The Silent Loss of Neuronavigation Accuracy: A Systematic Retrospective Analysis of Factors Influencing the Mismatch of Frameless Stereotactic Systems in Cranial Neurosurgery

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BACKGROUND: Neuronavigation has become an intrinsic part of preoperative surgical planning and surgical procedures. However, many surgeons have the impression that accuracy decreases during surgery.
OBJECTIVE: To quantify the decrease of neuronavigation accuracy and identify possible origins, we performed a retrospective quality-control study.
METHODS: Between April and July 2011, a neuronavigation system was used in conjunction with a specially prepared head holder in 55 consecutive patients. Two different neuronavigation systems were investigated separately. Coregistration was performed with laser-surface matching, paired-point matching using skin fiducials, anatomic landmarks, or bone screws. The initial target registration error (TRE1) was measured using the nasion as the anatomic landmark. Then, after draping and during surgery, the accuracy was checked at predefined procedural landmark steps (Mayfield measurement point and bone measurement point), and deviations were recorded.
RESULTS: After initial coregistration, the mean (SD) TRE1 was 2.9 (3.3) mm. The TRE1 was significantly dependent on patient positioning, lesion localization, type of neuroimaging, and coregistration method. The following procedures decreased neuronavigation accuracy: attachment of surgical drapes (DTRE2 = 2.7 [1.7] mm), skin retractor attachment (DTRE3 = 1.2 [1.0] mm), craniotomy (DTRE3 = 1.0 [1.4] mm), and Halo ring installation (DTRE3 = 0.5 [0.5] mm). Surgery duration was a significant factor also; the overall DTRE was 1.3 [1.5] mm after 30 minutes and increased to 4.4 [1.8] mm after 5.5 hours of surgery.
CONCLUSION: After registration, there is an ongoing loss of neuronavigation accuracy. The major factors were draping, attachment of skin retractors, and duration of surgery. Surgeons should be aware of this silent loss of accuracy when using neuronavigation.

KEY WORDS: Accuracy, Frameless stereotaxy, Neuronavigation

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Neuronavigation has become an intrinsic part of preoperative planning and the surgical procedure itself. It allows frameless stereotactic guidance of various instruments, including the microscope. Technological improvements in recent years have enabled implementation of modern functional neuroimaging in preoperative planning and image-guided surgery.[1]

ABBREVIATIONS: BMP, bone measurement point; **DTRE2,** DTRE3; **MMP,** Mayfield measuring point; **TRE,** target registration error; **TRE1,** initial target registration error; **TRE2,** target registration error at the Mayfield measurement point; **TRE3,** target registration error at bone measurement point

The crucial point of frameless stereotaxy is to optimize accuracy; inaccuracies of a few millimeters can make the difference between a successful and a less successful surgery.

Using standardized coregistration procedures such as paired-point matching using skin fiducials and laser surface–matching means that neuronavigation accuracies between 1.8 and 5 mm have been achieved (Table 1).[2-20] However, for use in procedures involving eloquent structures, this range in precision is not sufficient. Furthermore, these measured accuracies are only mean values,

TABLE 1. Coregistration Accuracy Reported in the Literature[a]

Ref.	Work Group	Navigation System	Paired Point Matching, mm			Surface Matching		
			Landmarks	Fiducials	Screws	Pointer	Laser	Misc
Watanabe et al[2]	Neurosurgery, Tokyo, Japan	Neuronavigator		2.5				
Laborde et al[3]	Neurosurgery, Aachen, Germany	Computer-assisted localizer		3				
Zinreich et al[4]	Neuroradiology, Johns Hopkins Hospital, Baltimore, MD	FARO Surgicom (phantom study)		1-2 mm; 95% <3.7				
Golfinos et al[5]	Neurosurgery, St. Joseph's, Phoenix, AZ	FARO Surgicom	5.6 (CT)	2.8 (CT)				
			6.2 (MR)	3.0 (MR)				
Sipos et al[6]	Neurosurgery, Johns Hopkins Hospital, Baltimore, MD	FARO Surgicom	3.1 (CT)	2.3 (CT)				
			2.7 (MR)	2.8 (MR)				
Ryan et al[7]	Neurosurgery, University of Chicago, Illinois, IL	Flashpoint 3D digitizer and Sparcstation2 (Sun)						4.8 ± 3.5 mm
Hassfeld et al[8]	Maxillofacial and Craniofacial Surgery, University of Heidelberg, Germany	SPOCS (Aesculap)			<2			
Helm and Eckel[9]	Neuroradiology, Johns Hopkins Hospital, Baltimore, MD	FARO Surgicom (phantom study)		2.1				
Brinker et al[10]	Nordstadt Hospital, Hannover, Germany	Zeiss MKM			0.7 ± 0.2			
Germano et al[12]	Neurosurgery, Mount Sinai Hospital, New York, NY	OD System	3.4 ± 0.2	Preop: 1.7 ± 0.2				
				Postop: 2 ± 0.2				
Villalobos and Germano[13]	Neurosurgery, Mount Sinai Hospital, New York, NY	OD System	3.4 ± 0.4	1.6 ± 0.1				
Gumprecht et al[14]	Neurosurgery, München-Bogenhausen, Germany	BrainLab VectorVision		4 ± 1.4				
Raabe et al[15]	Neurosurgery, Frankfurt am Main, Germany	BrainLab VectorVision2					1.8 ± 0.8 mm frontal	
							2.8 ± 2.1 mm occipital	
Wolfsberger et al[16]	University of Vienna Medical School, Vienna, Austria	EasyGuide Neuro frameless stereotactic navigation system (Philips)	3.2 ± 1.0	2.9 ± 1.0				
Marmulla et al[18]	Cranio-Maxillofacial Surgery, Heidelberg, Germany	SSN++ (Carl Zeiss)					1.2 ± 0.3 mm	
Woerdemann et al[17]	Neurosurgery, Rudolf-Magnus-Institute of Neuroscience, Utrecht, the Netherlands	StealthStation TREON Plus (Medtronic)	CT: 4.0 ± 2.1 frontal	CT: 2.5 ± 1.1 frontal		CT: 4.8 ± 2.2 frontal		
			6.0 ± 2.7 nonfrontal	3.2 ± 1.1 nonfrontal		6.0 ± 2.7 nonfrontal		

(Continues)

TABLE 1. *Continued*

Ref.	Work Group	Navigation System	Paired Point Matching, mm			Surface Matching		
			Landmarks	Fiducials	Screws	Pointer	Laser	Misc
			MR: 4.0 ± 2.0 frontal 5.6 ± 1.8 nonfrontal	MR: 1.9 ± 0.8 frontal 2.3 ± 1.0 nonfrontal		MR: 4.0 ± 2.0 frontal 5.5 ± 1.8 nonfrontal		
Pillai et al[23]	Neurosurgery, The Ohio State University Medical Center, Columbus, OH	Stryker Navigation System			0.91 ± 0.28			
Pfisterer et al[19]	Neurosurgery, St. Joseph's Hospital, Phoenix, AZ	StealthStation (Medtronic)	4.0 ± 1.7	3.5 ± 1.1		3.3 ± 1.7		
Shamir et al[11]	Neurosurgery, Hebrew University, Jerusalem, Israel	FaceScan II (Brueckmann)						0.9 mm (0 cm DTF) 4.5 mm (15 cm DTF)
Thompson et al[20]	Neurosurgery, Oregon Health & Science University, Portland, OR	StealthStation (Medtronic)		1.9 ± 0.5	1.3 ± 0.5			

[a]CT, computed tomography; DTF, distance to face; MR, magnetic resonance.

so there is still need for improvement in this field. A key issue, however, is whether the accuracy observed in the beginning—immediately after co-registration—is valid throughout the surgery. Our impression is that accuracy decreases with duration of surgery. This impression is supported by reports from Golfinos et al[5] and Germano et al,[12] who found a reduced accuracy at an intra- or postoperative accuracy check, but could neither quantify nor explain it.

To quantify the decrease of neuronavigation accuracy with surgery duration and to identify possible origins of this phenomenon, we performed a retrospective quality-control study.

PATIENTS AND METHODS

Patients

Between April 2010 and July 2011, we operated on 55 consecutive patients for intracranial lesions using neuronavigation in conjunction with a specially prepared Mayfield head holder (Figure 1). Patient demographic data and information about lesions and procedures are provided in Table 2. Local ethics committee approval was obtained (protocol number 150971).

Head Fixation

The head was fixed in the specialized Mayfield head holder (Figure 1A), which had an additional arm holding a Mayfield measuring point (MMP) at the upper end that was rigidly fixed to the 1-pin side of the frame, with the measuring point 6 cm from the rotation axis (Figure 1B). At this arbitrary level, it was about as far from the rotation axis of the head holder as most of the lesions that were operated on. Immobility of the head inside the head holder was double-checked before the beginning of the registration procedure.

Coregistration Procedure

Depending on the patient positioning required for the surgery and the neuronavigation system, we used different registration methods for matching images with the patient. For some frontal lesions (5 patients), we performed laser surface matching using the BrainLab Z-touch pointer. For other patients, and especially in cases of posterior lesions, we used the BrainLab SoftTouch-tool in addition (26 patients) to acquire points on the patient's head in the area of the lesion to achieve a higher accuracy. In rare cases, we used the SoftTouch pointer solely (8 patients) if necessary due to the patient positioning or a need for early placement of facial needle electrodes for electrophysiological monitoring when there was no free line of sight toward the patient's face, which is required for use of the Z-touch. In case of face-down prone positioning, we used fiducial markers for paired-point matching (2 patients). Two patients with complex lesions underwent implantation of bone screws the day before surgery to permit paired-point matching. In 1 patient, we performed coregistration using anatomic landmarks. All patients who were operated on using the Medtronic StealthStation (Medtronic, Minneapolis, Minnesota) for neuronavigation (11 patients) were registered using the Tracer function (Table 2).

In 1 patient we used coregistration by anatomic landmarks (nasion, ears, lateral rim of orbit) because the surface scanning procedure was not successful. In the 2 patients with coregistration using bone screws, the markers (3-mm micro bone screws, Biomet) were placed through stab incisions with the patient under local anesthesia after local hair removal and skin disinfection. Screws were placed in a cross-shaped arrangement next to the intended craniotomy, so that they would be accessible after skin incision and after craniotomy in the definitive surgery.

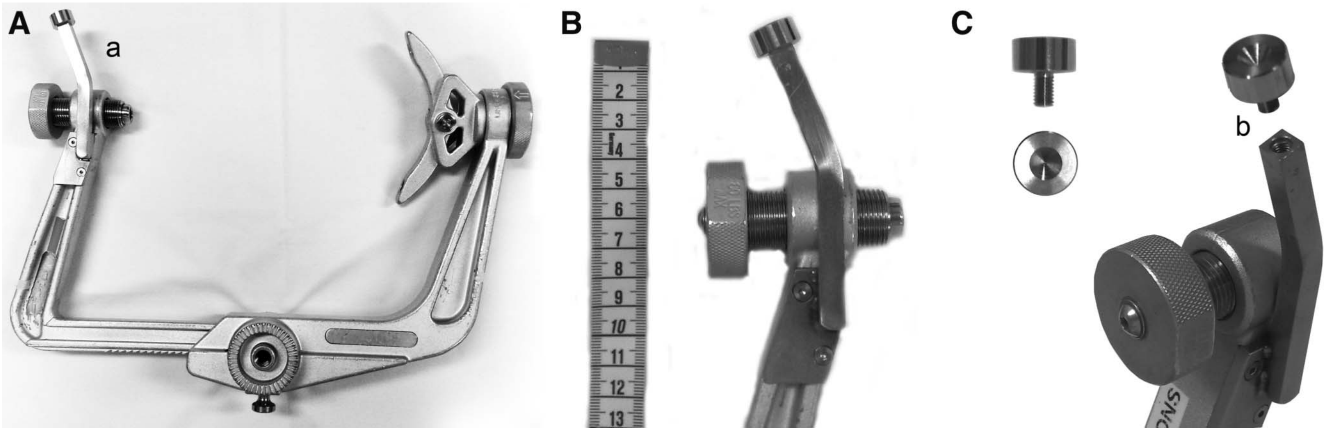

FIGURE 1. *The modified Mayfield head holder frame.* **A**, *a standard Mayfield head holder was used for positioning of the patient's head.* **a**, *an additional arm was attached to the 1-pin side of the head holder.* **B**, *the Mayfield measurement point at the end of the arm was 6 cm from the rotation axis of the head holder.* **C**, *the measurement pin (***b***) could be replaced by a sterile pin after installation of the sterile surgical drapes.*

Neuronavigation

Neuronavigation was performed using a BrainLab VectorVision2 (BrainLab, Feldkirchen, Germany) neuronavigation system in 44 of the 55 patients, and a Medtronic StealthStation (Medtronic) in the other 11 patients. Both systems consist of a mobile computer unit with a 3-dimensional infrared camera and touch screen. The reference star is mounted on a flexible arm, which is fixed to the Mayfield frame. The standard instrument for navigation is a pointer, which can be located by the 3-dimensional camera by 2 (for BrainLab) or 5 (for Medtronic) passive marker spheres.

Accuracy of the registration procedure was measured at a marker point at the center of the nasion, as reported by Raabe et al.[15] The result was recorded in the patient protocol (initial accuracy target registration error [TRE1]). The accuracy was also checked according to landmarks such as the external auditory canal, lateral rim of the orbit, and midline.

Before installation of needle electrodes for electrophysiological monitoring and attachment of surgical drapes, an intraoperative marker point was acquired (baseline target registration error at the Mayfield measurement point [TRE2]). When all preparations for surgery were completed, the measurement pin was replaced by a sterile pin. By positioning the sterile navigation pointer at the center of the measuring point, movements between the Mayfield frame and the reference star were registered. The result and the time of the measurement were recorded in the patient protocol, in accordance with the course shown in Figure 2.

Surgical Procedure

After completion of the coregistration procedure the skin was sterilized, and disposable sterile drapes (Mölnlycke Health Care) were attached. Before skin incision, the accuracy of neuronavigation was checked at the MMP. The deviation was recorded as a change in accuracy caused by attachment of surgical drapes (TRE2).

After skin incision and before use of retractors, a small hole was made in the bone next to the planned craniotomy (bone measurement point [BMP]). The navigation pointer was placed at this hole and another measuring point was acquired (target registration error at bone measurement point [TRE3]). This point was used for accuracy controls throughout the surgery.

Use of Skin Retractors (Fish Hooks)

We used standard Yaşargil skin retractors by Aesculap (FF022R) in combination with rubber bands by Lyreco (120 $\times$ 5 mm), applying a mean force of 14 N each. Usually 3 or 4 retractors were used at the same time to retract the myocutaneous skin flap. Before and after application, the neuronavigation accuracy was checked at both measurement points. The deviation was recorded as change in accuracy caused by attachment of retractors (TRE2 and TRE3).

Statistical Evaluation

Statistical evaluations were performed using the Kruskal-Wallis test and Mann-Whitney U test. A significance level of $P < .05$ was considered significant. The mean overall deviation after coregistration is approximately 3.0 $\pm$ 2.0 mm according to the literature (Table 1). As there is no mention in the literature concerning the additional deviation caused by certain surgical procedures, we used the experience from the first 4 surgeries for analysis of statistical power. We observed an additional deviation of 2.8 $\pm$ 2.0 mm caused by the attachment of sterile drapes. Together with the initial deviation, this results in a deviation of up to 5.8 $\pm$ 4.0 mm. Using a level of significance (α) of .05 and 1-β error, also of .05, this results in a sample size of 31 patients. As the second most important factor, based on our surgical experience, we expected that the use of Yaşargil retractors would produce an additional mean deviation of 1.7 $\pm$ 1.0 mm. To show a significant effect of this factor, a sample size of 49 patients is required.

RESULTS

Target Registration Error at the Beginning of the Surgery

The TRE1 was measured immediately after completion of the coregistration process. The mean (SD) TRE1 over all procedures was 2.9 (3.3) mm.

TABLE 2. Demographic Data, Lesions, Procedures, Positioning, and Coregistration Methods Used for the Patients Included in the Study[a]

Demography	Female (n = 26)		Age, Mean (SD), 56 (13.6) y	
	Male (n = 29)			
Lesions	24	Gliomas		
		18	High grade (WHO grades III and IV)	
		6	Low grade (WHO grades I and II)	
	15	Meningiomas		
		9	WHO grade I	
		5	WHO grade II	
		1	WHO grade III	
	4	Metastases		
	2	Arteriovenous malformations		
	2	Intracerebral hemorrhage		
	1	Anaplastic ependymoma		
	1	Aneurysm		
	1	Cavernoma		
	1	Craniopharyngioma		
	1	Hemangioblastoma		
	1	Hydrocephalus (navigated ventriculocisternostomy)		
	1	Neuroblastoma		
	1	Primitive neuroectodermal tumor		
Procedures	49	Tumor removal		
	2	Navigated biopsy		
	2	Frameless stereotactic puncture of intracranial hemorrhage		
	1	Ventriculocisternostomy		
	1	Clipping of aneurysm		
Lesion localization	29	Frontal lobe (52.7%)		
	10	Parietal lobe (18.2%)		
	9	Temporal lobe (16.4%)		
	4	Posterior fossa (7.3%)		
	2	Occipital lobe (3.6%)		
	1	Cranial base (1.8%)		
			No.	Coregistration method
Patient positioning and method used for coregistration	37	Supine (67.3%)	20	Combination of LSM and SoftTouch
			9	StealthStation tracer
			3	LSM
			2	SoftTouch surface matching
			2	Bone screws
			1	Anatomic landmarks
	3	Prone (5.5%)	1	SoftTouch surface matching
			1	Skin fiducials
			1	StealthStation tracer
	15	Side (27.3%)	6	SoftTouch surface matching
			5	Combination of LSM and SoftTouch
			3	StealthStation tracer
			1	Skin fiducials
Neuronavigation system	44	BrainLab VectorVision2		
	11	Medtronic StealthStation		
Neuroimaging used for navigation	50	MRI alone (90.9%)		
	3	MRI and CT (5.5%)		
	2	CT alone (3.6%)		
Anesthesia	50	General anesthesia		
	5	Local anesthesia (awake surgery)		

[a]WHO, World Health Organization; LSM, laser surface matching; MRI, magnetic resonance imaging; CT, computed tomography.

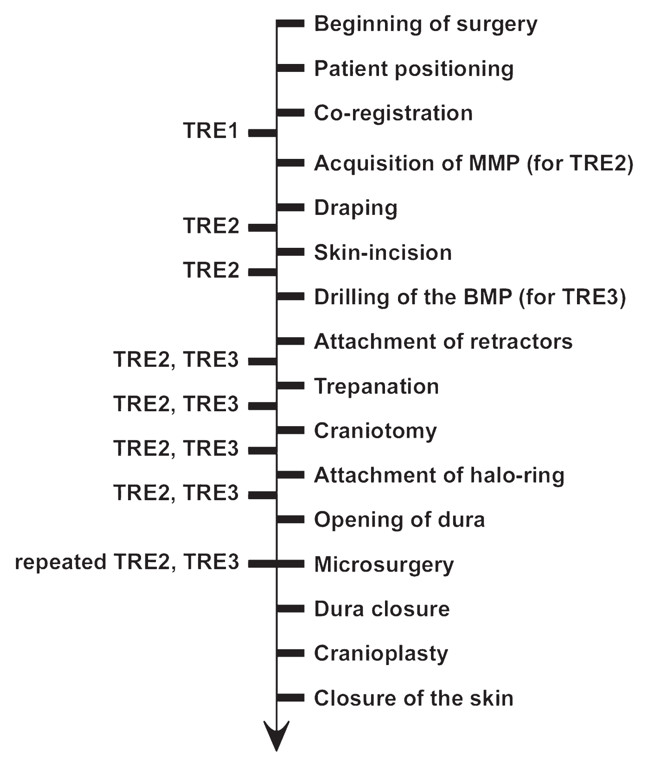

FIGURE 2. *Course of surgery and events of target registration error (TRE) acquisition. The TRE was acquired at certain locations before and after important surgical events. The TRE1 (initial TRE) was recorded at the nasion right after completion of the coregistration process. The target registration error at Mayfield measurement point (TRE2) was acquired at the Mayfield measurement point (MMP) immediately after and then checked after draping and skin incision. The target registration error at bone measurement point (TRE3) was acquired at a small burr hole that was drilled outside the margins of the planned craniotomy (bone measurement point [BMP]). Both TRE2 and TRE3 were recorded after major surgical events and on a regular basis throughout the surgery.*

Influence of Surgical Events on Accuracy

Measurement of TRE2 and TRE3 before and after surgical events (Figure 2) allowed evaluation of their possible influence on neuronavigation accuracy.

We found a significant influence of the attachment of surgical drapes on the Mayfield head holder's relative position with respect to the reference frame. The mean (SD) and median decrease of accuracy at the Mayfield measurement point were 2.7 (1.7) mm and 2.5 mm ($P < .005$) (Table 3). The skin incision had little influence on the system's accuracy (mean [SD] DTRE2, 0.5 [0.6] mm; median, 0.4 mm; not significant).

Attachment of skin retractors had a small but significant influence on the additional TRE caused by the force between the Mayfield clamp and the reference frame (additional mean [SD] DTRE2, 1.0 [0.9] mm;, median, 0.9 mm; $P = .028$), but showed a higher additional TRE when measured at the BMP (mean [SD] delta target registration error measured at bone measurement point [DTRE3] 1.2 [1.0] mm; median, 1.2 mm; $P = .018$). Trepanation, craniotomy, and attachment of a halo ring showed only minor influence on the accuracy (Figure 3, Table 3).

Influence of Time on Accuracy

Throughout the surgery, the TRE was recorded as often as possible at the MMP and the BMP. Although the TRE2 measured at the MMP stayed relatively constant (Figure 4A), TRE3 showed a significant tendency to increase over time when measured at the BMP (Figure 4B, Table 4).

DISCUSSION

Numerous factors contribute to the overall deviation of frameless stereotactic systems. These can be grouped into physical, technical, operational, and biological factors.[21] To the physical factors belong artifacts caused by inhomogeneous reflection of infrared light flashes in navigation systems, which use a 3-dimensional stereo camera and passive marker spheres for image-patient coupling.[22] In case of magnetic coupling, other magnetic fields caused by computers and instruments can influence the accuracy (Table 5). The most important technical factor is the patient-image coregistration. Many different techniques are used, all of which have a distinct contribution to the overall deviation.[17] These are mainly paired-point matching with either use of anatomic landmarks, use of skin fiducials, or use of bone screws,[10,23] and different (laser) surface-matching techniques.[15] Another technical factor is the limited resolution of the imaging datasets. Operational factors are those caused by the surgeon, assistants, and nurses who come in contact with parts of the neuronavigation system. Surgical procedures may contribute to the deviation as well. The major biological factor is the so-called brain shift.[24] After craniotomy, opening of the dura and consequent loss of cerebrospinal fluid, removal of tissue, and brain edema can cause shifting of the brain tissue that affects neuronavigation accuracy.

The coregistration accuracy reported in the literature using surface matching technologies is 1.8 (0.8) mm[15] and using paired-point matching by skin fiducials is between 2 and 5 mm (Table 1). Only paired-point matching by bone screws provides a deviation less than 1.0 mm,[10,23] which is comparable to the accuracy achieved using stereotactic frames (0.9-1.2 mm including brain shift).[25] In most studies, the accuracy is measured by pointing a navigated instrument on a landmark (usually the nasion) or a skin fiducial after completion of the coregistration procedure. An increase in the deviation with growing distance to the landmarks, fiducial markers, or skin region used is recognized.[11,15] Despite that, in most studies, neuronavigation systems are assumed to work with the measured initial accuracy until the end of surgery. However, in our experience, even in cases of a good or very good initial accuracy, at a certain point during surgery, we realize that the deviation must have increased.

In the worst case, even complete loss of useful neuronavigation is possible due to and unacceptable mismatch. In such cases usually

TABLE 3. Additional Target Registration Errors Caused by Surgical Events: Influence of Surgical Events on the Neuronavigation Accuracy Is Shown in Figure 3[a]

	Attachment of Surgical Drapes	Skin Incision	Attachment of Retractors		Trepanation		Craniotomy		Attachment of Halo	
	ΔTRE2 (MMP)	ΔTRE2 (MMP)	ΔTRE2 (MMP)	ΔTRE3 (BMP)	ΔTRE2 (MMP)	ΔTRE3 (BMP)	ΔTRE2 (MMP)	ΔTRE3 (BMP)	ΔTRE2 (MMP)	ΔTRE3 (BMP)
No.	49	22	10	9	5	5	37	33	25	22
Mean	2.7	0.5	1	1.2	0.9	0.6	0.8	1.0	0.7	0.5
SD	1.7	0.6	0.9	1.0	1.2	0.2	1.1	1.4	0.7	0.5
Median	2.5	0.4	0.9	1.2	0.5	0.5	1.1	1.8	0.5	0.3

[a]TRE2, target registration error measured at the Mayfield measurement point; TRE3, target registration error measured at the bone measurement point; MMP, Mayfield measurement point; BMP, bone measurement point.

only a coregistration using anatomic landmarks is possible, although with low accuracy. Use of navigated ultrasound for coregistration using soft-tissue landmarks such as vessels might be supported in the near future.

To determine a reliable estimation of the accuracy of frameless stereotactic systems and to analyze the factors affecting them, we performed a retrospective quality-control study.

Initial Target Registration Error

The TRE1 measured immediately after completing the coregistration procedure was 2.9 (3.3) mm and was thus comparable to the results reported in the recent literature (Table 1). The lowest TRE1s were achieved using a combination of laser-surface matching and pointer-surface matching (TRE1, 2.1 [1.2]). The fact that we used an anatomic landmark for measurement of the TRE1 requires further discussion. We agree with the general consensus that the TRE should be measured at a marker that is not used for coregistration and allows 100% objective measurement. A bone landmark would be optimal, although one is usually not available at this stage of the procedure. A skin fiducial is an alternative, but it is subject to movements of the skin. As our study was designed to evaluate quality control, we dispensed with additional imaging procedures that would be required to localize such a fiducial. To solve this, we used the nasion as a landmark. It can be identified easily both in the imaging and on the skin in the midline of the nose and as the deepest point of the nasion in lateral view. For both imaging and skin identification, localization of this landmark is possible with an estimated accuracy of 2 mm.[15]

Influence of Draping and Surgical Procedures on the Navigation System's Accuracy

The following key results of the study have not been previously reported. We continued measuring the TRE2 and TRE3 throughout the surgery to identify the influence of certain surgical procedures and surgery duration on the neuronavigation accuracy. To distinguish changes arising from movements between the head and the Mayfield head holder from those between the Mayfield head holder and the reference frame, we used 2 landmarks for TRE measurement: 1 at the BMP and 1 at the MMP (Figure 1).

The attachment of surgical drapes showed a considerable influence on the accuracy (mean DTRE2, 2.7 mm). Although we were surprised by the extent of this influence, it can be explained by the weight of the surgical drapes and their connections to the Mayfield frame, reference frame, patient's head, patient's body, anesthetic frame, and other instruments, machines, and tables in the operating room. During attachment of the drapes, they are often pulled and straightened to achieve a smooth sterile field, which enhances the forces exerted on the patient and frame. The increasing weight of the drapes when soaked through with irrigation liquid and blood may increase this effect.

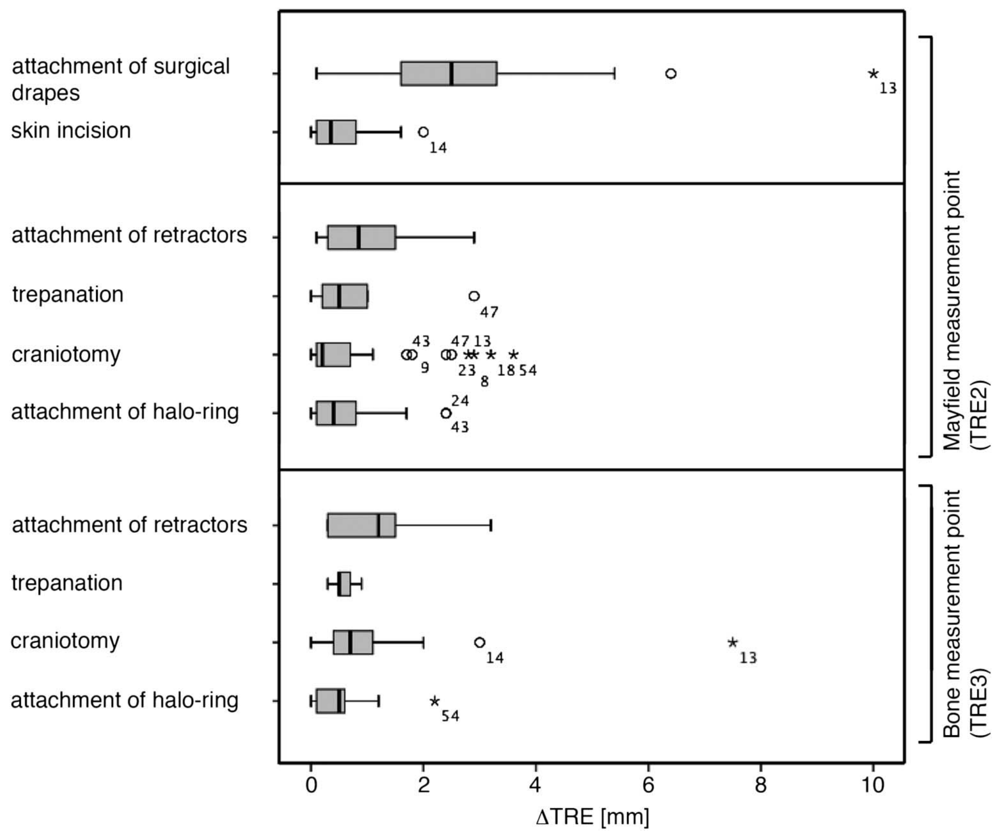

FIGURE 3. *The influence of surgical events on the target registration error (TRE2, target registration error measured at the Mayfield measurement point; TRE3, target registration error measured at the bone measurement point). Heavy vertical lines indicate the median; left and right borders of the gray rectangles indicate the 25th and 75th percentiles, respectively; whiskers indicate 1.5 times the interquartile range. The attachment of surgical drapes showed the greatest influence on the accuracy measured at the Mayfield measurement point (decrease of accuracy at the Mayfield measurement point, mean [SD] DTRE, 2 2.7 [1.7] mm). Furthermore, the attachment of retractors had a large influence on the accuracy, especially if measured at the bone measurement point (decrease of accuracy at the bone measurement point, mean, [SD] DTRE3 1.2 [1.0] mm). See Table 3.*

The next procedure, which also had a considerable effect on the accuracy, was the attachment of skin retractors (Figure 5). The mean DTRE2 (measured at the MMP) was 1.0 mm, and the mean DTRE3 was 1.2 mm (measured at the BMP). The importance of this effect becomes even more evident if the maximum values are considered: the maximum DTRE2 was 2.9 mm and the maximum DTRE3 was 3.2 mm. In case of pterional craniotomies, there are as many as 4 retractors pulling the skin in 1 direction with an approximate lateral force of 10 to 15 N each to the Mayfield head holder. In the case of 4 retractors, that would be 40 to 60 N, which easily explains the considerable influence on the accuracy.

Trepanation and craniotomy did not lead to relevant increases of the navigation mismatch. This was unexpected, but may be due to the fact that neurosurgeons are usually trained to perform these manipulations carefully to prevent movements of the patient's head in the head holder or to avoid influencing the navigation system's accuracy. Two theories about the minimal influence on the accuracy are that (1) we were extremely careful during trepanation and craniotomy because we expect a possible influence on the accuracy and (2) the effect was of only short duration and was dependent on the effective force applied.

Influence of Duration of Surgery

Our previous impression that the navigation mismatch increases throughout the duration of surgery proved to be correct. We found a significant increase in the mean TRE3 (measured at the BMP) from 1.3 to 4.5 mm during 6 hours of surgery. The fact that this increase did not occur with measurements at the MMP (TRE2) shows that there is a shift between the head and the Mayfield head holder rather than between the Mayfield head holder and the reference frame.

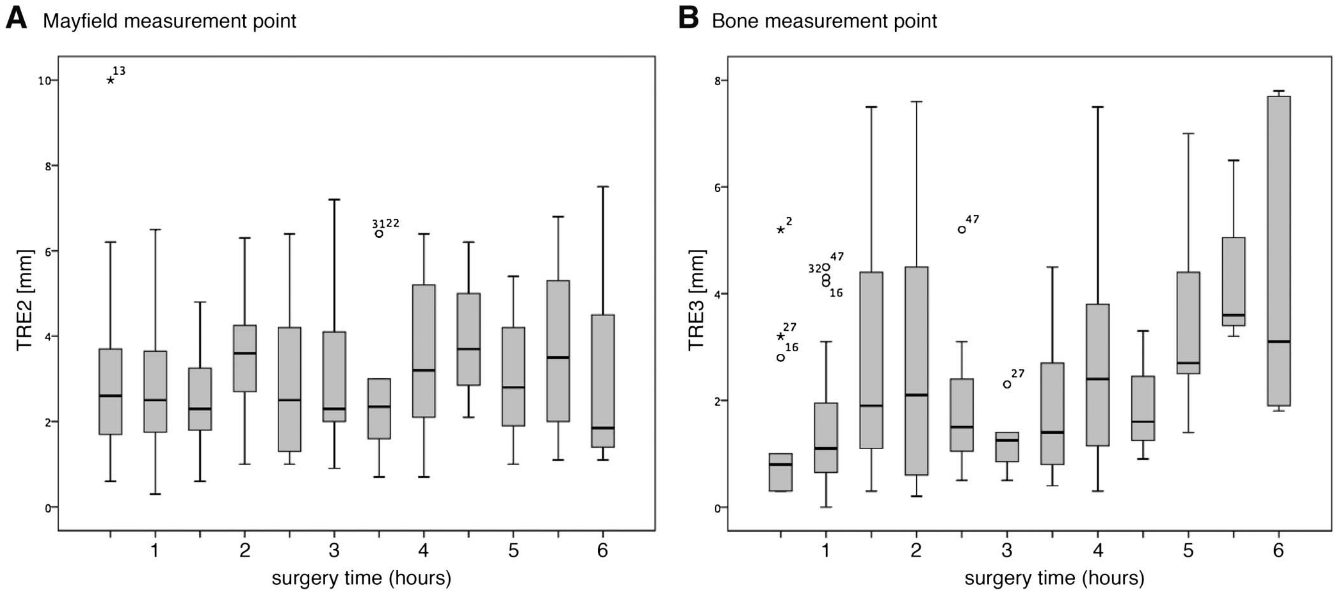

FIGURE 4. *The influence of time on the target registration error.* **A**, *the absolute target registration error measured at the bone measurement point (TRE2) is shown Although there was some change in this value throughout the surgery (Table 4), the differences from the initial target registration error (TRE1) were not statistically significant.* **B**, *the absolute target registration error measured at the bone measurement point (TRE3). This value tended to increase with the time of surgery. The changes at later time points were statistically significant (Table 4).*

Is Neuronavigation Reliable?

All data presented here prove that the increase in the neuronavigation system's mismatch is not related to the hard- or software of the image guidance system, but rather to the head fixation and application of additional forces after coregistration. Furthermore, these results underline the fact that there are some weak points in frameless stereotaxy, and these should be recognized by the surgical team. Table 5 summarizes the large number of different steps belonging to navigated cranial surgery, each harboring some danger of additional mismatch. The effective TRE at a certain time of surgery is the sum of all steps performed up to that time. Therefore, we consider identification and analysis of each of these steps to be

TABLE 4. Changes in Target Registration Errors With Time of Surgery[a]

TRE2 Measured at MMP (Measured at 0.5-6 h)

T, h	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
No.	41	39	16	15	14	14	10	10	4	11	5	6
Mean	2.9	2.8	2.4	3.6	3	3.1	2.9	3.4	3.9	3.1	3.7	3.0
SD	1.8	1.5	1.2	1.5	1.9	1.9	2	1.9	1.7	1.5	2.3	2.5
Median	2.6	2.5	2.3	3.6	2.5	2.3	2.4	3.2	3.7	2.8	3.5	1.9

T (5, 5.5, and 6 h) vs T (1-3.5 h) (P = .300-.978)

TRE3 Measured at BMP (Measured at 0.5-6 h)

T, h	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
No.	13	28	17	14	12	8	7	8	3	7	3	5
Mean	1.3	1.5	2.8	2.7	1.9	1.2	1.9	2.8	1.9	3.6	4.4	4.5
SD	1.5	1.2	2.1	2.3	1.3	0.6	1.5	2.4	1.2	2	1.8	3.1
Median	0.8	1.1	1.9	2.1	1.5	1.3	1.4	2.4	1.6	2.7	3.6	3.1

T (4) vs T (T1): P = .021; T (5) vs T (1.5): P = .004; T (6) vs T (2): P = .040

[a]TRE2, TRE2, target registration error measured at the Mayfield measurement point; MMP, Mayfield measurement point; T, duration of surgery; No., number of patients contributing to the measurement; BMP, bone measurement point. For the measurements at the MMP, the distribution is equal (P = .3-.978), but there was a constant and significant increase in the TRE3 measured at the BMP (Kruskal-Wallis test, $P < .05$).

TABLE 5. Neuronavigation Workflow and Possible Origins of Deviation[a]

Preoperative	(Placement of skin fiducials)	Improper placement/positioning
	↓	
	Preoperative neuroimaging	Limited resolution of MRI/CT
		Patient position in scanner not identical with position in OR (soft- tissue displacement by gravity, head rest)
		Motion artifacts in MRI/CT
	↓	
	(Delay until begin of surgery)	Displacement of skin fiducials
		Use of too few skin fiducials
	↓	
	Planning	Deviations by
		Improper selection of skin fiducial center
		Image fusion mismatch
		Software-dependent deviation
	↓	
Intraoperative	Patient positioning	Soft-tissue displacement by head holder frame
		Soft-tissue displacement by tracheal tube
		Improper fixation of reference frame
	↓	
	Coregistration	Deviations by
		Physical error of optical localization method
		Improper threshold of 3-D skin reconstruction for surface matching
		Displacement of skin fiducials during Paired-point matching or improper targeting of fiducial center
		Software-dependent deviation
	↓	
	Preparations for surgery	Movement of head in head holder frame by weight or traction from attachment of surgical drapes
	↓	
	Surgery	Deviations by
		Movement of head in head holder frame by
		Trepanation
		Craniotomy
		Retractors
		Accidental displacement of reference frame
		Damaged neuronavigation tools (reference frame, pointer)
		Improper calibration of instruments (microscope)
		Improper attachment of reference marker balls to instruments
		Deviation by accidental movement of the patient (seizure)
		Deviation by accidental movement of the patient resulting from improper positioning or movement of the operating table
		Other

[a]MRI, magnetic resonance imaging; CT, computed tomography; OR, operating room; 3-D, 3-dimensional.

useful for improving the accuracy of image-guided surgery and improving patient outcomes.

An important step is to improve the Mayfield head rest frame. This head rest was invented in 1974, long before the invention of frameless stereotaxy. It was designed to enable firm fixation of the head and rapid closure. The system's brilliance is reflected in the fact that it has been used for most cranial surgeries since its invention. Despite the success of the Mayfield head rest, it was not intended to support frameless navigation and therefore allows minor movement of the head, which results in considerable navigation mismatch in cases in which strong forces are applied.

The second step is to reconsider the optimal time for coregistration in cases in which minimization of the mismatch is required. Our results show that procedures before tumor localization and removal, as well as the duration of surgery, decrease neuronavigation accuracy. The use of bone screws for paired-point matching allows the coregistration to be performed immediately before the critical phase of the surgery and thus avoids the inaccuracies caused by certain procedures and prolonged surgery times.

The brain shift problem cannot be addressed in this manner. After the dura is opened, there might be movements of the intracranial soft tissue that reduce the value of neuronavigation without influencing

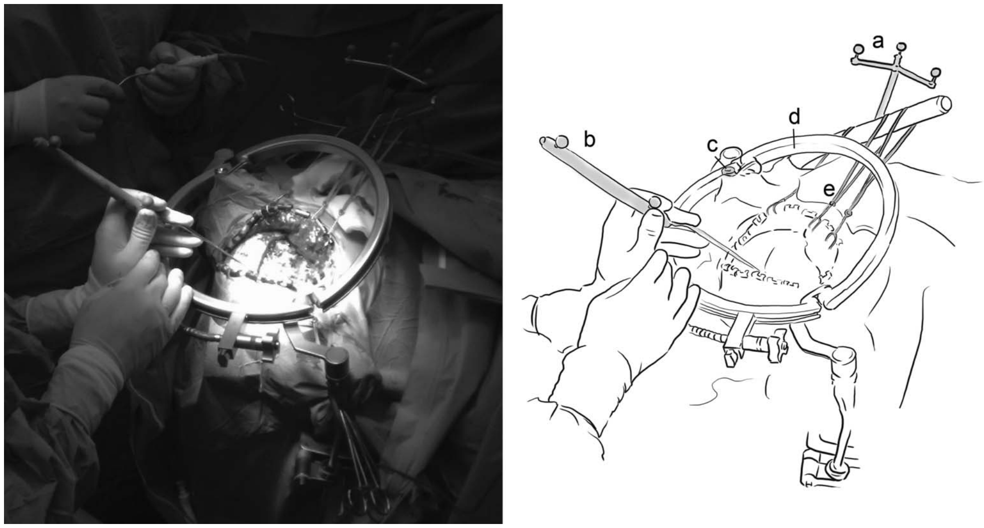

FIGURE 5. *Tissue retraction using skin retractors. A typical intraoperative situation with the reference frame (a); a neuronavigation pointer (b), the Mayfield measurement point (c), a halo ring attached to the Mayfield head holder (d), 3 retractors pulling a skin flap in one direction (e).*

its physical accuracy. In such situations, both intraoperative imaging and attempts to minimize the surgical approach are useful. For minimally invasive frame-based procedures, as for deep brain stimulation, brain shift is reported to be less relevant.[26]

CONCLUSION

In a standard setup, neuronavigation is susceptible to numerous events that decrease the accuracy. The attachment of surgical drapes and use of skin retractors are of special importance because they apply considerable force to the head holder. The surgical team should be aware that the navigation mismatch will increase with certain surgical procedures and with increasing duration of the procedure. This should be considered during planning and execution of procedures in eloquent structures, and regular accuracy checks should be mandatory.

Disclosures

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COMMENTS

The authors report a retrospective analysis of 55 consecutive operations, evaluating factors that may influence loss of accuracy from frameless neuronavigation systems during surgery. This is certainly an important topic in neurosurgery. Frameless stereotaxis has been extensively adopted as a standard technology in the operating room. Although this technology can be very useful, it is important to keep in mind its limitations and factors that may influence its accuracy. The authors showed that loss of neuronavigation accuracy can occur at several points during the course of operations and even before skin incision. Accuracy was affected by placing the surgical drapes as well as skin retractors. Interestingly, the forces related to placement of the burr holes and craniotomy had only minor effects on accuracy. One of the limitations of this work is related to the method for coregistration. Most patients in the study had coregistration with devices from a single company. The technique for coregistration relied mostly on anatomic landmarks and surface scanners. It is possible that coregistration with skin or bone fiducials would be associated with fewer changes in accuracy during surgery. Future studies could be powered for direct comparison of the different coregistration methods (with and without fiducials) as well as for comparison of neuronavigation systems. It would be interesting to learn whether factors affecting accuracy during surgery differ across coregistration techniques and devices.

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The authors present a detailed analysis of frameless neuronavigation accuracy during 55 consecutive intracranial procedures. Moreover, they provide a comprehensive overview of factors that may lead to navigation errors during the surgical work flow.

Their results confirm that navigation accuracy deteriorates over time during an intervention. Attachment of surgical drapes and, to a lesser degree, of skin retractors produced the most significant negative impact on registration accuracy. Minor movement in the Mayfield head rest frame was identified as a potential causative factor; an updated design that provides superior rigidity of fixation would acknowledge its extra role in frameless neuronavigation. Brain shift, resulting from cerebrospinal fluid loss and "brain slump" or from brain re-expansion during surgery for mass lesions, generates additional navigation errors to those identified in this study.

Awareness of potential pitfalls is the first step toward minimizing their negative impact. Neurosurgeons increasingly rely on frameless neuronavigation, making this study a valuable contribution to the literature.

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