Advances in Cranial Navigation

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Abstract:

The aim of this study is to assess the accuracy and applicability of an advanced cranial navigation setup. Therefore, continuous electromagnetic instrument navigation was employed in 136 neurosurgical cases using a standard navigation system. A phantom head in an intraoperative MRI environment was used to compare the accuracy of the advanced to the standard navigation setup. No significant difference was observed at the intracranial target points between the standard navigation setup using optic tracking, fiducial marker registration and pointer.
Our data confirms that the application of preoperative imaging, surface-merge registration and continuous electromagnetic tip-tracked instrument navigation may provide a seamless integration of navigation systems into the neurosurgical operating workflow without significant reduction in accuracy compared to standard navigation.

Key words: Cranial navigation, electromagnetic tracking, surface registration, instrument tracking

1 Problems

More than 25 years after its introduction by Roberts[1], cranial navigation today is still most commonly performed by registration with fiducial markers, tracking with optic technology, and intermittent pointer-based intraoperative application in routine clinical settings. If navigation support is desired during a microsurgical procedure, the neurosurgeon interrupts the dissection and exchanges the current instrument for the pointer device. Care is taken to obtain an unobstructed line-of-sight between the pointer and the camera bar. This may require repositioning of the operating microscope or even removal of an endoscope from the operating field. An advanced cranial navigation technique will seamlessly translate into the operating workflow and provide optimal accuracy.

2 Methods

Accuracy Test of Continuous EM Instrument Navigation

Setup: A phantom head made from high-density polyurethane foam was prepared with 7 self-adhesive radiopaque fiducial surface markers for point-to-point registration. A cross-shaped navigation target of 2 acrylic plastic bars containing 22 surface drill-holes was affixed in the center of the phantom head and served as checkpoint. The phantom head was fixed in a metal-free skull clamp.
For optic navigation, a pointer device with 5 infrared light reflecting spheres on its handle was available. For EM navigation, a pen-shaped rigid pointer or a flexible wire (length 23.7 cm) with two coils at its tip was used. Originally designed for shunt catheter placement[2], this so-called “stylet” can alternatively be inserted in hollow instruments such as suction devices, endoscopes and biopsy needles. For testing the accuracy within a metal instrument, we inserted the EM stylet into a standard single-use metal suction.
A CT-scan of the phantom head was acquired and imported into the navigation system. The 7 fiducial marker positions were stored for registration. First, separate target points were assigned to the 22 drill-holes of the acrylic bars using the CT scans. Then, the navigation probe was inserted into the drill-holes and the distance between the actual tip position and the predefined target point was measured by the system (Cranial 2.2 software) and recorded as the target error. The experiment was performed in an operating suite equipped with a ceiling-mounted 3T MR scanner (IMRIS, Winnipeg, Canada).

Accuracy tests: Initially, the accuracy of a standard navigation setup (optic tracking, fiducial marker registration, pointer device) was calculated. Then, the advanced navigation setup was introduced stepwise to assess potential sources of inaccuracy: First, EM replaced optic tracking. Then, surface-merge replaced fiducial markers; next, the tracking device was exchanged from pointer to stylet. To complete the advanced setup, we introduced the stylet into the suction tube. Then, the MR magnet was brought closer to the experiment setup (between 5 and 50 Gauss line) and the accuracy tests were repeated. To simulate an intraoperative MR scan the EM system was removed/re-attached and the accuracy checked.
From 3 passes of each navigation setup the root mean square error (RMSE) was calculated. After registration, the error was calculated by the system only for point-to-point, not for surface-based registration. We used the students T-test to compare the target RMSE of the different steps of the advanced navigation with the standard setup. A p-value of <0.05 was considered significant.

Clinical Experience

The advanced navigation was used in 136 routine cranial neurosurgical cases with the following setup:
Electromagnetic tracking: The EM patient reference tracker was attached to the patient's head via the skull clamp or directly to the skin depending on the type of procedure. In cases performed within the iMRI suite, it was fixed to a non-ferromagnetic skull clamp via a custom-made repositioning device. This tool allowed realignment of the reference tracker after MR imaging, which requires temporary removal of the entire EM equipment. The EM field emitter was typically positioned horizontally on any side of the patient between shoulder and skull clamp at around 25 cm distance to reference tracker and operating field.
Multimodality retrospective image application: As registration was performed without skin fiducials, retrospective scans were employed routinely.
Surface-based registration: Patient-to-image registration was performed using the surface-based method provided by the system. Thereby, 3 specified points and 350 arbitrary surface points widely distributed over the patient's head were collected with a surface probe. As the system does not calculate registration error, anatomic landmark checks were performed routinely at 7 points (nasion and lateral canthus, philtrum/nose angle, groove medial to tragus[3]).
Continuous instrument navigation. For intraoperative application the EM stylet was inserted into hollow instruments for continuous tip-tracked instrument navigation. Anatomic landmark checks were repeatedly performed during surgery to detect potential target error and consequently abandon navigational guidance.

3 Results

Accuracy Test
Seven navigation setups were evaluated for accuracy. The standard navigation setup (optic tracking, fiducial marker registration, pointer-based navigation) revealed an error for registration of 0.2 mm (0.2 – 0.3 mm) and of 0.7 mm (0.4 – 1.0 mm) at the target points. Changing to EM navigation, a submillimetric increase in error was observed for registration (RMSE 0.4 mm, range 0.2 – 0.5 mm) but not for targeting. During the stepwise transition to the complete advanced setup (EM tracking, surface-based registration, navigation of stylet in a metal suction tube), no significant changes in accuracy were observed at the target points (RMSE 0.7 mm, range 0.3 – 1.2 mm).
When the experiment was performed closer to the iMRI magnet (within the 5 and outside the 50 Gauss line), we observed a significant decrease in accuracy (RMSE 0.9 mm, range 0.7 – 1.3 mm). Accuracy decreased even more when the patient reference tracker was temporarily removed during acquisition of an iMRI and subsequently repositioned in its holder. In sum, no significant difference in target accuracy was noted between standard navigation versus the proposed advanced navigation setup when performed outside the iMRI 5 Gauss line.

Clinical Experience
Continuous EM instrument navigation was feasible and accurate in all but six cases of 136, which were performed during the initial month after the installation (3/6 ferromagnetic interference, 2/6 movement of skin-attached patient reference tracker, 1/6 patient movement in skull clamp during awake surgery). After an initial learning curve, no difference in setup time was found between standard and advanced navigation setup.
Besides catheter placement (n=9), continuous EM instrument navigation was used in the following procedures:

(1) Intracranial microsurgical tumor resection (n=71). In 8 cases of microsurgical tumor resection, the EM stylet was mounted to the suction tool of the neuroArm neurosurgical robot (IMRIS, Winnipeg, Canada). The neuro- surgeon controlling the robot was able to observe the current robot working position onscreen at the work- station outside the operating room.
(2) Endoscopic transsphenoidal surgery (n=46).
(3) Intracranial endoscopy (n=6).

(4) Biopsy (n=4).

Accuracy
Registration techniques: Previous studies on the different methods of registration using optic tracking have shown that besides bone-screws (error 0.23 ± 0.03 mm under lab conditions[4]) that are not applicable in the routine clinical setting, skin fiducial marker registration provides the highest accuracy (error 1.1 – 4.0 mm[5,6,7]). Registration relying solely on anatomic landmarks had the lowest accuracy (3.2 – 3.9 mm[6,8]), and registration based on surface points was found to provide intermediate accuracy (3.3 ± 1.65 mm[6]). Our phantom accuracy experiment revealed an equally low calculated error for registration (mean error 0.2 – 0.4 mm) with optic and EM navigation[4]. Our submillimetric higher mean target error of 0.7 mm corresponds well to the previous lab experiments[4,9] given the fact that we used fiducial marker or surface-based registration, not bone screws. We did not find any significant difference in target error between fiducial marker and surface merge registration.
Navigation imaging: Previous studies have reported higher accuracy when using CT scan for patient registration than MR images due to small inhomogeneities of the magnetic field[8,10]. In cases when high accuracy was needed, such as frameless biopsies of small targets, we always used a fusion of CT scan for registration and MR for target selection. Tracking techniques: Few studies comparing optic versus EM tracking exist. In the experiment of Kral et al[9] optical tracking was significantly more accurate than EM tracking (median target error 0.12 mm versus 0.37 mm, respectively, $p<0.001$). However, they used fiducial marker registration and bone affixed screws as targets. In contrast, we did not find a significant difference between optical and EM tracking (mean target error 0.7 versus 0.6 mm, respectively). In our experience, evaluation of accuracy in the submillimetric range is limited by the display resolution when manually defining target points. It is of note that the highest accuracy (error ≤ 0.5 mm[9]) was always found in the center of the phantom, whereas the highest error (up to 1.2 mm) was encountered in the target points at the periphery of the EM field. Therefore, we recommend positioning the EM emitter approximately 25 cm distant and pointing to

the center of the surgical target for highest accuracy.

4 Discussion

Integration into surgical workflows

The ergonomic advantage of the presented setup lies in the seamless integration into the surgical workflow. While the surgeon operates with the accustomed suction fitted with the EM stylet, the tip of the suction continually updates on the navigation screen, always providing information about the distance to tumor border, eloquent fibre tracts and surrounding structures. In contrast, in standard optic pointer-based navigation the surgeon has to interrupt dissection and exchange the current instrument with the navigation pointer and check for free line-of-sight. The EM stylet can both be inserted into the suction tube and be introduced into the working channel of an endoscope. In ventriculostomy cases, the endoscope can then be advanced under EM guidance through the intervertricular foramen. Once the endoscope is in the appropriate position inside the third ventricle, the EM stylet can be advanced further to puncture the target point under direct endoscopic view and EM guidance.

Although navigation of instruments with the EM stylet inside metal tubes has been reported[11], we are unaware of literature reporting the inaccuracy of this setup. Our results show equal accuracy between standard navigation and our advanced navigation setup. Further, this is the first report on accuracy tests of EM navigation in an iMRI environment. Outside the 5 Gauss line, no significant difference between optic and EM navigation was observed. As expected, the higher magnetic field (just inside the 5 Gauss line) led to decreased accuracy of the EM navigation.

Setup and learning curve

The introduction of EM navigation possesses a learning curve. This is reflected by the erroneous six cases in our series, which all occurred within the first months of the experiment. Within the scope of this project we have acquired knowledge about the optimal setup of EM navigation. First, no metal parts should reside between emitter and patient tracker. Second, the EM field emitter does not need to be fixed to the patient’s head but can be manually re-adjusted during registration or during surgery in case of bad communication with the system. Third, the patient reference tracker needs to be firmly fixed to the patient’s head throughout the procedure. If no rigid head fixation with a skull clamp is desired, this can be achieved either by a skull-mounted tracker via 2 bone screws. Alternatively, a skin-adhesive tablet-shape patient tracker is available. If the patient’s head is fixed in a skull clamp, the adhesive patient tracker can be attached to the clamp either with a distance of approximately 4 cm (in case of a metal skull clamp) or to the clamp directly (in case of non-ferromagnetic clamp). We routinely use the latter configuration as it provides maximum accuracy. Finally, although our study shows that EM navigation can be safely and accurately employed in the iMRI environment, execution of an intraoperative scan requires removal of all parts of the EM navigation setup. Although the position can

be marked or a holding device can be left in place, it is of note that reattachment of the patient reference tracker is prone to considerable inaccuracy.

Dedicated EM Instruments

As EM navigation is relatively new to the field of neurosurgery, current equipment can be improved and the development of dedicated EM instruments is necessary. Therefore, we advocate the design of dedicated EM instruments for neurosurgery such as microneurosurgical suctions which include the EM coils around the tip wall of the suction tube.

Conclusion

Continuous instrument navigation is the prerequisite for seamless integration of navigation systems into the neurosurgical operating workflow. Our data confirms that the application of preoperative imaging, surface-merge registration and continuous electromagnetic tip-tracked instrument navigation provides such integration without significant reduction in accuracy compared to standard optic navigation with skin fiducials. Further, the proposed advanced navigation setup was tested with equally high accuracy in the safety zone of the intraoperative MR environment outside the 5 Gauss line. However, technical refinements of navigated instruments are required.

5 References

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