Accuracy Validation of Neuronavigation Comparing Headholder-Based System with Head-Mounted Array—A Cadaveric Study

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■ BACKGROUND: **Neuronavigation is widely used for intracranial neurosurgical procedures and is commonly based on the standard reference array being fixed to the headholder. Some cases require the reference array to be attached directly to the head. The aim of this cadaveric study was to compare operational accuracy of a head-mounted reference array with the standard headholder-based system.**

■ METHODS: **Navigation accuracy was evaluated with 10 cadaveric specimens. Each specimen was prepared with 8 titanium microscrews that served as reference points on the external skull, and computed tomography was performed. Registration of all specimens was done using surface matching with infrared laser on three-dimensional reconstructed high-resolution computed tomography. In all 10 specimens, the head-mounted reference array and headholder-based system were compared by 10 repetitive measurements. The deviation was evaluated for each screw and compared using nonparametric Mann-Whitney *U* test between groups and screws. A Bland-Altman plot was generated for comparison.**

■ RESULTS: **A total of 1600 measurements were conducted. Mean deviation was 1.97 mm (95% confidence interval, 1.90–2.03 mm) with the head-mounted reference array and 2.10 mm (95% confidence interval, 2.04–2.18 mm) with the headholder based system. There was no significant difference between methods in 9 of 10 specimens. In 1 specimen, the head-mounted array was superior. The deviation in either method showed a significant correlation, indicating high pertinence for registration (*P* < 0.001).**

■ CONCLUSIONS: **Navigation with the head-mounted reference array demonstrated comparable accuracy to the headholder-based system and can be used without reduced accuracy. Careful registration is mandatory.**

INTRODUCTION

Image guidance systems are commonly used in neurosurgical intracranial procedures.[1,2] These systems consist of algorithms to calculate coordinates based on preoperative imaging and bring them in correlation to the head position. Therefore, fixed points within the surgical field have to be registered by cameras (optic systems) and matched with the preoperative imaging.[3] For patients or the surgical team to benefit from unrestricted head movement, common optical neuronavigation systems are not feasible to use, as rigid head fixation is required. In this case, a directly mounted reference array can be used. The reference array is mounted with 1 craniomaxillofacial screw directly on the skull, allowing optical navigation while the patient's head can still move. Shaving is not mandatory for fixation, and fixation is normally well tolerated.[4]

Historically, navigation systems were based on direct point matches of bone-implanted fiducials, leading to high accuracy. However preoperative placement of screws caused enormous discomfort.[5] Therefore, modern neuronavigation systems use a surface matching algorithm by referencing multiple points on the patient's skin following three-dimensional virtual reconstruction of the imaging dataset. Although application accuracy of image guidance is lower without implanted cranial markers, surface matching has proven to be accurate enough for daily use in most neurosurgical cases with a reported accuracy between 1.8 mm and 5 mm.[6-8]

Key words
- Accuracy
- Head-mounted
- Neuronavigation
- Reference array

Abbreviations and Acronyms
TRE: Target registration error

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Navigation systems need a recognizable reference array for a camera to serve as a starting point for the algorithm to calculate the position within the surgical field. This is a feasible and well-established arrangement for most intracranial procedures, as head fixation is frequently unavoidable in cranial microsurgery.[3] In the setting of an awake craniotomy, however, the use of rigid fixation of the head can be disadvantageous. Allowing movement of the limbs as well as free head positioning can add comfort for the patient and increase cooperation during testing. Fixing the reference array to the headholder is possible in most of these cases.[4,9] The objective of our cadaveric model study was to simulate surgical image guidance and compare the operational accuracy of a head-mounted reference array with the commonly used headholder-based system.

MATERIALS AND METHODS

The simulation was performed in 10 cadaveric heads. The bodies were donated to the Division of Clinical and Functional Anatomy of the Medical University of Innsbruck.[10,11] Preservation of cadavers has been described previously.[12] According to legal regulations, body donors were kept anonymous, and approval by the local ethics committee for the present analysis is not necessary.

Each specimen was prepared with 8 self-drilling titanium screws that served as reference points on the external skull. Three screws were placed frontally, 3 were placed parietally, and 2 were placed occipitally. Thereafter, cadavers were scanned using a high-resolution computed tomography protocol. The specimens were placed 1 by 1 in an upright position to avoid skin deformities related to storage. Registration was performed according to the manufacturer's instructions. We used surface matching registration with the Z-touch (Brainlab AG, Munich, Germany) infrared laser system and an optical tracking system with camera (Kick, Brainlab AG) (**Figure 1**). The same point cloud generated through the Z-touch system was used for both methods.

The coordinates of all reference points (microscrews) were planned, and all reference points were aimed for with the navigation pointer. Measurements were done first with the reference array fixed to the headholder followed by a second registration based on the head-mounted array. In all 10 cadaveric specimens, we conducted 10 repetitive measurements with both. To objectify clinical accuracy, the target registration error (TRE) was used. This parameter has been reliably evaluated in other studies and represents the deviation of the displayed position from the real anatomic target.[5,13,14] TREs were determined through the use of a paired *t* test. Coordinates obtained by registration via the head-mounted reference array were compared directly with the coordinates determined by the standard headholder.

IBM SPSS Version 21 (IBM Corp., Armonk, New York, USA) was used for statistical analyses. Differences with a P value < 0.05 were considered statistically significant. Intraclass correlation coefficient was calculated to assess the consistency of the results of the 10 repeated registrations and TRE measurements. Spearman correlation was conducted between both registration methods. Equality of both methods was tested using a Bland-Altman plot.

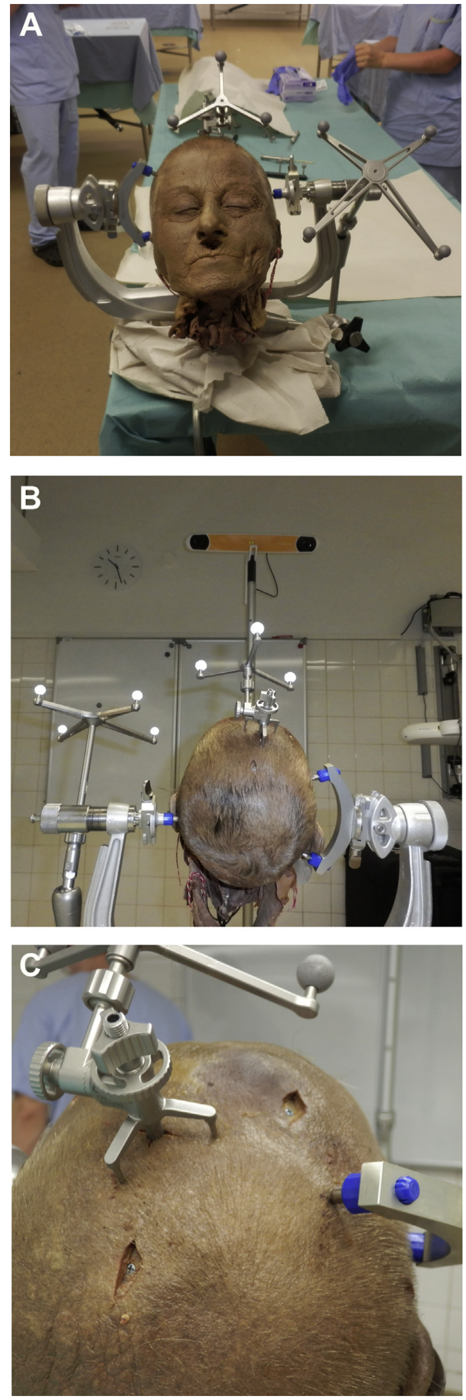

Figure 1. (**A**) Experimental setup with headholder-based system and head-mounted array (frontal view). (**B**) Experimental setup with optical tracking system (view from behind). (**C**) Close-up view of the screws in a cadaveric head.

RESULTS

The 10 specimens were registered 10 times each, so that 8 points were registered accordingly with both methods, resulting in a total of 1600 single measurements of target points. Mean deviation was 1.97 mm (95% confidence interval, 1.90–2.03 mm) with the head-mounted reference array and 2.10 mm (95% confidence interval, 2.04—2.18 mm) with the headholder-based system. In 9 of 10 specimens, there was no significant difference between the methods (Table 1). In 1 specimen, the head-mounted array was superior ($P < 0.001$), but with a much wider distribution in range than in the other 9 specimens, possibly indicating experimental error. Equality of both methods was confirmed by a Bland-Altman plot showing no statistically significant difference (Figure 2). A statistical analysis comparing the deviation in either method showed equal deviation in a correlation analysis ($P < 0.001$).

DISCUSSION

Neuronavigation has become standard in cranial neurosurgery. Although a rigid fixation of the patient is desired in most cases, sometimes use of neuronavigation in combination with an unfixed head or even in awake patients is necessary.[4,15] There are several reports in which neuronavigation in combination with an unfixed head or in awake patients was used with sufficient accuracy in awake glioma surgery or small surgical interventions (i.e., external ventricular drain).[4,8,15,16] We previously reported a series of 18 consecutive patients who underwent awake craniotomy without rigid pin fixation, where resection could reliably and accurately be supported by neuronavigation.[4] Given the algorithm of the navigation software, using the surface of the face in relation to the reflecting balls of the array, the registration accuracy remains the same also by moving the head during registration. However, it is a major advance to register in the straight supine position (to reach the whole face by the laser pointer), regardless of the mounting point of the array, because it is possible to reposition the patient in basically every position after finishing the registration. As long as the head-mounted array is not moved, accuracy remains the same.

Table 1. List of Cadaveric Heads with Data

Cadaveric Head	Mean (mm)	Range (mm)	SD	*P* Value
1				0.374
Mayfield	2.16	0.54—4.12	0.82	
Head-mounted	2.08	0.57—4.51	0.91	
2				0.339
Mayfield	2.03	0.29—5.67	0.13	
Head-mounted	1.81	0.16—6.02	0.11	
3				0.369
Mayfield	1.79	0.18—4.41	0.09	
Head-mounted	2.00	0.36—4.84	0.11	
4				0.238
Mayfield	2.17	0.41—4.40	0.11	
Head-mounted	2.02	0.57—5.80	0.11	
5				0.88
Mayfield	2.22	0.54—5.82	0.14	
Head-mounted	2.44	0.29—6.58	0.13	
6				0.210
Mayfield	2.09	0.44—5.41	0.11	
Head-mounted	1.84	0.51—4.32	0.08	
7				0.645
Mayfield	2.22	0.53—5.82	0.14	
Head-mounted	2.44	0.29—6.58	0.13	
8				0.091
Mayfield	2.25	0.56—5.10	0.12	
Head-mounted	1.96	0.34—4.08	0.10	
9				0.065
Mayfield	2.33	0.39—5.88	0.13	
Head-mounted	2.06	0.36—6.43	0.13	
10				<0.000
Mayfield	1.81	0.28—4.28	0.09	
Head-mounted	1.22	0.24—2.18	0.05	

In the present study, we examined the accuracy of 2 different arrays using a standard optical navigation system with surface matching. Although both arrays are commercially available from the manufacturer, there is no validation study in a clinical environment because clinical use was approved by theoretical demonstration of the accuracy of the algorithm behind the method. Moreover, information on the consistency of the registration process was gained by evaluating multiple repetitions of the whole registration process. Although the accuracy of optic tracking is mathematically in indirect proportion to the distance between reference array and head, both the headholder-fixed system and the head-mounted reference array showed similar results with no difference in TRE. Similar to most other studies, the accuracy was measured by pointing a navigated instrument on a landmark after completion of the registration procedure.[3,8] Navigational accuracy was the primary objective.

We measured an overall navigation accuracy of 1.97 mm and 2.1 mm, respectively. Stieglitz et al.[8] reported in their retrospective analysis a mean deviation of 1.8—5 mm, whereas other authors reported mean accuracies of 0.79—2.16 mm.[7] We previously reported an accuracy <1 mm in awake surgery[4] on known anatomic landmarks, but much less sophisticated measurements were taken compared with the present study, possibly overestimating accuracy. Data obtained using crafted phantoms tended to show higher accuracy with ranges <1.5 mm.[17,18] It has to be considered, however, that most cadaveric studies used artificial landmarks (i.e., screws) for registration and evaluation of target accuracy.[6,8,18] This created the false impression of enormously high accuracy that could not be transferred to clinical situations. Therefore, we used the standard surface registration algorithm in our trial. Despite the superior accuracy, preoperative placement of reference screws in patients has been rarely used because of the added morbidity and discomfort for the patients. Furthermore, the most important step in image guidance is the registration process, which aligns the image data with the patient's geometry. This process has a strong influence on navigation accuracy, which was also proven in our data with similar deviation in both groups.[18] We verified that the increase in a neuronavigation system mismatch is not related to the reference array of the image guidance system but rather to other causes. It

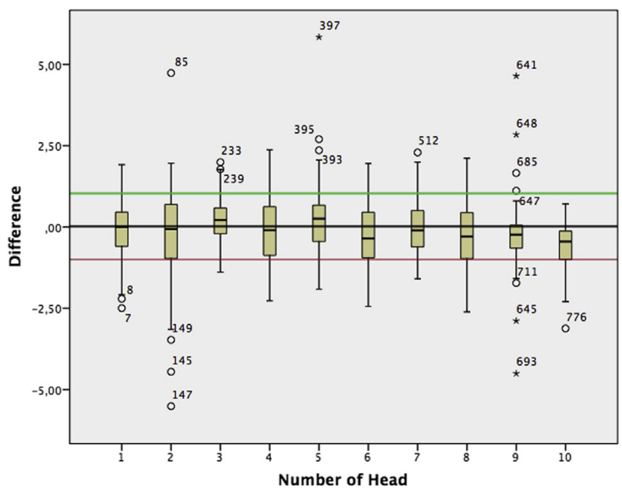

Figure 2. Bland-Altman plot comparing both methods. Outliers are marked with *circles* and *asterisks*.

has been shown previously that registration, and therefore accuracy is affected by many parameters. Such influencing factors are skin conditions, placement of the camera, and distance of the array to the surgical field.[8] Brain shift caused by releasing cerebrospinal fluid during the operation does not alter accuracy because both arrays are in rigid contact with the skull, and any shift of the brain in relation to the bony skull causes inaccuracies equally.

As the quality of the registration accuracy is also very sensitive to soft tissue changes, deviation may be due to deformities attributable to the storage of the specimens in our study. Furthermore, the angle between the specimen and camera may vary. As TRE is known to be smaller in the anterior part of the head as opposed to the posterior part, summation of all obtained TREs of different anatomic regions in our study may also have an effect on the mean deviation.[19] Finally, we did not assess how accuracy might have changed over time. This has been described in several publications with the use of pin fixation and optical tracking[3,4,8] and might represent a shortcoming when it comes to translation into clinical application. All of these limitations could potentially explain the statistical outlier in our series.

CONCLUSIONS

Navigation with the head-mounted reference array was as accurate as the headholder-based system. The head-mounted array allows individualized use of optic neuronavigation even without head fixation according to the needs of patients and surgeons. Nevertheless, careful registration is mandatory for high accuracy.

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