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Augmented Reality in Otology/Neurotology: A Scoping Review with Implications for Practice and Education

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Abstract

Objective: To determine how augmented reality (AR) has been applied to the field of otology/neurotology, examine trends and gaps in research, and provide an assessment of the future potential of this technology within surgical practice and education.

Data sources: PubMed, EMBASE, and Cochrane Library were assessed from their inceptions through November 2021. A manual bibliography search was also conducted.

Review methods: A scoping review was conducted according to PRISMA-ScR guidelines. Data from studies describing the application of AR to the field of otology/neurotology were evaluated, according to *a priori* inclusion/exclusion criteria. Exclusion criteria included non-English language articles, abstracts, letters/commentaries, conference papers, and review articles.

Results: Eighteen articles covering a diverse range of AR platforms were included. Publication dates spanned from 2007 to 2022 and the rate of publication increased over this time. Six of 18 studies were case series in human patients while the remaining were proof of concepts in cadaveric/artificial/animal models. The most common application of AR was for surgical navigation (14 of 18 studies). Computed tomography was the most common source of input data. Few studies noted potential applications to surgical training.

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Conclusion: Interest in the application of AR to otology/neurotology is growing based on the number of recent publications that use a broad range of hardware, software, and AR platforms. Large gaps in research such as the need for submillimeter registration error must be addressed prior to adoption in the operating room and for educational purposes.

Lay reader summary:

Augmented reality technology has the potential to change the future practice of otology/neurotology and improve how we teach trainees to do complex ear surgeries. We performed a scoping review to describe the current state of this research and identify gaps in knowledge.

Keywords

extended reality; mixed reality; otolaryngology; surgical simulation; surgical training; resident education; surgical navigation; anatomy curriculum; presurgical planning

Introduction

Augmented reality (AR) is a term that encompasses any method to impose computer generated graphics, sound, or other sensory stimuli onto a user’s experience of a real-life environment. Unlike virtual reality where the entire experience is digitally rendered, AR overlays digital information onto real-world elements, keeping the real world central to the experience while enhancing it with new layers of perception or information. Common technologies used in AR include tools such as cameras, monitors, headphones, and/or smart glasses. Prominent examples of AR include the Google Glass smartglasses that allowed users to check their email while looking ahead through the lenses or the popular smartphone game Pokémon GO. Emerging applications of AR have the potential to change the nature of procedural activities in all aspects of society, from assisting car drivers[1] to teaching skilled trades[2] to promoting real estate sales.[3] Using AR in surgery and surgical education is a natural extension of these applications.

In otolaryngology, initial forays into AR have primarily been built upon existing surgical navigation technologies[4] using commercially available platforms such as the Microsoft HoloLens 2 (pictured for reference in Figure 1). Because existing surgical navigation tools are most accurate when applied to fixed bony anatomy as compared to deformable soft tissue landmarks, AR will likely be most transformative for specialties that primarily operate on bony structures in its early stages. Therefore, otology/neurotology, a specialty centered on the temporal bone and lateral skull base, may be especially well suited to the application of AR.

Beyond its direct use in the operating room, AR has the potential to transform the way we teach anatomy and operative techniques in otology/neurotology. Surveys of program directors and graduates of otolaryngology residency training programs,[5] as well as quantitative longitudinal studies of resident intraoperative experiences,[6,7] indicate that otology procedures rank among the most difficult for trainees to master. Possible barriers to teaching these procedures include the complex three-dimensional anatomy, its single-operator nature of the surgeries, the intrinsic difficulty of microsurgery and the relative rarity of certain disease processes. All of these factors can result in limited trainee exposure to and autonomy in complex cases.[8]

The classic model of surgical training is a skills apprenticeship, whereby trainees spend time with mentors in and out of the operating room, gradually gaining autonomy until they are ready for independent practice. However, in the face of the modern pressures of surgical training, including a greater emphasis on surgeon/hospital productivity and patient safety,[9,10] a purely apprenticeship-based model is no longer an efficient way to train residents. The concept of cognitive apprenticeships, where deliberate thinking is modeled out loud by expert surgeons to formally articulate how perioperative and surgical decisions are made, is a strategy to accelerate the current surgical training paradigm.[11] However, most surgical educators are not trained to provide instruction in the cognitive apprenticeship model. Additionally, there may be limited opportunities for repetition and reinforcement of teaching in the operating room for more advanced skills or skills related to rare diseases in otology/neurotology.

Due to these challenges, simulation is playing a growing role in surgical education. Surgical simulation fulfills many of the needs of adult learners as it allows for self-directed, problem-based learning. One way that AR can improve surgical simulation is through creating realistic learning environments that facilitate transference of skills into the operating room.[12] Additionally, AR technology may one day be able to offer direct feedback to trainees to guide their deliberate practice and improve the cognitive apprenticeship of surgical training.

Therefore, as AR may significantly impact the future practice of otology/neurotology and improve how we educate trainees in this field, we herein perform a scoping review for the application of AR to this specialty. The most recent systematic review of AR in the field of otolaryngology was published in 2018,[4] but since then, many more papers have appeared in the literature specifically regarding its application to otology/neurotology. We aim to describe the current state of AR in otology/neurotology, identify gaps in research, and discuss future areas of application in the operating room and in surgical education.

Methods

A review of the literature was performed and the results were reported following the 2020 PRISMA-ScR guidelines.[13] A search was performed on October 5th, 2022 in PubMed, EMBASE and Cochrane Library. No time limits were applied. The objective was to identify all publications related to AR in the field of otology/neurotology. For database searches, terms were selected to create a broad search with two strings combined with the Boolean term AND, searched in all fields. The strings used were (“augmented reality”) and (otolaryngology OR ENT OR otorhinolaryngology OR otology OR ear OR “skull base” OR neurotology OR mastoid OR mastoidectomy OR “temporal bone”). Results were imported into Covidence (Melbourne, Australia) to conduct the comprehensive title, abstract and full article review. Inclusion criteria included articles that reported the application of AR to the field of otology/neurotology. Exclusion criteria included non-English articles, fields of application other than otology/neurotology, letters, commentaries, abstracts, conference presentations, book chapters, and secondary sources of data (e.g., review articles). Reference lists from criteria-meeting publications and the most recent systematic review on AR in otolaryngology[4] were manually searched for additional studies, yielding additional potential articles. The search was conducted by authors JXC and SY, and differences were resolved with consensus between reviewers.

A data-charting table was developed by four authors (JXC, SY, ASD, FXD). Information from each included article was extracted by two authors (SY, ASD) and the extraction was verified by a third author (JXC, conferring with FXC). Extracted study data described level of evidence, subjects, specific AR applications, and funding sources. Level of evidence was defined as follows (informed by the Oxford Centre for Evidence-based Medicine 2011 categories):[14] 1, randomized controlled trials or observational study with dramatic effect; 2, non-randomized controlled cohort/follow-up study; 3, case-series, case-control studies, or historically controlled studies in humans ; 4, proof of concepts in a non-organic, cadaveric, or animal model with mechanism-based reasoning. For each AR platform, the following data were extracted: the data inputs and display outputs, specialized hardware/software, registration techniques, and the registration errors, if stated. Descriptive statistics were used to examine the findings of included papers.

Results

Electronic database searches returned 336 titles. One hundred and twenty-one duplicates were removed, and 179 articles were excluded after titles and abstracts were screened according to the aforementioned a priori inclusion and exclusion criteria. Thirty-six full text articles were initially reviewed and 19 excluded: 13 were poster or oral presentations, 6 were not original studies of AR in otology/neurotology. Manual search of included articles' references lists as well as the most recent systematic review of AR in otolaryngology[4] revealed 4 additional potential titles of which 2 were excluded, as they were book chapters, and one was excluded, as it did not apply AR technology. From the manual search, one article was therefore added to the list of extracted papers resulting in 18 total papers. Figure 2 details the stages of article search, including the articles from the manual bibliography review.

Table 1 summarizes the characteristics of the 18 studies included in this review.[15–32] Publication years ranged from 2007 to 2022, with an increasing number of publications in recent years (Figure 3). Most papers were published in the past three years, from 2020 to 2022. Six of 18 studies were case series in human patients, while the remainder were proof of concept experiments in cadaveric, phantom/artificial human temporal bones, or animal models. The most common use of AR was for surgical navigation (n=14). Less common applications included using AR to assist in preoperative planning (n=2), clinical diagnosis (n=2), directly treat patients for vestibular disease (n=1) and conduct surgical training/assessments (n=1). Funding sources for studies were varied, ranging from non-profit/government funding to industry sponsors.

Table 2 summarizes the technical specifications of the AR platforms described in studies. Commonly cited hardware used included operating microscopes, video cameras, endoscopes, beam splitters, computers and other proprietary equipment from specific existing surgical navigation systems. Each study had its own self-designed software package. Input data came from computed tomography (CT) and magnetic resonance imaging (MRI) scans, as well as real time recordings from glasses, video cameras or microscopes. Outputs included AR headsets, surgical microscopes, and endoscopic monitors. A few common headsets include various proprietary smartglasses (i.e., head mounted wearable devices that bring a display in front of the eyes to present data) such as HoloLens (Microsoft; Redmond, WA). Registration was accomplished through surface matching, fiducial markers or paired points. Registration accuracy was reported in 12 of 18 studies. Among those that reported registration errors, fiducial registration errors ranged from 0.21mm[25] to 0.84mm[23] and target registration errors ranged from 0.31mm[26] to 10.62mm.[24]

Only one study directly applied AR to surgical training. Yong et al. used smartglasses in the temporal bone lab with residents to practice microsurgical skills on cadaveric specimens.[28] Surgical supervisors could see the trainees' field of view from the smartglasses in a different room and give real-time feedback using audio, text and annotated still images taken with the glasses. Retrospective surveys of participants found that both groups enjoyed the ability to communicate remotely. However, there were significant limitations to using these smartglasses such as the inability to use the operating microscope with the glasses in place.

Discussion

The application of AR to otology/neurotology is a relatively new field of research, with 18 relevant papers identified in this scoping review. Many new papers have been published in the field of otology/neurotology since the most recent systematic review on AR in otolaryngology from 2018, which included fewer than half the studies identified in this review.[4] Among included papers, the vast majority describe applications to surgical navigation in the operating room. Few studies discuss the potential future use of this technology for surgical education. A variety of hardware, software, and AR platforms are currently being explored with a large range of registration accuracies reported from different research groups. All studies offer low levels of evidence, representing primarily small case series in patients or proof of concept studies in the lab. The low levels of evidence represented in these studies results in a significant risk for reporting bias. Additionally, papers reporting funding from private industry sources may have been affected by sponsorship bias.

Barriers to adoption in the field of otology/neurotology

A primary barrier to adoption of AR in otology/neurotology is the lack of high-quality studies. For example, for direct-to-patient applications, there are no cohort trials to determine the long-term benefits and side effects of these techniques on treating otologic disorders in comparison to standard of care. For surgical applications, there are no randomized controlled trials to determine if various platforms of AR (whether used for preoperative planning or intraoperative navigation) improve surgical efficiency/outcomes, decrease surgical complications, or decrease surgical difficulty for specific procedures. The absence of studies with higher levels of evidence found in this scoping review, combined with the large variety of hardware and software represented across studies, suggests that there are substantial technical challenges that still must be overcome before AR can be applied to the field.

Several technical challenges can be readily identified in this scoping review. Firstly, while current AR technology may already be useful for surgical navigation in fields such as general surgery or orthopedics, the level of registration accuracy needed in neurotologic surgery is a substantial barrier to its clinical implementation. Existing AR technology that involves head mounted displays do not yet have submillimeter target registration accuracy in routine usage conditions and AR microscope overlays similarly lack high accuracy three-dimensional registration.[24] While some papers in the literature report submillimeter target registration errors,[19,33,26,31,32] many papers either do not present enough information in their methods to determine the source of error measurements or measure only one of many possible sources of error. Some studies have been able to reduce registration error by placing an optical tracking probe in the field but this can be limiting in a surgical setting.[22]

Secondly, many of these studies describe methods that require significant manual labor in setting up the systems, which is not sustainable for large scale application. For example, manual segmentation of the input data (i.e., temporal bone imaging) is often required to identify critical anatomical structures to highlight during surgery. To improve the scalability of AR in the operating room, novel methods for fully automated segmentation of temporal bone CT scans to identify key anatomical structures have recently been described.[34–36] Similar advances in these technical components may decrease the overall technical and logistical barriers to large-scale adoption of AR in otology and neurotology.

Thirdly, as described in this scoping review, the published studies describe a wide range of AR software and hardware requirements for neurotologic applications, making it difficult for advances in one lab to rapidly translate into further developments in others. Furthermore, there remain unsolved challenges to displaying depth to users through most of the existing AR displays, which will be critical for neurotologic surgeries. This is not just a limitation in our field, but one that has been acknowledged as a major barrier for any surgical application of AR.[37]

Finally, there is at least one possible deleterious effect of using AR for advanced surgical navigation: sensory overstimulation in an AR environment may have a negative effect on surgeon attention during the procedure, which can cause the surgeon to miss unexpected findings due to “inattentional blindness”. One study of AR in endoscopic anterior skull base surgery performed in cadaveric specimens by surgeons and trainees found that 0 of 15 participants identified a pre-dissected critical complication (optic nerve transection) in the AR group compared to 7 of 17 in the control group.[38] Similarly, only 1 of 15 AR users detected a foreign body in the surgical field compared with 7 of 17 in the control group. This is a serious risk of AR technology that warrants careful study of different display designs to balance any gains in surgical accuracy and efficiency with the attentional costs of AR.

Future application to surgical education

This study found a dearth of research on the application of AR to surgical education for otology/neurotology. Education interventions are typically poorly funded; it therefore seems unlikely that the use of AR platforms for educational purposes will be widespread before they are used in the operating room to improve surgical efficiency, medical outcomes, and/or patient safety. Outside of the field of AR, several virtual reality temporal bone surgical simulators have recently been developed for educational purposes.[39,40] While these systems have their own limitations, it is possible that continued interest in this arena will also bring more attention to the educational potential of AR platforms. It is challenging to perform a cost-benefit analysis for educational AR simulation,[41] as it is difficult to weigh the costs of implementing this technology against the possible gains in training efficiency or patient safety. Additionally, the costs of AR need to be compared to the costs of maintaining cadaveric temporal bone labs and recruiting surgical educators. Although this review focused on the use of AR in otology/neurotology whereby virtual images are overlaid upon the real world, some of the included papers use platforms like the Microsoft HoloLens that have mixed reality (MR) capabilities whereby users can also interact directly with the virtual world. MR temporal bone dissection labs could, for example, be an answer to the rising cost and declining access to human cadaveric temporal bones that has become increasingly problematic.[42]

Despite the investment needed to customize AR platforms for otology/neurotology surgical education, it may yield significant returns. First, it has the potential to dramatically improve the fidelity of surgical simulation. Second, combining the auto-segmentation of critical anatomical structures from imaging with artificial intelligence (AI) agents will enable the development of AI coaches for trainees or, at a minimum, the ability for educators to review and critique trainees remotely or asynchronously as most AR approaches allow for video recording. Third, there is a significant shortage of otologists and neurotologists in developing countries,[43,44] and even within certain areas of developed countries.[45] Although it is likely that multiple issues contribute to this disparity, one factor that can exacerbate this problem is limited access to surgical training. Many think-tanks, non-governmental organizations and governmental agencies are already exploring ways to “leapfrog” education technology in underserved areas and developing countries using 5G connections and AR.[46–48] Even without the development of AI coaches, the ability to transmit images of the operative field to a remote supervising surgeon who can give real time feedback (as Yong et al. described[28]) using AR may enable otologists/neurotologists to train surgeons in areas of high need.

Study limitations

There are a few study limitations. First, only English papers were reviewed that explicitly used the words “augmented reality” to refer to their technology, which overlooks publications that use other languages or terminology. Second, the present review only examines papers that explicitly detail the application of AR technology to the field of otology/neurotology. Other publications describing applications in closely related fields like sinus surgery, anterior skull base surgery or neurosurgery could be translated to applications in the lateral skull base and temporal bone. Third, the large heterogeneity of techniques described in the papers made it difficult to perform detailed comparisons of outcomes (e.g., registration accuracy) across studies or to meaningfully estimate the cost of the applying AR systems.

Conclusion

Research into the application of AR in the field of otology/neurotology is growing. The most likely initial application of AR will be to improve surgical navigation, but further investigation is needed to optimize the specifications of AR platforms. Future studies will hopefully provide higher levels of evidence to quantify the risks and benefits of using this technology. Major barriers to adoption are the technical limitations of current AR technology and the logistical complexities of setting it up, which may be improved by automating the steps to AR implementation. Educational applications of AR may follow the operative application of this technology. There is the potential to significantly increase access to otologic/neurotologic surgery in underserved areas of the world by using AR for surgical education.

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References

1. Wintersberger P, Frison AK, Riener A, von Sawitzky T. Fostering User Acceptance and Trust in Fully Automated Vehicles: Evaluating the Potential of Augmented Reality. PRESENCE: Virtual and Augmented Reality. 2019;27(1):46–62. doi:10.1162/pres_a_00320
2. Diao PH, Shih NJ. BIM-Based AR Maintenance System (BARMS) as an Intelligent Instruction Platform for Complex Plumbing Facilities. Applied Sciences. 2019;9(8):1592. doi:10.3390/app9081592
3. Sihi D. Home sweet virtual home: The use of virtual and augmented reality technologies in high involvement purchase decisions. Journal of Research in Interactive Marketing. 2018;12(4):398–417. doi:10.1108/JRIM-01-2018-0019
4. Wong K, Yee HM, Xavier BA, Grillone GA. Applications of Augmented Reality in Otolaryngology: A Systematic Review. Otolaryngol Head Neck Surg. 2018;159(6):956–967. doi:10.1177/0194599818796476 [PubMed: 30126323]
5. Chen JX, Riccardi AC, Shafique N, Gray ST. Are otolaryngology residents ready for independent practice? A survey study. Laryngoscope Investigative Otolaryngology. n/a(n/a). doi:10.1002/lio2.678
6. Chen JX, Kozin ED, Bohnen JD, George BC, Deschler D, Emerick K, Gray ST. Assessments of otolaryngology resident operative experiences using mobile technology: a pilot study. Otolaryngol Head Neck Surg. 2019;161(5):939–945. doi:10.1177/0194599819868165 [PubMed: 31405355]
7. Chen JX, Deng F, Filimonov A, Shuman EA, Marchiano E, George BC, Thorne M, Pletcher SD, Platt M, Teng MS, Kozin ED, Gray ST. Multi-institutional Study of Otolaryngology Resident Intraoperative Experiences for Key Indicator Procedures. Otolaryngol Head Neck Surg. Published online October 5, 2021:01945998211050350. doi:10.1177/01945998211050350
8. Totten DJ, Marinelli JP, Spear SA, Bowe SN, Carlson ML. With the Incidence of Otosclerosis Declining, Should Stapedectomy Remain a Key-Indicator Case for Otolaryngology Residents?

Otolaryngol Head Neck Surg. 2020;163(6):1070–1072. doi:10.1177/0194599820941836 [PubMed: 32689881]

9. Chen JX, Kozin E, Bohnen J, George B, Deschler D, Emerick K, Gray ST. Tracking operative autonomy and performance in otolaryngology training using smartphone technology: A single institution pilot study. Laryngoscope Investigative Otolaryngology. 2019;4(6):578–586. doi:10.1002/lio2.323 [PubMed: 31890874]
10. Elfenbein DM. Confidence Crisis Among General Surgery Residents: A Systematic Review and Qualitative Discourse Analysis. JAMA Surg. 2016;151(12):1166–1175. doi:10.1001/jamasurg.2016.2792 [PubMed: 27603429]
11. Merriam SB, Bierema LL. Adult Learning : Linking Theory and Practice. John Wiley & Sons, Incorporated; 2013.
12. Kovoor JG, Gupta AK, Gladman MA. Validity and effectiveness of augmented reality in surgical education: A systematic review. Surgery. 2021;170(1):88–98. doi:10.1016/j.surg.2021.01.051 [PubMed: 33744003]
13. Tricco AC, Lillie E, Zarin W, O’Brien KK, Colquhoun H, Levac D, Moher D, Peters MDJ, Horsley T, Weeks L, Hempel S, Akl EA, Chang C, McGowan J, Stewart L, Hartling L, Aldcroft A, Wilson MG, Garritty C, Lewin S, Godfrey CM, Macdonald MT, Langlois EV, Soares-Weiser K, Moriarty J, Clifford T, Tunçalp Ö, Straus SE. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018;169(7):467–473. doi:10.7326/M18-0850 [PubMed: 30178033]
14. OCEBM Levels of Evidence Working Group. The Oxford 2011 Levels of Evidence. Accessed October 23, 2022. http://www.cebm.net/index.aspx?o=5653
15. Caversaccio M, Langlotz F, Nolte LP, Häusler R. Impact of a self-developed planning and self-constructed navigation system on skull base surgery: 10 Years experience. Acta Oto-Laryngol. 2007;127(4):403–407. doi:10.1080/00016480601002104
16. Pothier DD, Hughes C, Dillon W, Ranalli PJ, Rutka JA. The use of real-time image stabilization and augmented reality eyewear in the treatment of oscillopsia. Otolaryngol Head Neck Surg. 2012;146(6):966–971. doi:10.1177/0194599811434708 [PubMed: 22261498]
17. Liu WP, Azizian M, Sorger J, Taylor RH, Reilly BK, Cleary K, Preciado D. Cadaveric feasibility study of da Vinci Si-assisted cochlear implant with augmented visual navigation for otologic surgery. JAMA Otolaryngol Head Neck Surg. 2014;140(3):208–214. doi:10.1001/jamaoto.2013.6443 [PubMed: 24457635]
18. Cho NH, Jang JH, Jung W, Kim J. In vivo imaging of middle-ear and inner-ear microstructures of a mouse guided by SD-OCT combined with a surgical microscope. Opt Express. 2014;22(8):8985–8995. doi:10.1364/OE.22.008985 [PubMed: 24787787]
19. Marroquin R, Lalande A, Hussain R, Guigou C, Grayeli AB. Augmented Reality of the Middle Ear Combining Otoendoscopy and Temporal Bone Computed Tomography. Otol Neurotol. 2018;39(8):931–939. doi:10.1097/MAO.0000000000001922 [PubMed: 30113553]
20. Barber SR, Jain S, Son YJ, Chang EH. Virtual Functional Endoscopic Sinus Surgery Simulation with 3D-Printed Models for Mixed-Reality Nasal Endoscopy. Otolaryngol Head Neck Surg. 2018;159(5):933–937. doi:10.1177/0194599818797586 [PubMed: 30200812]
21. Lee J, Wijesinghe RE, Jeon D, Kim P, Choung YH, Jang JH, Jeon M, Kim J. Clinical Utility of Intraoperative Tympanomastoidectomy Assessment Using a Surgical Microscope Integrated with an Optical Coherence Tomography. Sci Rep. 2018;8(1):17432. doi:10.1038/s41598-018-35563-5 [PubMed: 30479360]
22. McJunkin JL, Jiramongkolchai P, Chung W, Southworth M, Durakovic N, Buchman CA, Silva JR. Development of a Mixed Reality Platform for Lateral Skull Base Anatomy. Otol Neurotol. 2018;39(10):e1137–e1142. doi:10.1097/MAO.0000000000001995 [PubMed: 30239435]
23. Bárdosi Z, Plattner C, Özbek Y, Hofmann T, Milosavljevic S, Schartinger V, Freysinger W. CIGuide: in situ augmented reality laser guidance. Int J Comput Assisted Radiol Surg. 2020;15(1):49–57. doi:10.1007/s11548-019-02066-1
24. Creighton FX, Unberath M, Song T, Zhao Z, Armand M, Carey J. Early Feasibility Studies of Augmented Reality Navigation for Lateral Skull Base Surgery. Otol Neurotol. 2020;41(7):883–888. doi:10.1097/MAO.0000000000002724 [PubMed: 32569148]

25. Hussain R, Lalande A, Marroquin R, Guigou C, Bozorg Grayeli A. Video-based augmented reality combining CT-scan and instrument position data to microscope view in middle ear surgery. Sci Rep. 2020;10(1):6767. doi:10.1038/s41598-020-63839-2 [PubMed: 32317726]

26. Hussain R, Lalande A, Berihu Girum K, Guigou C, Grayeli AB. Augmented reality for inner ear procedures: visualization of the cochlear central axis in microscopic videos. Int J Comput Assisted Radiol Surg. 2020;15(10):1703–1711. doi:10.1007/s11548-020-02240-w

27. Tian X, Gao ZQ, Zhang ZH, Chen Y, Zhao Y, Feng GD. Validation and Precision of Mixed Reality Technology in Baha Attract Implant Surgery. Otol Neurotol. 2020;41(9):1280–1287. doi:10.1097/MAO.0000000000002749 [PubMed: 32925861]

28. Yong M, Pauwels J, Kozak FK, Chadha NK. Application of augmented reality to surgical practice: A pilot study using the ODG R7 Smartglasses. Clin Otolaryngol. 2020;45(1):130–134. doi:10.1111/coa.13460 [PubMed: 31610087]

29. Leuze C, Neves C, Gomez AM, Daniel BL, Navab N, Blevins NH, Yona V, McNab JA. Augmented reality guided retrosigmoid approach. J Neurol Surg Part B Skull Base. 2021;82(SUPPL 2). doi:10.1055/s-0041-1725268

30. Schwam ZG, Kaul VF, Bu DD, Iloreta AMC, Bederson JB, Perez E, Cosetti MK, Wanna GB. The utility of augmented reality in lateral skull base surgery: A preliminary report. Am J Otolaryngol Head Neck Med Surg. 2021;42(4). doi:10.1016/j.amjoto.2021.102942

31. Guigou C, Hussain R, Lalande A, Bozorg Grayeli A. Augmented Reality Based Transmodiolar Cochlear Implantation. Otol Neurotol. 2022;43(2):190–198. doi:10.1097/MAO.0000000000003437 [PubMed: 34855687]

32. Hussain R, Guigou C, Lalande A, Bozorg Grayeli A. Vision-Based Augmented Reality System for Middle Ear Surgery: Evaluation in Operating Room Environment. Otol Neurotol. 2022;43(3):385–394. doi:10.1097/MAO.0000000000003441 [PubMed: 34889824]

33. Condino S, Turini G, Parchi PD, Viglialoro RM, Piolanti N, Gesi M, Ferrari M, Ferrari V. How to Build a Patient-Specific Hybrid Simulator for Orthopaedic Open Surgery: Benefits and Limits of Mixed-Reality Using the Microsoft HoloLens. Journal of Healthcare Engineering. 2018;2018:e5435097. doi:10.1155/2018/5435097

34. Ding AS, Lu A, Li Z, Galaiya D, Siewerdsen JH, Taylor RH, Creighton FX. Automated Registration-Based Temporal Bone Computed Tomography Segmentation for Applications in Neurotologic Surgery. Otolaryngol Head Neck Surg. Published online September 7, 2021:01945998211044982. doi:10.1177/01945998211044982

35. Neves CA, Tran ED, Kessler IM, Blevins NH. Fully automated preoperative segmentation of temporal bone structures from clinical CT scans. Sci Rep. 2021;11(1):116. doi:10.1038/s41598-020-80619-0 [PubMed: 33420386]

36. Neves CA, Tran ED, Blevins NH, Hwang PH. Deep learning automated segmentation of middle skull-base structures for enhanced navigation. International Forum of Allergy & Rhinology. 2021;11(12):1694–1697. doi:10.1002/alr.22856 [PubMed: 34185969]

37. Sielhorst T, Bichlmeier C, Heining SM, Navab N. Depth perception--a major issue in medical AR: evaluation study by twenty surgeons. Med Image Comput Comput Assist Interv. 2006;9(Pt 1):364–372. doi:10.1007/11866565_45

38. Dixon BJ, Daly MJ, Chan HHL, Vescan A, Witterick IJ, Irish JC. Inattentional blindness increased with augmented reality surgical navigation. Am J Rhinol Allergy. 2014;28(5):433–437. doi:10.2500/ajra.2014.28.4067 [PubMed: 25198032]

39. Varoquier M, Hoffmann CP, Perrenot C, Tran N, Parietti-Winkler C. Construct, Face, and Content Validation on Voxel-Man® Simulator for Otologic Surgical Training. International Journal of Otolaryngology. 2017;2017:e2707690. doi:10.1155/2017/2707690

40. Locketz GD, Lui JT, Chan S, Salisbury K, Dort JC, Youngblood P, Blevins NH. Anatomy-Specific Virtual Reality Simulation in Temporal Bone Dissection: Perceived Utility and Impact on Surgeon Confidence. Otolaryngol Head Neck Surg. 2017;156(6):1142–1149. doi:10.1177/0194599817691474 [PubMed: 28322125]

41. Sheik-Ali S, Edgcombe H, Paton C. Next-generation Virtual and Augmented Reality in Surgical Education: A Narrative Review. Surg Technol Int. 2019;35:27–35. [PubMed: 31498872]

42. Mick PT, Arnoldner C, Mainprize JG, Symons SP, Chen JM. Face validity study of an artificial temporal bone for simulation surgery. Otol Neurotol. 2013;34(7):1305–1310. doi:10.1097/MAO.0b013e3182937af6 [PubMed: 23921940]

43. Salisu AD. Otology practice in a Nigerian tertiary health institution: A 10-year review. Annals of African Medicine. 2010;9(4). Accessed December 9, 2021. https://www.ajol.info/index.php/aam/article/view/67168

44. Mulwafu W, Ensink R, Kuper H, Fagan J. Survey of ENT services in sub-Saharan Africa: little progress between 2009 and 2015. Glob Health Action. 2017;10(1):1289736. doi:10.1080/16549716.2017.1289736

45. Powell W, Jacobs JA, Noble W, Bush ML, Snell-Rood C. Rural Adult Perspectives on Impact of Hearing Loss and Barriers to Care. J Community Health. 2019;44(4):668–674. doi:10.1007/s10900-019-00656-3 [PubMed: 30949965]

46. Istance D, Paniagua A. Learning to Leapfrog: Innovative Pedagogies to Transform Education. Center for Universal Education at The Brookings Institution; 2019. Accessed December 8, 2021. https://eric.ed.gov/?id=ED602937

47. Vegas E, Ziegler L, Zerbino N. How Ed-Tech Can Help Leapfrog Progress in Education. Center for Universal Education at The Brookings Institution; 2019. Accessed December 8, 2021. https://eric.ed.gov/?id=ED602936

48. Dietz AJ. Will Africa leapfrog?: Accelerated development is set to lift the continent’s economies with big implications for financial markets and sustainable development goals. Published online 2021. Accessed December 8, 2021. https://hdl.handle.net/1887/3214560

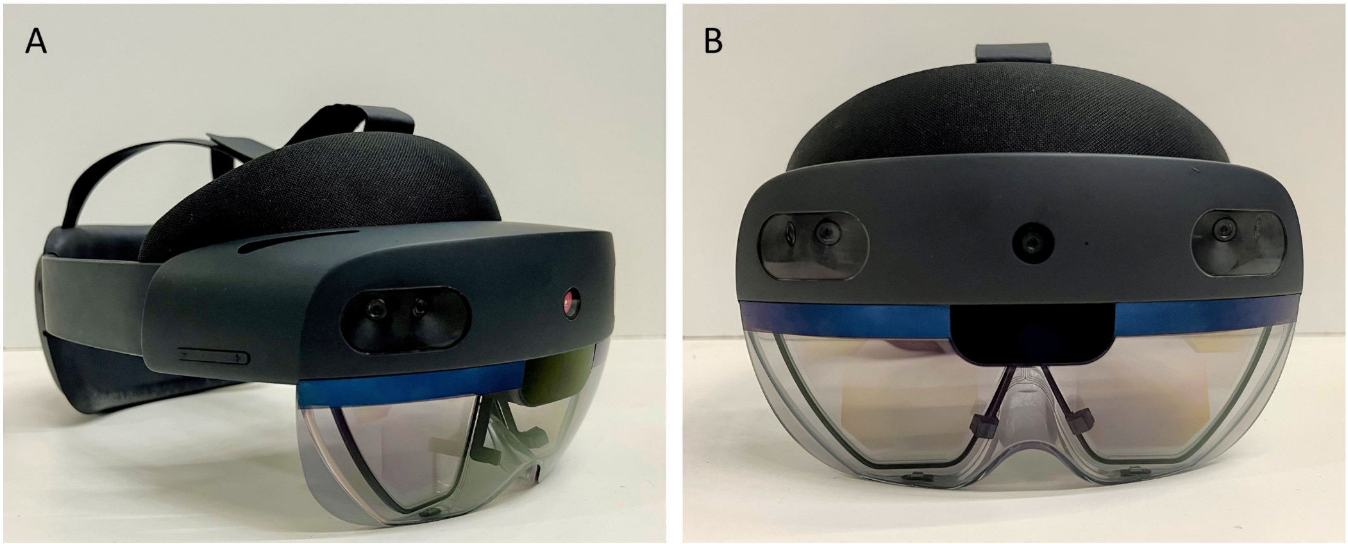

Figure 1.

Example of an augmented reality (AR) headset, the Microsoft HoloLens 2, which the authors have experience using in feasibility studies of AR intraoperative navigation for lateral skull base surgery.[24] The oblique view (A) shows the head strap, the side volume buttons and head tracking cameras (two on each side). The frontal view (B) shows a central RGB camera and a depth camera over a transparent display visor that can be flipped up when not in use. Not pictured internally are the inertial measurement units (accelerometers, gyroscopes, magnetometers) and eye tracking infrared cameras. The headset weighs 556g and can be worn with eyeglasses.

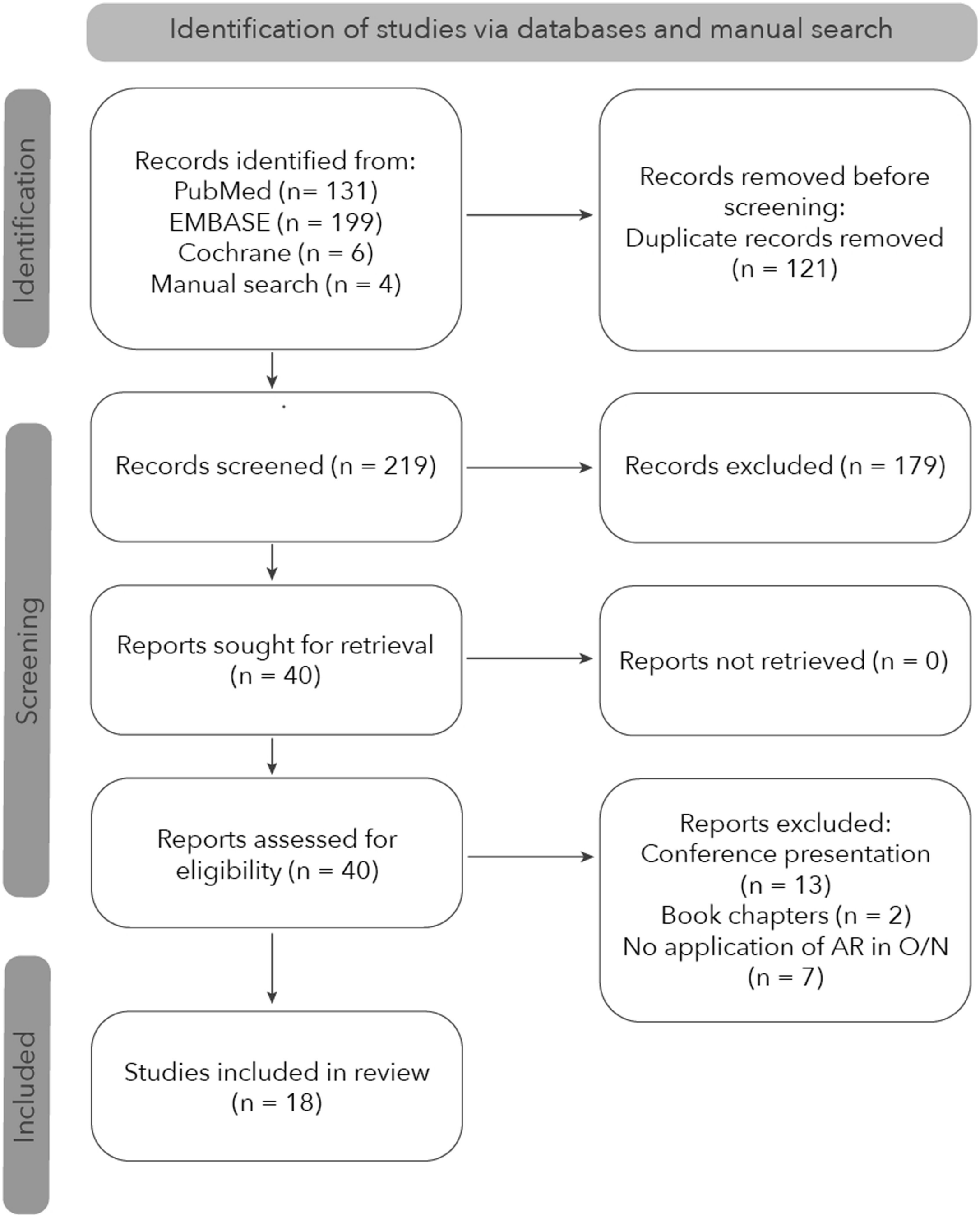

Figure 2.

Flow diagram showing the stages of study identification. Augmented reality, AR; otology/neurotology, O&N.

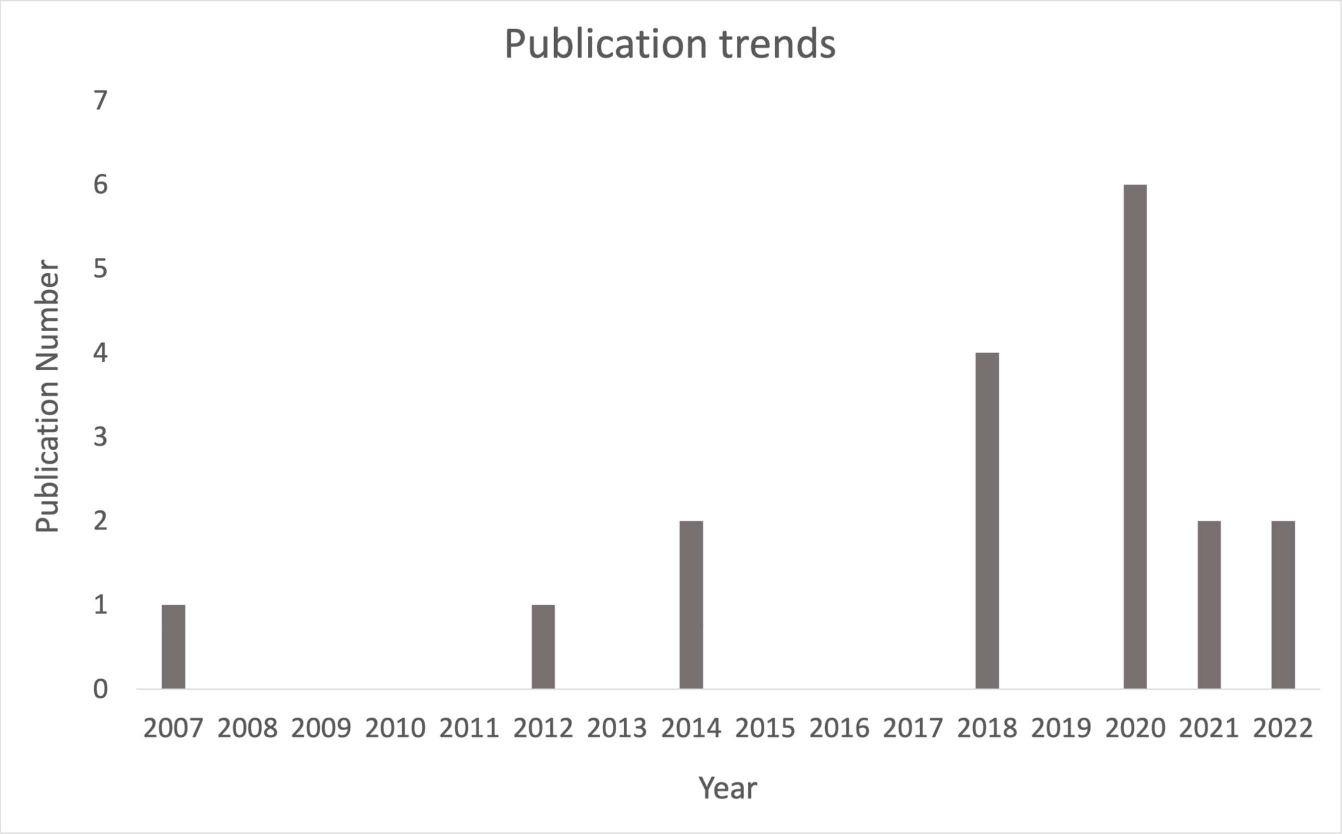

Figure 3.
Publication trends in papers on augmented reality in the field of otology/neurotology.

Table 1.

Study Characteristics

Study	Level of evidence	Application of augmented reality	Study setting	Subject type (Number)	Funding source
Caversaccio et al. 2007[15]	3	Surgical navigation for anterior and lateral skull base cases	Operating room	Patients (406)	-Swiss National Research Foundation
Pothier et al. 2012[16]	3	Glasses to provide real-time image stabilization for patients with bilateral vestibular loss	Clinic	Patients (7)	-Departmental grant
Liu et al. 2014[17]	4	Surgical navigation and intra-operative guidance for robotic cochlear implant surgery	Operating room	Cadaver (1)	-Government of Abu Dhabi -Intuitive Surgical Inc. -Johns Hopkins University internal funds
Cho et al. 2014[18]	4	Clinical diagnosis of otologic conditions and surgical navigation to restore hearing function	Animal surgery lab	Animals (5)	-Korea Ministry of Health & Welfare -Korea Ministry of Trade, Industry & Energy -Korea Institute for Advancement of Technology -National Institutes of Health
Marroquin et al. 2018[19]	4	Surgical navigation for transcanal minimally invasive robot-based procedures	Cadaveric lab	Temporal bones (4)	-Oticon Medical -Société ORL de Bourgogne -Le Centre National de la Recherche Scientifique -Collin Medical SA
Barber et al. 2018[20]	3	Surgical planning for lateral skull base cases	Surgical lab Preoperative planning	3D printed model (1) Patient (1)	None
Lee et al. 2018[21]	3	Improving intraoperative evaluations by extension of the working distance during tympanomastoidectomy	Animal lab Cadaver lab Operating room	Guinea pig (2) Temporal bone (1) Patients (6)	-National Research Foundation, Korea -Ministry of Education, Korea -Ajou University School of Medicine -Korea Institute for Advancement of Technology
McJunkin et al. 2018[22]	4	Surgical navigation for lateral skull base surgery	Cadaveric lab	Temporal bones (NS)	-Washington University in St. Louis School of Engineering and Applied Science Grant
Bárdosi et al. 2020[23]	4	Surgical navigation for lateral skull base surgery	Cadaveric lab	Plastic skull phantom (1) Cadaver (1)	-Austrian Research Funding Agency -Austrian National Bank Jubilee Fund
Creighton et al. 2020[24]	4	Surgical navigation for lateral skull base surgery	Surgical lab	Human temporal bone phantom (1)	Not stated
Hussain et al. 2020a[25]	4	Surgical navigation for keyhole middle ear procedures through a tympanic membrane puncture	Surgical lab	Human temporal bone phantoms (6)	-Oticon Medical
Hussain et al. 2020b[26]	4	Visualizing the cochlear axis to enable transmodiolar cochlear implantation of the auditory nerve	Surgical lab	Human resin temporal bones (8)	-Oticon Medical -NVIDIA

Study	Level of evidence	Application of augmented reality	Study setting	Subject type (Number)	Funding source
Tian et al. 2020[27]	4	Guiding implantation of Baha Attract	Cadaveric lab	Temporal bones (4)	-Beijing Natural Science Foundation Proposed Program
Yong et al. 2020[28]	4	Otologic and microsurgery skills training for residents	Cadaveric lab	Temporal bones (5)	Not stated
Leuze et al. 2021[29]	4	Guiding placement of retrosigmoid craniotomy	Cadaveric lab	Temporal bones (8)	Not stated
Schwam et al. 2021[30]	3	Surgical navigation for lateral skull base surgery	Operating room	Patients (40)	None
Guigou et al. 2022	4	Surgical navigation to identify the cochlear axis for transmodiolar implantation of the auditory nerve	Surgical lab	Human resin temporal bones (8)	-Oticon Medical
Hussain et al. 2022	3	Surgical navigation for transcanal and retro-auricular middle ear procedures	Operating room	Patients (9)	-Oticon Medical

Level of evidence: 1, randomized controlled trials or observational study with dramatic effect; 2, non-randomized controlled cohort/follow-up study; 3, case-series, case-control studies, or historically controlled studies in humans; 4, proof of concepts in a non-organic, cadaveric, or animal model with mechanism-based reasoning

Table 2.

Technology Characteristics

Study	Description of AR platform	Hardware	Software	Input	Output or Display	Tracking	Registration technique	Registration error
Caversaccio et al. 2007[15]	Frameless optically based navigation system (Bernese SurgiGATE ORL Medivision) with overlaid image guidance	-Hardware for the navigation system (infrared based 3D localizer, dynamic reference base, needle pointer, etc.) -Mini-tracker -Operating microscope	VTK or Coin	CT, MRI	Surgical microscope	Optical	Surface matching	Position detection accuracy of 1.1–1.8 mm when using AR
Pothier et al. 2012[16]	VR glasses (iWear VR920) with a compact digital video camera (iWear CamAR)	-iWear VR920 glasses -iWear CamAR	Lucas-Kanade optical stabilization software	Video camera	Eyewear	N/A	Screen capture of video with overlaid key points to stabilize video in real time	NS
Liu et al. 2014[17]	Da Vinci Si with overlaid image guidance	-da Vinci Si system -Custom drill adaptor -Phillips fiducial screws -3D endoscope camera	ITK-Snap for manual segmentation	Cone beam CT	da Vinci Si display	Optical	Fiducials	NS
Cho et al. 2014[18]	Combined an OCT system with a microscope used for intraoperative imaging	-OCT system (complementary metal oxide semiconductor line-scanning camera, superluminescent diode, etc.) -Galvanometer scanner -Operating microscope	Software written in LabVIEW	Live OCT images Microscope video	Surgical microscope	N/A	OCT image is overlaid onto the microscope eyepiece video without registration	NS
Marroquin et al. 2018[19]	Overlaid 3D CT scan reconstructions of the tympanic membrane and middle ear cleft onto recorded otoendoscopic video images	-Otoendoscope -High-definition video camera	-OsiriX virtual endoscopy -Custom OsiriX plugin	CT Otoendoscopy video recordings	Otoendoscope monitor	Multiple methods tested including optical-flow-based and various feature-based methods	Paired points	Mean registration error: 0.25+/− 0.16mm for round window niche; 0.15 +/− 0.32 mm for incus Mean tracking error < 0.15 mm; maximum error < 0.35 mm for round window niche
Barber et al. 2018[20]	AR smartphone application	-Android Smartphone	-ITK Snap -Unity v5.6 -Vuforia	CT	Smartphone screen	NS	N/A	N/A

Study	**Description of AR platform**	**Hardware**	**Software**	**Input**	**Output or Display**	**Tracking**	**Registration technique**	**Registration error**
Lee et al. 2018[21]	Integrated OCT with surgical microscopy	-Beam splitters Surgical microscope -Spectrometer -Computer -OCT	NS	Live OCT images Microscope video	Surgical microscope	NS	NS	NS
McJunkin et al. 2018[22]	Mixed reality head mounted display using HoloLens	-HoloLens -Optitrack camera bar	-ITK Snap -MeshLab - Unity -Visual studio	CT	HoloLens	Optitrack camera bar	Surface registration	Mean TRE for 7 landmarks between 3 observers: 5.76 mm ± 0.54.
Bárdosi et al. 2020[23]	Cochlear implant guide (CIGuide) using a laser beam aligned to the surgical access path and the target (e.g. incus)	-iSYS-1 robot with modified robotic end-effector for laser guidance -Surgical microscope -Rhinospider registration tool -High resolution camera -Dual plate controller and 5D Aurora sensors for laser alignment	CIGuide software	CT	Laser beam into the microscope field of view	Two-step hybrid magnetic-optical control scheme	Fiducials	Mean FRE for cadaver: 0.84 ± 0.13 mm Estimated TRE for cadaveric incus target: 2 mm
Creighton et al. 2020[24]	HoloLens system	-HoloLens -Multi-view stereoscopic infrared depth camera -Inertial measurement unit -Video camera -Waveguide display	-3D Slicer -Software application developed in Unity to upload meshes to HoloLens OST-HMD	CT	HoloLens	HoloLens internal environment	Fiducials	Mean TRE: 10.62 ± 5.90 mm
Hussain et al. 2020a[25]	3D reconstruction of CT imaging registered onto microscope view based on homography transformation	-Micromanipulator -Surgical microscope -High-definition camera	-Osirix's 3D virtual endoscopy function -Custom software developed using OpenCV, Eigen libraries and Ximea API	CT	Surgical microscope	Based on RANdom SAmple Consensus (RANSAC) and Speeded-Up Robust Features (SURF)	Fiducials	Mean FRE: 0.21 ± 0.10 mm Mean TRE: 0.52 ± 0.15 mm
Hussain et al. 2020b[26]	Combines CT imaging with real-time video from microscope, using deep learning architecture to locate landmarks to register the scan	-Stereo microscope -2 high-definition cameras -Computer with dedicated GPU	Deep Q Network	CT Microscope video	Surgical microscope	Based on SURF	Paired points	Mean FRE: 0.28 ± 0.08 mm Mean TRE: 0.31 ± 0.10 mm for the cochlear apex and 15.10 ± 1.28○ for the cochlear axis
Tian et al. 2020[27]	HoloLens system	-HoloLens -Tablet	-Star Atlas mixed reality 3D interaction system	CT or MRI	HoloLens	HoloLens internal environment	Paired points	Median TRE tracking the center of the implant: 2.97 mm in distance and 2.76° in angle

Study	Description of AR platform	Hardware	Software	Input	Output or Display	Tracking	Registration technique	Registration error
			-HoloLens program					
Yong et al. 2020[28]	Osterhout Design Group (ODG) R7 Smartglasses	-ODG R7 Smartglasses -Smartphone	-iOS/Android -Controller App to stream smartglass view	Anatomical still images/ annotations Smartglasses camera	Smartglasses	N/A	NS	NS
Leuze et al. 2021[29]	Magic Leap One head mounted display	-Surgical microscope -Magic Leap One head-mounted display	-Custom application using Unity3D	CT	Magic Leap One display	Magic Leap One internal environment	Fiducials	TRE: Surgeon A, mean 0.6 ± 4.7 mm. Surgeon B, mean 3.7 ± 2.3 mm
Schwam et al. 2021[30]	Surgical Theater (AR system) with a microscope to project landmarks onto the field	-Zeiss microscope -BrainLab Curve image guidance system -Surgical Theater system	NS	MRI	Surgical microscope	NS	NS	NS
Guigou et al 2022	3D reconstruction of CT imaging registered onto microscope view	-Leica microscope with video capture card -iMac desktop computer	-Osirix -Unity	CT	iMac display	Based on SURF	Surface registration with bony landmarks	Mean 2D error: 0.41 ± 0.24 mm Mean entry point error: 0.61 ± 1.00 mm Mean implant angular error: 13.46 ± 8.93°
Hussain et al. 2022	3D reconstruction of CT imaging registered onto microscope view	-Leica microscope with video capture card -iMac desktop computer	-Osirix -Unity	CT	iMac display	Based on SURF	Fiducials	Mean FRE: 0.38 ± 0.23 mm Mean TRE: 0.36 ± 0.15 mm

Augmented reality, AR. Computed tomography, CT. Fiducial Registration Error, FRE. Magnetic Resonance Imaging, MRI. Optical see-through head-mounted display, OST-HMD. Optical Coherence Tomography, OCT. Target Registration Error, TRE. Not Stated, NS. Not applicable, N/A