreviations and Relevant Terms

Term	Abbreviation	Definition
Augmented Reality	AR	See here
Cochlear Implant	N/A	A surgical implant inserted into the cochlea (inside the ear) to help treat hearing loss
Computerized Tomography	CT	A series of x-ray pictures that are combined to get pictures of the body
Cone Beam Computed Tomography	CBCT	A radiographic imaging system that allows for a 3D image of hard tissue structure
Cranial Base	N/A	The most inferior (back) area of the skull
Endoscope	N/A	A small thin tube with a camera attached that is used to look inside the body
Eear, nose, throat (Otorhinolaryngology) (otolaryngologist)	ENT	A field of medicine that deals with conditions of the head and neck
Fiducial Markers	N/A	An object or marker that is placed in or on the body of a patient to be used by a medical system to be used as a spatial reference
Head-Mounted Display	HMD	A display worn on your head
Hepatobiliary	N/A	Study of the liver, bile ducts, and gallbladder
Image-Guided Therapies	N/A	Using medical imaging to assist, guide, and evaluate surgical procedures
Intraoperative Navigation	IN	Systems that provide guidance or navigation during operation
Magnetic Resonance Imaging	MRI	A medical imaging technique utilizing magnetic fields and radio waves to create detailed images tissues and organs in the body
Microsoft HoloLens™	HoloLens	An AR system developed by Microsoft consisting of a head-mounted display and many sensors.
Navigational Guides	N/A	See here
Neurology	N/A	Study of the nervous system which consists of the brain and spinal cord
Open Computer Vision	OpenCV	Library of computer vision algorithms
Orthopedic	N/A	Study of the musculoskeletal system which consists of bones, muscles, joints, cartilage, tendons, ligaments, and connective tissue

Otology	N/A	The study of the ear's anatomy and its diseases
Simultaneous Location and Mapping	SLAM	A machine learning technique that allows the user to map an unknown environment
Subdermal	N/A	Beneath the skin
Virtual Reality	VR	A type of technology that uses computer-generated scenes to completely replace the user's perception with a virtual scene.
Visual Oriented Augmented Reality	VOAR	See here
Vestibular Schwannoma Tumors	VS	A tumor that is found on the main nerve leading from the inner ear to the brain