Image-Guided Robotic Skull Base Surgery

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Abstract

Objectives To describe the potential uses of computed tomography image guidance in concert with the surgical robot for skull base surgery.

Design An anatomical study was conducted.

Setting Tertiary academic center.

Participants Cadaveric skull.

Main Outcome Measures The primary outcome measure was to measure the accuracy of robotic arm positioning to anatomical landmarks on a skull using image guidance and the surgical robot synchronously. Instruments with different angles of rotations were used. Estimated systematic error was calculated and compared with achieved errors. Clinical applications of metachronous image guidance and robotic system were discussed.

Results The skull model approximated < 1 mm accuracy using standard image guidance instruments and the 0-degree robotic arm positioning. Increased angles of instruments from 20 to 60 degrees on the robotic system revealed more significant increases in error than estimated.

Conclusions Image guidance may be useful for transoral robotic approaches. Precise movements are improved by limiting the angle of deviation. Future studies will help optimize the combined technologies before validating the study in clinical settings.

Keywords

- image guidance
- robotic surgery
- transoral robotic surgery
- skull base

Introduction

Advances in surgical technology have resulted in more patients with skull base tumors treated with minimally invasive surgical approaches. Traditionally, removal of skull base tumors required sizable incisions to mobilize large amounts of normal tissue. The advent of the expanded endoscopic endonasal approach combined with computer tomography (CT) image guidance modalities have allowed for safe resection of orbital and anterior skull base masses.^{1–3} However, many skull base masses require significant retraction and resection of surrounding tissues that are not ideal for endoscopic resection.

More recently, several studies have been conducted on the development of the transoral robotic surgery (TORS) application to the anterior skull base in preclinical, experimental, canine, and cadaver models.^{4–7} Subsequently, recent case

series on the TORS approach to resect anterior and lateral skull base tumors in patients were reported.^{7,8} There are limitations to robot-assisted surgery in the skull base including no tactile feedback along vital structures (e.g., carotid artery) and restrictions in the design of current robotic instruments. Also, when resecting lesions beyond the mucosal surface, trajectory planning is essential and can be difficult.

The objective of this study was to describe the feasibility of using image guidance in conjunction with the surgical robot for skull base surgery.

Methods

A noncontrast maxillofacial CT of a human skull model was obtained using 1-mm axial sections with multiplanar reconstruction in sagittal and coronal planes. For the

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preclinical skull experiments, standard operating room tables and instrument setup were used (**Fig. 1A**) in two experimental settings. The skull was positioned on a doughnut on the operating table. The CT of the skull was uploaded to the Brainlab navigation system (Brainlab, Inc., Westchester, IL). The Brainlab reference star was affixed to the skull, and the skull was registered according to the manufacturer's instructions. Validation measurements of deviation were acquired by approximating the straight probe to five landmarks (i.e., infraorbital foramen, zygomaticofrontal suture, maxillary spine, infraorbital fissure, and supraorbital foramen) on the external skull and anterior skull base.

Sensors of the Brainlab were attached to the robotic arms of the da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) (**Fig. 1B**) and registered to the platform. Multiple registrations with the reference star to sensors on robotic arms were performed with each different instrument. Measurements of deviation were then taken at the same five anatomical landmarks on the skull using one of four robotic instrument arms (**Fig. 2**) that varied in length from the most distal joint. The surgeon rotated the instrument arms to varying degrees around the distal joint and reapproximated the instrument tips to the set point. The error in distance relative to the set point was acquired at each of the rotated

Fig. 2 Four robotic instruments of different lengths.

positions of the instrument arms. The degree of angulation around the distal joint was also measured.

Results

To quantify the systematic error associated with angulation of the instrument arms in the axial plane, the amount of deviation was measured using each of the instruments of varied lengths at ranging angles of rotation on the skull model system. When each robotic arm is registered, the Brainlab navigation system assumes a fixed distance between the tracker and the distal tip of the instrument (**Fig. 2** and **3**).

Other than the straight probe, the Maryland bipolar forceps was determined to consistently provide the smallest deviation due to short length (14-mm instrument arm or 31.75 mm from articulation) and have the finest instrument tip (**Table 1**). However, the ProGrasp forceps was the longest instrument (19-mm instrument arm or 38.1 mm from articulation) and therefore the most inconsistent. For these reasons, the Maryland bipolar and ProGrasp forceps were measured. The deviation of measured distance from set point (e.g., the supraorbital foramen) was taken (**Table 2**). At a low angle, the Maryland bipolar was found to deviate less (18.67 mm at 33.67 degrees) than the ProGrasp forceps (25.5 mm at 34.5 degrees). Likewise, at a high angle, the Maryland bipolar was still found to deviate less (29.55 mm at 63 degrees) than the ProGrasp forceps (42.25 mm at 61.5 degrees). The measured deviation depends on the ability of the surgical operator to reapproximate the instrument arm to the set point.

Because the instruments on the robotic arms of the da Vinci Surgical System are able to rotate axially at the distal articulation, there is an intrinsic error to the system. The expected error has a direct relationship with the length of the pivot arm and the degree of angulation around the pivot

Fig. 1 (A) Surgical robot and image guidance system positioning relative to the operating room bed. (B) Cadaver skull with attached image guidance reference star and robotic instruments.

Fig. 3 Image guidance view of cadaveric skull. The pointer is directed at the supraorbital foramen.

(► **Fig. 4**). The law of cosines formula may be used for calculating the expected amount of deviation of the instrument tip from the set point with a given degree of angulation of $b^2 = a^2 + a^2 - [2a^2 \cos(A)]$, where b is the length of deviation from the initial set point in the axial plane, a is the length of the instrument arms distal to the arc of rotation, and A is the angle of rotation around the distal articulation. Using this formula, it was determined that the expected error in the axial plane could be reliably predicted (► **Table 1**). Specifically, as the length of the instrument increases, a larger degree of error in the axial plane is expected. The calculated expected

error of the Maryland bipolar was 18.39 mm at 33.67 degrees and 33.00 mm at 63 degrees, whereas the calculated expected error of the ProGrasp forceps was 22.6 mm at 34.5 degrees and 39.00 mm at 61.5 degrees. The measured deviation depends on the ability of the surgical operator to reapproximate the instrument arm to the set point.

However, there is additional error from the set point that is not predicted by the formula. Because the robotic arms can move in three dimensions, the radial rotation is not accounted for. The additional error intrinsic to the system may be determined by calculating percentage error: % Error = (Measured

Table 1 Deviation of measured distance from set point (supraorbital foramen)

	Straight probe	Maryland bipolar forceps	ProGrasp forceps
Instrument length from articulation, mm	–	31.75	38.10
Average deviation (neutral position: 0 degrees), mm	1.02	1.8	1.27
Angle of rotation (low angle), degrees	0	33.67	34.5
Measured deviation (low angle), mm	0.92	18.67	25.5
Expected deviation (low angle), mm	0	18.39	22.6
% Δ error	–	1.47	12.83
Angle of rotation (high angle), degrees	0	63	61.5
Measured deviation (high angle), mm	0.79	29.55	42.25
Expected deviation (high angle), mm	0	33.00	39.00
% Δ error	–	–10.45	8.33

Table 2 Calculated expected deviation for a given angle of rotation

Instrument arm	Length of instrument arm, mm	Angle of rotation, degrees	Deviation from set point, mm
Maryland forceps	14	30	7.2
ProGrasp forceps	19	30	9.8
Maryland forceps	14	70	16
ProGrasp forceps	19	70	27

deviation – Expected deviation)/Expected deviation. Using this formula, the expected deviation for a given angle of rotation was calculated (►Tables 1 and 2). The Maryland bipolar had 1.47% error at a low angle of deviation and –10.45% error at a high angle of deviation, whereas the ProGrasp forceps had 12.83% error at a low angle of deviation and 8.33% error at a high angle of deviation. When considering the additional intrinsic error caused by radial rotation, the amount of error intrinsic to the system increases.

Overall, the skull model system approximated < 1-mm accuracy using standard image guidance instruments and the 0 degrees robotic arm positioning. Increased angles of instruments from 20 to 60 degrees on the robotic system revealed significant increases in error than estimated (►Table 2).

Several issues were encountered for the practical setup of the technologies in a live operative field. Due to the short length of the instruments distal to the insertion point on the robotic arm, the image-guided sensors had to be placed proximal to the instrument holder. This significantly limited the depth of arm insertion transorally. Also, while registering the instrument

arms, the overall length was recognized by the system as too long. Furthermore, when the operating surgeons manipulated the robotic arms from the surgical console, they did not have the ability to see the position of the sensors relative to the optical input. The position of the tracker was frequently turned inward and the direct line of sight to the optical input was obstructed, thus making the robotic arm unrecognizable. Additionally, the CT image for anatomical correlation on the navigation system was not in view from the surgical console, and only the bedside assistant was able to see the image guidance system.

Discussion

Using image guidance in concert with the surgical robot can have many potential uses for operating in the skull base. However, there are restrictions in the current designs of robotic instruments and lack of integration of the two systems.

One of the major advantages of the surgical robot is the ability of its arms to move in three dimensions. However, image guidance inaccuracies are related to the surgeon's movements, the length of the instruments, degree of angulation around the pivot, and the radial movements made. Given current instruments available for the robotic system, our study demonstrated that the expected error can be reliably predicted in the axial plane. As expected, with longer instruments, a larger degree of error is calculated. However, the formula for calculating the expected error in the axial plane underestimates the true error intrinsic to the system. When accounting for radial movements of instruments, the predicted error is further increased.

Furthermore, there are practical issues in setting up the image guidance system with the robotic system in an actual operative case. Most notably, it is difficult to place sensors on the robotic arms in an applied real-world way, and the surgeon cannot observe the navigation system while operating in the surgical console for the robotic system. Therefore, using both systems simultaneously is helpful in obtaining trajectory assessments with the help of the bedside assistant, but it is not practical in guiding the surgeon while operating.

Many of the practical issues may be addressed by integrating the two surgical systems. The difficulty with maintaining a direct line of sight with the optical input could be solved by creating a circumferential tracker that may be attached to the instruments on robotic arms and providing multiple optical inputs around the surgical field. An additional video navigation input in the surgical console will permit the surgeon to view and apply the image guidance system while operating. Integrating image guidance with the robotic surgical system will optimize visualization and may allow for applications to the nasal cavity, orbit, and skull base. Future studies may assess for feasibility, safety, and margins in the surgical management of head and neck diseases.

Conclusions

CT image guidance systems may feasibly be used with the robotic surgical systems. Currently, precise movements are improved by limiting the angle of deviation of instrument tips

Fig. 4 Pictorial representation of the expected deviation.

from the neutral position. Future studies will help optimize the combined technologies before validating the study in clinical settings. Successful merging of technologies will allow optimization of robotic approaches to the nasal cavity, orbit, and skull base.

Notes

Oral presentation at the 23rd Annual North American Skull Base Society Meeting, February 15, 2012, Miami, FL (Abstract 45002).

Conflict of Interest

Adam M. Zanation is a consultant for Intuitive Surgical, Inc. The other authors have no conflicts of interest to disclose.

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