Interactive Image Guidance in Skull Base Surgery Using an Opto-Electronic Device

ABSTRACT—The applicability of an image guidance frameless system based on an opto-electronic sensor device in skull base surgery was explored in this study. Five embalmed heads with external fiducial markers placed in noncoplanar points were scanned (CT scan) and different skull base approaches were reproduced in these specimens. The opto-electronic system is comprised of an infrared camera, a local rigid body, and a 24-light-emitting diode probe attached to different surgical instruments. DOS-based calibration and transformation software and Unix-based surgical planning software were also used. The anatomic landmarks identified during the dissection were matched with the corresponding points derived from computed tomographic (CT) scans. This information allowed the surgeon to develop a three-dimensional representation of the surgical field and to anticipate the next anatomic structure encountered during the dissection. This infrared device operated in real time, is not affected by external factors with regard to its accuracy, and does not interfere with standard neurosurgical techniques. This frameless system is helpful in minimizing the risk of morbidity and provides an accurate guide during the approach, as well as unobstructed access to the surgical field.

A thorough understanding of skull base anatomy and meticulous application of microsurgical techniques are critical to success in resecting skull base tumors. Orientation during surgery that relies exclusively on visual recognition of anatomic landmarks and their three-dimensional (3-D) relationship may hamper the procedure. Intraoperative digitization becomes an interesting refinement for facilitating surgical localization and guiding the surgeon during the dissection.

Image-guided stereotaxis defines the trajectory to the target through the preplanning process,¹ but it poses two problems: it requires a stereotactic frame and does not provide intraoperative real-time localization. Frameless stereotactic systems overcome both

limitations.²⁻⁶ Intraoperative digitization has generated strong interest in skull base and spine surgery because the relative rigidity of the skull base and spine makes these areas particularly amenable to the use of precaptured images to guide surgical procedures.

Our study explored the feasibility and functionality of the real-time intraoperative localization of surgical instruments for different skull base approaches using an opto-electronic sensor device. The purpose of this study was to adapt a laboratory system to the intraoperative environment and standardize the technique that will be used in patients. Important points to be considered are: the placement of the components of the system into the regular OR set-up, the training of the OR team to work

Description of the Position Tracking System

The intraoperative real-time localization was achieved using an opto-electronic system comprised of the following hardware and software components (Fig. 1a, b):

- A camera-bar formed by three lens systems, each one consisting of a sensor and supporting electronics mounted within a 1.1-m long bar. This device measures 3-D positions of markers (Fig. 2a).
- A local rigid body (LRB) plate—an aluminum plate with six light-emitting diodes (LEDs)—that can be attached to any physical body, thus providing a frame of reference which establishes the rela-

tionship between that physical body and the camera space.

- Emitter probes formed by 24 infrared emitting markers mounted in a cylindrical probe that can be attached to surgical instruments (Fig. 2b).
- A system unit which is the central control, interfacing, and processing unit and which handles the sequencing of markers and acts as a link between the computer and the cameras.
- DOS-based calibration and transformation software. This software runs on a PC which is locally networked so that the information of the position of the LEDs is transferred to the SUN workstation.
- The Neurosurgical Planning System (NSPS), a two-dimensional (2D)/(3D) multiuser, multitask Unix-based software was used to process the image data. This software runs on a SUN SPARC2 workstation (Sun Microsystems, Mountain View, CA). It has 160 MB of RAM server memory, 4 GB disk space capable of loading complete imaging data for up to three patients at one time, and GX (or GS)

Figure 1. (a) Intraoperative position tracking system. Components: Infrared camera, local rigid body, 24-emitter probe connected to a surgical tool, system unit, PC-based software, Sun Workstation. (b) Operating room set-up. (A) Infrared camera. (B) LED probe surgical tool. (C) local rigid body. (D) fiducial markers. (E) PC and Sun Workstation.

Figure 2. (a) Infrared camera mounted on special holder that allows horizontal, vertical, and rotational changes in orientation of the camera. (b) 24 LED probe with bayonet attached.

graphics accelerator. This planing system functions by combining and coordinating the output from the following software modules: Patient Database Management module, Projective Image Visualization module, Tomographic Image Visualization module, 3-D Visualization Module, Trajectory Visualization Module, Position Tracking module, and Multi-Modality Visualizer and Image Matching Module. Detailed description of this software was presented elsewhere.⁷

Preoperative

1. Image data acquisition

Five embalmed human heads injected with colored silicone rubber (Dow Corning) were used in this study. Five external fiducial markers consisting of Vitamin D spheres (5-mm diameter) were glued to the skin of each head. These are MRI/CT scan compatible markers, but in this study only CT scan images have been used. CT scans of the heads were performed using the following algorithm: axial slice of 2-mm thickness without gap. The image data were transferred to the workstation through the local network.

2. Surgery Planning

Using the NSPS, the surgical procedure can be simulated, preplanning the surgical steps involved in each procedure.

Intraoperative

The applicability of this localizing frameless system in skull base surgery was studied performing different operative procedures. Transpetrosal, transoral, transphenoidal, and transmaxillary approaches were reproduced in the specimens using surgical instrumentation matching the standard operation room equipment.

Calibration

The cadaver heads previously scanned (CT scan) were fixed to the surgical table with a Mayfield clamp. The local rigid body was attached to the head-holder. The external fiducial markers (vitamin D spheres) were touched with the 24-LEDs probe, and they were matched with their projection in the images. Then the x, y, and z coordinates were assigned to them. After the coordinates for each of the fiducial markers were established, the total transformation is calculated by the system by the following equation^{6,7}:

$$T(I - CT/MRI)_i = T - 1(C - 1)_i \times T(C - P)_i * \\ T(P - F) * T(F - CT/MRI)$$

Once completed, the head-holder, head, and local rigid body can be moved as a unit without needing a new calibration. However, a direct view-line must be maintained between the LEDs, the local rigid body, and the camera to allow continuous monitoring.

Surgical Procedure

The LED probe was attached to bayonet forceps used in the dissection, and the instrument position tracked and displayed in the monitor in real time during all the surgical procedures. At least three LEDs must remain visible to the camera. The system has 3500 Hz/NM (NM = number of markers) frame rate which allows for real-time rigid body reconstruction and display.

The anatomic structures identified during the dissection and the corresponding points in axial, coronal, and sagittal CT scans were simultaneously captured and documented photographically.

RESULTS

Selected anatomic landmarks were identified based on standard neurosurgical anatomy, which helped orient the surgeon. The intraoperative digitization system veri-

fied the instrument position before drilling. Each anatomic structure touched with the tip of the forceps in the cadaver head and the corresponding point in the CT scan were displayed simultaneously in real time in the surgical microscope and computer monitor. Based on these two different sorts of data, the surgeon developed an accurate 3-D visual representation of the surgical field and was able to anticipate the next anatomic structure encountered during the dissection, gaining celerity and safety during the procedure.

Transoral Approach

During the transoral approach, the anterior tubercle of the atlas was identified by palpation and confirmed with the digitization probe in order to place the incision. Along the dissection, the odontoid process, anterior edge of the foramen magnum, lateral masses of C1, occipital condyles, hypoglossal canals, and clivus were visually identified. Concurrently, the tip of our instrument was tracked with the intraoperative digitization system and shown in the computer monitor that displayed the CT scan. The exact position of the carotid arteries, twelfth cranial nerves, inferior petrosal sinus, and vertebral arteries was established in advance. This information was useful to maximize the lateral extension of the removal of the clivus without risking damage to vital structures.

Le Fort I Osteotomy

Using this approach, the clivus and sphenoid sinus were exposed.² Intraoperative localization provided an accurate method of finding the cavernous carotid artery, inferior petrosal sinus, sella turcica, optic canals, and suprasellar structures, thus minimizing the risk of injury to these structures during bone removal.

Anterior Petrosectomy

A subtemporal craniotomy was performed, and the petrous apex removal was planned in the way described by Kawase.^{8,9} The floor of the middle fossa was explored with the LED probe. The foramen spinosum, foramen ovale, and arcuate eminence were identified defining Glasscock's triangle. Using intraoperative digitization, the exact position of the horizontal segment of the petrous carotid artery was confirmed and visualized in reformatted coronal and sagittal reconstruction of the temporal bone. With the forceps attached to the probe, the arcuate eminence and the underlying superior semicircular canal were found. The internal acoustic meatus and the cochlea were localized using the same method prior to drilling the bone overlying them. Their position and orientation in the space was determined beforehand by the surgeon, allowing safe removal of the petrous apex (Fig. 3).

Posterior Petrosal Approach

A retrolabyrinthine presigmoid approach was performed.^{10,11} The spatial relationship of the sigmoid sinus jugular bulb, bony labyrinth, and fallopian canal was established. Intraoperative digitization helped corroborate surgical instrument position during temporal bone dissection. Although the literature provides detailed information about the landmarks to perform this dissection, monitoring the position of the surgical instruments using computer images during the procedure was very useful in preserving hearing structures and facial nerve integrity (Figs. 4, 5).

System Accuracy

Although the purpose of this study was not intended to test the accuracy of this equipment, it is necessary to note the present assumptions regarding this issue. Intraoperative digitization using an infrared system is based on the 3-D motion analysis system (Optotrak 3D Bar, Northern Digital, Waterloo, Canada). Intraoperative real-time localization is achieved by an opto-electronic system with LEDs. The motion of rigid bodies, the skull frame unit, and the tools are tracked by this opto-electronic sensor. The system tracks target points defined by up to 256 miniature LEDs. Its accuracy in locating the spatial position of an LED marker in a volume of 1.0 m × 1.0 m at distance of 2.0 m, as proposed by the manufacturer, is 0.1 mm, with a resolution better than 0.01 mm.

The accuracy of the system was checked during this study, applying the Zamorano-Dujovny localizing Unit (Fischer Instrumentation, Freiburg, Germany) to one of the heads used in this study. The external fiducial markers were also placed in this head, and the algorithm described above was followed to scan this specimen. While performing the surgical dissection, 25 points that served as anatomic landmarks were selected. The stereotactic coordinates (x, y, z) corresponding to these points were determined using the frameless system and the Z-D localizing Unit. Both sets of coordinates for each point were compared. The difference between the data collected from the frameless system and the Z-D localizing unit was less than 2 mm.

Further accuracy studies are presented in detail in other publications.¹²

DISCUSSION

Orientation in intracranial anatomy is a difficult task, particularly in areas such as the skull base which are unfamiliar to many neurosurgeons, or when the anatomic landmarks have been masked by pathology. Image-guided techniques respond to the challenge of

Figure 4. (a) Jugular bulb located with 24 LED probe during dissection. Position of instrument shown on CT scan images. (b) Forceps point to labyrinth; CT scan shows location of forceps. JB: jugular bulb. HSC: horizontal semicircular canal. PSC: posterior semicircular canal. SS: sigmoid sinus. SSC: superior semicircular canal.

accurately localizing lesions or anatomic structures during surgical procedures.¹ Intraoperative localization in the past has required the use of a stereotactic head frame and even stereotactic arc-centered systems specially adapted for open craniotomy, which present the neurosurgeon with a somewhat constrained surgical field.

Frameless stereotaxis allows not only localization in real time for any anatomic structure seen in the pre-captured images but also provides an unobstructed access to the surgical field. Multijoint articulated arms,⁵ sonic digitizers,^{2-4,13} and infrared digitizers⁶ are currently available for this purpose. Testing our localizing system in the laboratory, reproducing operating room conditions, was important to replicate the most appropriate set-up of this instrumentation during surgery, and also to better determine its limitations. The infrared device we have selected operates in real time during instrument tracking. It allows for free handling of instruments, environmental factors do not affect its accuracy, and it does not limit or interfere with patient positioning or standard draping techniques. An unobstructed line of view needs to be maintained between the camera and

the patient at a distance of 2 m to obtain the optimal field of view.

Mobility of intracranial contents after craniotomy is a recognized problem of any image-based neurosurgical localization using precaptured data. The possible alternatives to minimize this problem have been discussed in other reports.¹⁴ This limitation is a less critical problem in skull base surgery than in the removal of intraparenchymal lesions, as the skull base is a bony structure and the vessels, nerves, and hearing organs embedded in these bones should not be expected to undergo major position changes.

CONCLUSION

Intraoperative localization was very helpful as an orientation tool during the simulation of skull base surgical approaches. This device facilitates the surgery by assuring precise instrument position and allows the surgeon to anticipate the spatial relationship of the anatomic structures in conjunction with the surgeon's comprehensive knowledge of the neurosurgical anatomy.

Figure 5. Temporal bone after anterior and retro-labyrinthine approach. Tip of forceps points to portion of bone where cochlea is embedded, and CT scan corroborates position. C: cochlea. HSC: horizontal semicircular canal. IAC: internal acoustic canal. PSC: posterior semicircular canal. SSC: superior semicircular canal.

The experience with this study has encouraged the introduction of this device during real surgical procedures. Future efforts to improve accuracy, as well as incorporation of intraoperative imaging, are expected to further contribute to decreased morbidity associated with this surgery.

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