State of Robotic Mastoidectomy: Literature Review

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Over the past 30 years, the application of robotics in the field of neurotology has grown. Robots are able to perform increasingly complex tasks with ever improving accuracy, allowing them to be used in a broad array of applications. A *mastoidectomy*, in which a drill is used to remove a portion of the mastoid part of the temporal bone at the base of the skull, is one such application. To determine the current state of neurotologic robotics in the specific context of mastoidectomy, a review of the literature was carried out. This qualitative review explores what has been done in this field to date, as well as what has yet to be done. Although the research suggests that robotics can be and has been successfully used to assist with mastoidectomy, it also suggests the incompleteness of robotic development in the field. At present, only 2 robotic systems have been approved by the U.S. Food and Drug Administration for neurosurgical use and the literature lacks evidence of meaningful clinical testing of new systems to change that. The cost of robotics also remains prohibitive. However, strides have been made, with at least 1 robot for mastoidectomy having reached the point of cadaveric trials. In addition, the research suggests some of the characteristics that should be considered when designing robots for mastoidectomy, such as burr size and the type of forces that should be applied. Overall, the outlook for robots in neurotology, particularly mastoidectomy, is bright but some hurdles still remain to be overcome.

Key words
- Craniotomy
- Drills
- Mastoidectomy
- Neurotology
- Otology
- Robotics
- Robots

Abbreviations and Acronyms
CT: Computed tomography

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INTRODUCTION

The use of robotics in neurosurgery offers to improve both surgical precision and operative time. Although the cost of neurosurgical robots is currently prohibitive, technologic advances are bringing costs within a more feasible range. One area, in particular, that could benefit from robotic systems is neurotology, where precision and fine motor control are crucial. This review of the literature focuses on the current state of robotics in neurotology, specifically robotic mastoidectomy. Moreover, we delineate considerations for designing robotic systems that can perform a mastoidectomy on par with or better than a human surgeon.

Mastoidectomy is the surgical removal of part of the temporal bone in the lateral skull base. This procedure creates an entrance into the internal auditory canal to access anatomic structures adjoining the temporal bone.[1] Various approaches are used to perform a mastoidectomy; however, the most commonly used method is the translabyrinthine approach, in which the surgeon enters through the labyrinth within the temporal bone.[2] The translabyrinthine approach has been used to treat a number of conditions including vestibular schwannoma, facial nerve schwannoma, cholesteatoma involving the internal auditory meatus, and Meniere disease with refractory vertigo.[3]

As with any procedure involving the temporal bone, there are significant risks inherent in performing a translabyrinthine mastoidectomy. The temporal bone houses a number of vital anatomic structures, and the mastoid part in particular contains several venous foramina and connects to multiple head muscles. The facial nerve (seventh cranial nerve), which conveys taste sensation for much of the tongue and controls the ability to create facial expressions, runs through the temporal bone including the petrous and mastoid parts and is particularly vulnerable to injury during mastoidectomy.[1] Perhaps in part because of these risks, the mastoidectomy procedure imposes a significant cognitive load on surgeons.[4] This cognitive load may peak at roughly 10% above average during the later and more complex parts of the procedure. The fact that the most difficult elements of the procedure occur when the surgeon may already be mentally fatigued poses even greater risks.[4]

Therefore the precise nature of the mastoidectomy procedure and its high cognitive demands on surgeons underscore the need to develop robotic systems to assist with this surgery. The primary benefits of surgical robots are the abilities to perform more quickly and precisely without suffering excessive mental strain.[5]

To successfully carry out a mastoidectomy, surgeons must also adapt to anatomic variability.[6] Accordingly, techniques have been developed to assist surgeons in successfully navigating an individual patient's anatomy. Neurosurgical navigation has been traditionally done using cumbersome stereotaxic frames.[7] Stereotaxy is an approach in which a flat reproduction is made to feel 3-dimensional—a tactile equivalent to stereoscopy. While most approaches to neuronavigation have remained stereotaxic, the technology has improved significantly. For example, the use of invasive fiducial screws allows for extremely accurate navigation; however, this requires extra procedures for implanting marker screws.[8] Other researchers are studying image-based navigation methods that do not require traditional expensive, invasive techniques,[8] or electromagnetic imaging.[9]

Ultimately, the accuracy of these techniques is determined by their target registration error, which is the difference between the actual location of an anatomic structure and the location suggested by the navigation system. A target registration error of $\leq$2.0 mm is generally considered acceptable for the purposes of neurotology.[10] Researchers suggest that next-generation optical navigation systems may achieve (or at least should aim for) a target registration error of 1.0–1.5 mm.[7] The error involved in robotic drilling includes both the target registration error of the robotic guidance system and the actual error inherent in the robotic drilling. Thus robotic drilling will become more feasible with improvements in the target registration error of navigation systems.

With the increasing feasibility of robotics in neurotology, more studies have focused on what makes these robotic drilling systems practical and workable. Robots have several advantages over human surgeons, such as greater precision and shorter operative times. Yet to become truly viable, these machines must ultimately be able to fully reproduce the techniques employed by successful neurosurgeons. To better elucidate the current state of robotic mastoidectomy, we reviewed the literature to determine what has been done and what still needs to be done for robotic drilling to become standard practice.

METHODS

This review was qualitative in nature, seeking to identify the current progress in mastoidectomy robotics and the most important factors in designing these robotic systems. A literature search was carried out using the PubMed, EMBASE, MedLine, Ovid, and Google Scholar databases. The keywords used in this literature search included skull base, temporal bone, neuronavigation, robotics, mastoidectomy, mastoid surgery, target registration error, translabyrinthine, and appropriate combinations of these terms. To ensure the timeliness and relevance of the literature, all of the articles selected were published within 5 years preceding the review (2013–2017). After the initial search, candidate articles were selected on the basis of the relevancy of the title and abstract and the full text was subsequently examined to further refine the results of the search. Articles that were ultimately included in this review were directly relevant to understanding the current state of robotic mastoidectomy.

RESULTS

The results of the literature review suggest several themes of interest including the pros and cons of robotic systems, the accuracy of neurosurgical robots, and specific considerations for robotic mastoidectomy. Robots have been used in neurosurgery in varying capacities over the past 3 decades. Continual improvements in robotic and guidance systems have enabled robots to carry out increasingly complex tasks with ever greater precision.[5]

Advantages and Disadvantages

The literature highlights a specific set of plusses and minuses of robotics in neurotology. However, it was not possible to identify all of the positive and negative attributes because few robots have reached the stage of clinical trials.[11] Nonetheless, the advantages of robots primarily relate to their speed, precision, and ability to lighten the cognitive load of surgeons.

The various robotic designs that have been developed thus far serve different purposes. Some designs are intended to perform a fully automated mastoidectomy in lieu of a surgeon, whereas others are only designed to carry out part of the procedure or assist a human surgeon. Robotic assistance, such as navigation control systems that prevent a surgeon from overreaching the safe operative area, can improve patient safety and outcomes.[12] In a more general sense, robots are highly precise,[5] although a robot's precision is only 1 aspect of its overall accuracy. After an initial acclimation period, robotic surgery is also generally faster than human surgery,[5] although this is not always the case. The use of partial or full robotic drilling can also serve to lighten a surgeon's cognitive load, which is a significant concern during a mastoidectomy procedure.[4]

The greatest downside of robotics in the neurosurgical context is the cost, a fact supported by the literature[5] and by the paucity of fully developed robotic systems that have reached the phase of clinical testing.[11] Another limitation is that most neurosurgical robots cannot yet replicate the nuanced human approach to drilling, which is often case specific and may require shifts in technique during the course of the procedure.[12] Some work has already been done to identify ways in which mastoidectomy robots can better mirror the techniques employed by human surgeons. Finally, despite the high level of precision, the overall accuracy of robotic drilling may be limited by guidance and navigation systems.

Accuracy of Robotics

The accuracy of a robot used for neurotologic purposes (e.g., for a mastoidectomy) is dictated by 2 factors: accuracy of the robot itself and accuracy of the neuronavigational system that guides the robot. Among 3 notable studies regarding accuracy, 2 addressed the software element of handling error and 1 included the use of invasive fiducial screws for frameless navigation, which is considered the gold standard for optimizing accuracy.[8] Although accurate robots designed to use purely optical navigation would be preferable, these studies demonstrate the type of precision that can be achieved by properly designed and navigated robotic drilling approaches.

The first study by Siebold et al[13] was not directly empirical but instead focused on reducing target registration error from a design perspective. If the target registration provided by the navigation system is used as the true value, then the actual error achieved by the system will directly compound any possible registration error or the inherent error of the robot. Therefore this study carefully