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Frameless Stereotactic Guided Neurosurgery: Clinical Experience with an Infrared Based Pointer Device Navigation System

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Summary

An infrared based frameless stereotactic navigation device (Easy Guide Neuro) was investigated for its clinical applicability, registration/application accuracy and limitations in a standard operating room set-up.

In a five-month period 40 frameless stereotactic procedures (23 female, 17 male, mean age 46.4, yrs range 10–83) including 36 craniotomies and 4 spinal surgery procedures were performed. Image registration, data transfer and operation planning using skin fixed fiducials (between 5–10, mean 6.6) and CCT in 12 patients/MRI in 28 patients, generally was done the day before surgery.

Clinical applicability was proven in all procedures with an additional time for pre-operative imaging and system application in the OR of 50 min mean (35–120 range). A useful registration was achieved in 39/40 patients (97.5%) with a registration accuracy of 3.4 mm (range 1.8–6.7) for brain surgery cases and 14.4 mm (6.8–25) for spine cases. This resulted in intra-operative application accuracy values for brain surgery of 4.2 mm mean (range 1–12). Enhanced registration/application accuracy values over the test period from 4.2/3.8 mm mean (Cases 1–20) up to 3.2/2 mm mean (Cases 21–40) was observed. In spinal surgery an application accuracy of 11.3 mm mean (range 5–20) was found. An intra-operative re-calibration because of system-head drift was necessary in none of the patients, nevertheless, application accuracy degradation due to brain shift was detected in every case.

In conclusion, the system allowed a time sufficient accurate frameless intra-operative localisation guidance in cavernoma, meningioma, glioma, and brain metastasis surgery. In spinal surgery, the application accuracy exceeded clinical usefulness due to high registration inaccuracy using skin markers.

Keywords: Frameless stereotaxy; easy guide neuro; stereotactic surgery; neuronavigation.

Introduction

Frameless stereotactic guided surgery was developed for the localisation and resection guidance of small superficial or deep-seated lesions, avoiding the limitations of a stereotactic frame [12, 13]. To overcome the interference of the arc with the surgical exposure and the limitations of a stiff, linear trajectory, the stereotactic frame is replaced by skin fixed fiducials and the space information of a freehand movable pointer device or the operation microscope is registered to pre-operatively obtained, multiplanar reconstructed CT/MRI images on a computer workstation [12, 13].

Since the pioneer work of Roberts *et al.* in 1986 [27] several frameless stereotactic systems were developed and a few are commercially available now [2, 3, 8, 10–19, 22, 26–28, 32–36]. Nevertheless, clinical reports about the usefulness of the different systems are rare [6, 7, 11, 20, 24, 26].

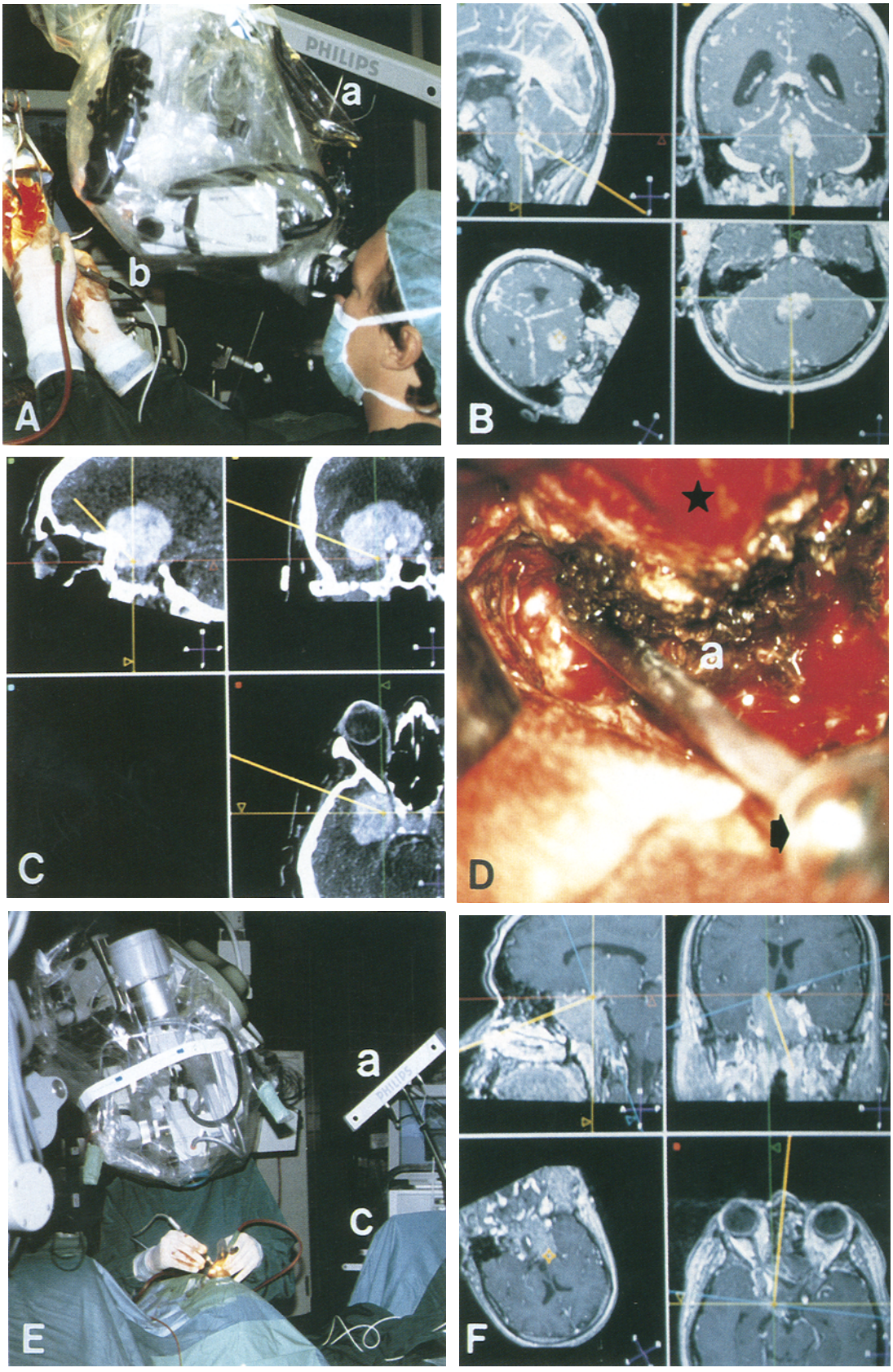
We have investigated the clinical applicability, adequacy of registration and application accuracy and clinical usefulness of a LED pointer device system in a standard operating room set-up.

Patient Population, Material and Methods

Patient Population

Between August/September 1995 and March to June 1996 the Easy Guide System was used for 40 frameless stereotactic guided procedures at the Department of Neurosurgery, University of Vienna Medical School, Vienna, Austria (Table 1). Small superficial or deep seated lesions for targeting and lesions in or near eloquent areas for image guidance were selected for evaluation (Table 1). The mean age of the 23 female and 17 male patients was 46.4 years (range 10–83).

Brain surgery included craniotomies for tumour surgery (32 cases, 77%: 11 meningiomas, 6 glioblastomas, 4 low-grade gliomas, 3 metastases, 2 anaplastic astrocytomas and 6 others, Table 1), approach planning for vascular neurosurgery (3), epilepsy and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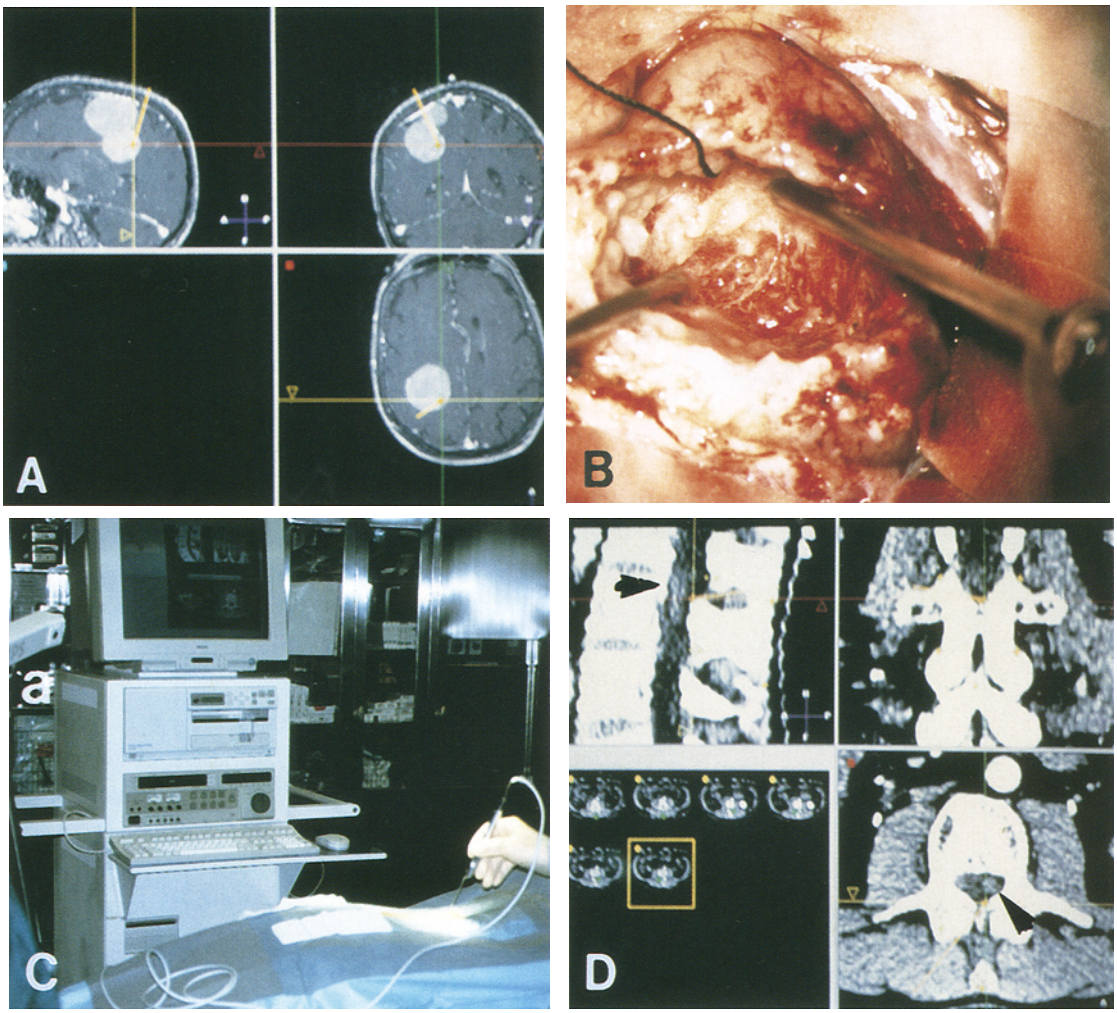

Fig. 2. (A, B) Frameless stereotactic guidance during resection of a convexity meningioma. Identification of lesion borders avoiding cortex injury during suction of the tumour. (A) Corresponding multiplanar reconstructed MRI images corresponding to the intra-operative location of the pointer device tip. (B) Frameless stereotactic guided resection is possible even using the microscope. (C) Spinal surgery, patient in prone position: frameless stereotactic guided resection of a nerve root lesion at L3 (suspected neurinoma, histologically: malignant melanoma). The primary skin fiducial based registration exceeded acceptable application accuracy. *a*: Position of the camera array. (D) Corresponding multiplanar reconstructed images during pre-operative planning with virtually elongated pointer. The top of the yellow trajectory is at the tumour. Arrowhead: marking the tumour

Fig. 1. (A) Easy Guide frameless stereotactic navigation during resection of a medulloblastoma under the microscope. The patient is in the sitting position, the camera array (*a*) is mounted on the operation table and positioned near the patient's head, to allow light emitting diode (LED) contact between the pointer device (*b*) and the camera (*a*). (B) Corresponding multiplanar reconstructed images on the workstation screen. The pointer trajectory is visible as a yellow arrow, leading to the lesion. Sinus localisation and placement of appropriate burr holes before bone flap excision as well as intra-operative orientation within the tumour are possible. (C) Neuronavigation during resection of a medial sphenoid wing meningioma. Frameless stereotaxy allowed on-line orientation within the tumour and on the borders of the tumour on multiplanar reconstructed images. The trajectory and tip of the pointer device is visible as a yellow arrow on the reconstructed images. (D) Corresponding intra-operative picture, seen through the operation microscope. *a* Resected tumour bed. Asterisk: cranial base, sphenoid wing. Arrowhead: LED of the pointer device. The tip of the pointer device at the anterior medial border of the tumour is shown on the multiplanar reconstructed images. (E) Frameless stereotactic guidance during transsphenoidal removal of a pituitary adenoma. The camera array (*a*) is positioned near the patient, just over the C-arm (*c*), to allow LED contact. (F) Corresponding multiplanar reconstruction on the computer workstation screen. The neuronavigation facilitates the orientation para- and suprasellar

Table 1. *Patient Data*

Case no.	Age	Sex	Diagnosis	Localisation	Procedure
1	10	f	glioblastoma	ri central	gross total resection
2	31	m	DNT/epilepsy	ri temporal	amygdalohippocampectomy
3	53	f	meningioma	ri petroclival	subtotal resection
4	38	f	meningioma	ri frontal	gross total resection
5	69	m	meningioma	ri sphenoid wing	gross total resection
6	65	f	glioblastoma	ri temporal	gross total resection
7	61	m	glioblastoma	le temporal	gross total resection
8	46	f	melanoma metastasis	ri L3 nerve root	resection
9	31	m	astrocytoma	le pre/central	subtotal resection
10	63	m	meningioma	re ant. skull base	gross total resection
11	33	f	aneurysm	ACA	clipping
12	15	f	medulloblastoma	cerebellar vermis	gross total resection
13	79	m	subdural haematoma	le parietal	2 burr holes
14	43	f	metastasis, hydrocephalus	le occipital	guided ventriculostomy
15	48	m	glioblastoma	le temporal	gross total resection
16	83	f	meningioma	ri central	gross total resection
17	76	f	meningioma	ri ant. skull base	gross total resection
18	62	f	metastasis	le postcentral	gross total resection
19	26	m	prolactinoma	endo/suprasellar	gross total resection
20	65	f	glioblastoma	le central	gross total resection
21	55	f	central pain	le motor cortex	burr hole localisation
22	40	m	aneurysm	BA	clipping
23	48	f	anaplastic astrocytoma	re frontal	subtotal resection
24	53	f	aneurysm	re MCA	clipping
25	35	m	capillary haemangioma	re cavum Meckeli	gross total resection
26	41	m	meningioma	le precentral	gross total resection
27	56	m	glioblastoma	re temporo-parietal	subtotal resection
28	41	m	demyelination	C2/3	biopsy
29	31	f	ganglioglioma	re temporal	gross total resection
30	56	f	cavernoma	ponto-mesenceph.	resection
31	12	m	low-grade astrocytoma	re frontomed.	gross total resection
32	43	m	ependymoma grade I	C3–7	gross total resection
33	35	m	meningioma	le central	gross total resection
34	46	m	craniopharyngioma	suprasell	gross total resection
35	46	m	chordoma	suprasell	gross total removal
36	21	f	ganglioglioma	mesencephal	cyst fenestration
37	87	f	meningioma	Th6	gross total resection
38	51	f	meningioma	le orbita	subtotal resection
39	29	f	cavernoma	pons	resection
40	42	f	meningioma	re petroclival	subtotal resection

no. number, *f* female, *m* male, *ri* right, *le* left, *DNT* dysembryoplastic neuroepithelioma, *BA* basilar artery, *MCA* middle cerebral artery, *ACA* anterior communicating artery, *infratent* infratentorial, *supratent* supratentorial.

functional neurosurgery (2), cavernoma removal (2) and guidance for burr holes, biopsies and drainages (5). Spinal surgery included 4 procedures for intraspinal tumours at various spinal levels (Table 1).

System Description

The Easy Guide Neuro (Philips Medical Systems, DA BEST, The Netherlands) is a LED (Light emitting diode)-based computer system for frameless stereotactic navigation consisting of 3 main components: a mobile workstation, a position digitizer (camera array) and a pointing device.

The position digitizer is based on two 2-dimensional charged coupled device (CCD) cameras in a compact housing, to be attached to the side rail of the operating table. Thus, head/body movement with simultaneous camera movement becomes possible without re-registration.

A freehand pointing device is equipped with 3 light emitting diodes (LED). From the position of the diodes, the computer calculates the position, direction and rotation of the tip of the instrument in space. This space information is registered to the pre-operative images loaded into the workstation.

Intra-operative re-registration is possible at any time in a few

minutes by defining 4 additional landmarks around the bone flap after craniotomy.

Fiducial Markers and Marker Placement

For pre-operative CCT scans, commercially available 1.5 mm metal beads on self sticking plates (Beekley Spots, Bristol, CT, USA), for pre-operative MRI imaging, self sticking ring markers with 1.5 cm diameter and a 1 mm defined centre (Topographic Markers, EZ-EM Inc., Westbury, NY, USA) were used. The markers were placed around the visible contours of the head seen from the expected traject of the entry point to target point by creating a stereotactic space. Attention was drawn, not to place markers on the place of the expected skin flap area. Stable scalp locations for marker placement were chosen: mastoid, frontal and parietal tuber, forehead.

Imaging Protocol and Registration

Imaging studies were generally obtained the day before surgery after application of fiducial markers using Philips CCT or MRI scanners. The imaging protocol for CT consisted of a spiral scan mode with 3 mm thick slices/1 mm reconstruction index. T1-weighted MRI was performed using 1.5 mm thick slices. In the tumour cases, contrast enhanced studies were performed. CT based navigation was performed in 12 patients, MRI based navigation in 28 patients.

The data transfer was done by magneto-optical disk (MOD) for reconstruction and planning using the computer workstation the evening before surgery. Fiducial markers were identified on the reconstructed images and defined as reference structures with the planning software. One major software breakdown occurred in the series of 40 cases, where the operation was finished according to standard neurosurgical guidelines without problems.

Evaluation of Registration Accuracy, Nearest Marker Test

The system is registered at the beginning of the operation after head fixation in the head clamp and mountage of the camera array in a stable position. The fiducial markers on the patient's scalp are localised with the pointer device tip one by one and confirmed on the workstation. The registration accuracy, given as the root mean square error (RMSE) in mm, is a computer calculated value, using a matching algorithm [23] after successful registration of all markers. It compares the relationship of the fiducial position on the images with that on the patients head after registration in the OR and gives information about fiducial/skin movement between scanning and registration and allows similar to the nearest marker test (pointing at the fiducials used for registration after the first registration) to exclude the fiducials with the worst shifts in a new registration. Attention was drawn to avoid skin shifts during patient positioning and fixation of the head in the automatic head arrest (standard Mayfield clamp). The stable camera position allows a free moveable table/patient without a re-registration during the operation.

Evaluation of Application Accuracy, Check Marker

The application accuracy is the total achieved accuracy of the system measured in mm, evaluated after successful registration by comparing target lesion/target contours with the workstation images at the beginning of every procedure. Additionally, a check marker, not used for registration, was applied in every case for this measurement, comparing the position of the marker on the images with its real position on the scalp. Application accuracy was evaluated at the beginning of every procedure. Inaccuracy due to head/system shift during the operation is ruled out by checking landmarks on the bone flap margin every 30 minutes and was not detected during the study.

Virtually Elongated Pointer Surgical Planning

After registration of the patient's head and accuracy check, a virtual pointer device elongation along the pointer trajectory provided by the software was used for operation planning. Skin incision, size of the bone flap, and contours of the target were drawn on the skin and distance to the target was measured (Table 2).

Results

The clinical applicability was proven for all standard patient positioning including the sitting position and prone position for spinal surgery.

The registration accuracy (root mean square error, RMSE) after patient to image registration of the 36 brain surgery patients was 3.4 mm mean (range 1.8–6.7 mm) as calculated by the computer software at the end of patient-to-image fiducial correlation

Table 2. *Results*

Application/Case no.	Diameter lesion cm	Distance to lesion cm	Marker no.	Registration accuracy (RMSE) mm	Application accuracy mm
Cranial surgery/n = 36					
Cases 1–20	mean 2.9 (range 1–5)	mean1.7 (range 0–10)	mean 7 (range 5–9)	mean 4.2 (range 2.5–6.7)	mean 3.8 (range 1–12)
Cases 21–40	mean 2.4 (range 1–4)	mean 3.1 (range 0–6)	mean 6 (range 6–8)	mean 3.2 (range 1.8–4.4)	mean 2.0 (range 2–5)
Spinal surgery/n = 4	mean 1.5 (range 1–3)	mean 6 (range 5–7)	mean 9 (range 8–10)	mean 14.4 (range 6.8–25)	mean 11.3 (range 5–20)

no. number, *RMSE* root mean square error.

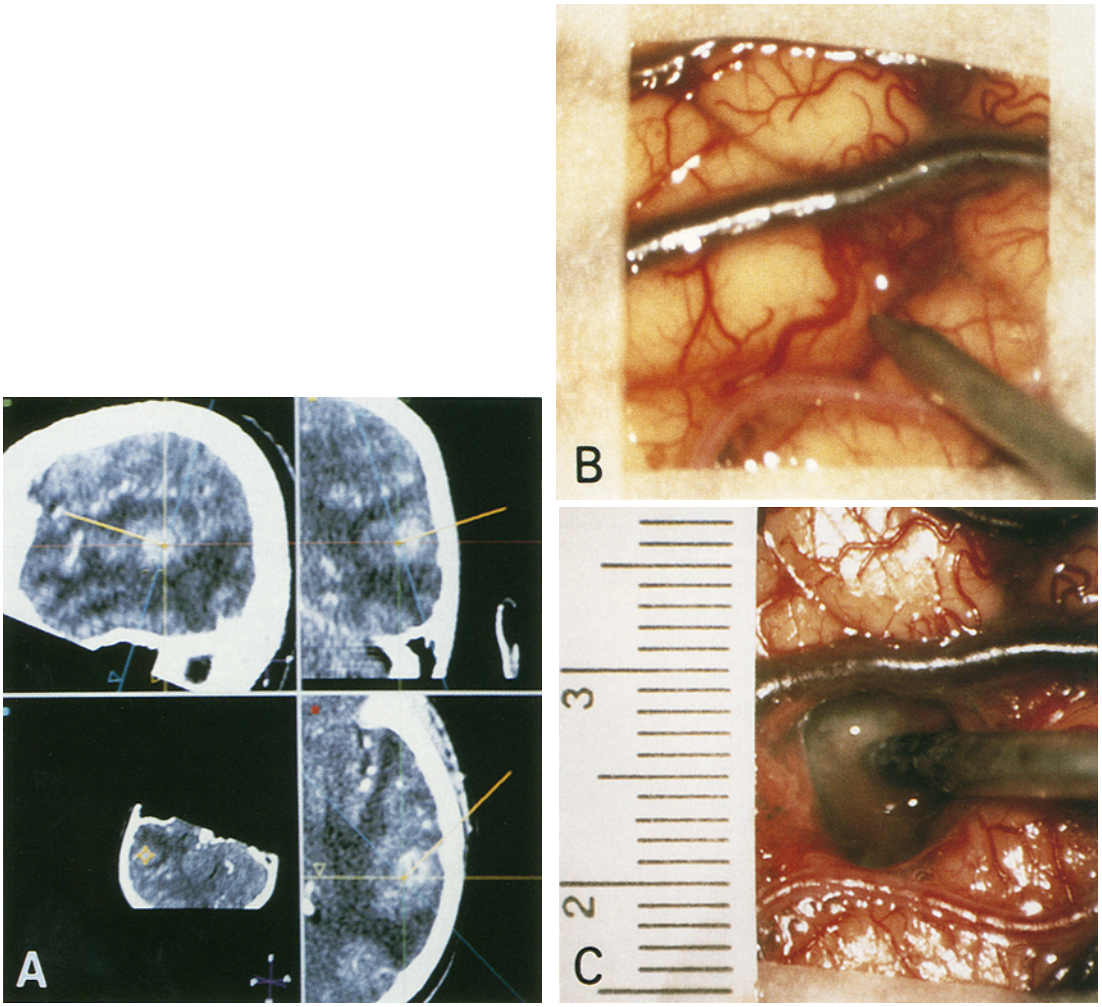

Fig. 3. (A) Frameless stereotactic localisation of a temporal lesion, where frame based localisation would have been the only alternative. The yellow trajectory is corresponding to image C, the pointer tip is at the lesion ground in all reconstructed images after successful resection of the enhanced focus. (B) The lesion is invisible after cortex exposure. The tip of the pointing device localised the lesion and allowed exact positioning of the corticotomy. (C) After corticotomy the intra-operative histological examination revealed an anaplastic astrocytoma

(Table 2). The 4 spinal surgery cases had an RMSE of 14.4 mm mean (range 6.8–25) after registration on skin markers.

The mean application accuracy values of the system in finding the target lesion or determining the lesion borders at the start of every cranial surgery procedure was found 4.2 mm (range 1–12). An enhanced registration as well as application accuracy over the test period from 4.2/3.8 mm mean (Cases 1–20) to 3.2/2 mm mean (Cases 21–40) was observed. In the spinal surgery cases an application accuracy of 11.3 mm mean (range 5–20) was detected.

The provided application accuracy allowed an optimised skin incision planning, craniotomy planning, lesion localisation and definition of the lesion borders in all investigated supra- and infratentorial brain tumour surgery. In transsphenoidal surgery, vascular neurosurgery, brain stem surgery and surgery around the floor of the 4th ventricle provided accuracy levels were of limited value, whereas trajectory guidance was useful for the approach preparation. In spinal surgery, accuracy levels exceeded clinical usefulness.

Discussion

Since the pioneer work of Roberts *et al.* 1986 [27], who integrated an ultrasound based frameless stereotactic localisation system into the operating microscope, many frameless stereotactic systems have been developed and a few are commercially available now [2, 3, 8, 10–19, 22, 26–28, 32–36]. Reports about the

clinical usefulness of commercially available frameless stereotactic localisation systems, based on different technical principles, are rare up to now [6, 7, 11, 20, 24, 26]. Thus, we have investigated a newly available infrared based pointer device localisation system.

Clinical Applicability

The pointer device localisation system proved to be easy to integrate in a standard operating room set-up with an additional time effort for scanning, data transfer and registration of 50 (range 35–120) minutes mean. In brain surgery, the system was applicable in supratentorial as well as in infratentorial procedures together with the microscope, even in the sitting position of the patient. In spinal surgery, the usage was possible without changing system components.

Registration Accuracy and Application Accuracy

A registration accuracy of 3.4 mm (range 2.0–6.7) for the 36 brain surgery cases was calculated by the computer workstation using a matching algorithm at the beginning of the procedures, giving information about shifts of fiducial markers in the time period between scanning and the registration. Values < 4 mm resulted in clinically useful application accuracy levels during lesion targeting, lesion border definition or identification of anatomical details of 4.2 mm mean (Cases 1–20), with enhanced values of up to 2 mm mean during the second half of the test period (Cases 21–40). Comparing these findings with the literature, a high mechanical accuracy of frameless stereotactic navigation systems, independent of their technical principles, is reported within an average of 1–2.5 mm, comparable to that of standard frame systems [2, 11, 26, 32–35]. In contrast to these experimentally recorded values, the application accuracy during clinical use is reported significantly lower, between 2–6 mm, depending on the system, the slice thickness of the images used, the reported number of patients, the location of fiducials, the time protocol of fiducial application, imaging and operation and the technique of head positioning in the head clamp [6, 24, 27, 34]. Compared to our results, higher accuracy levels reported by others [11] might have multiple causes.

Factors, Degrading Application Accuracy

Generally, we have performed pre-operative neuro-images after fiducial application the day before surgery. This may result in shifts of the self sticking fiducial markers over night due to the mechanical stress of scalp movement. This was avoided in other studies [11], but was not practicable in our radiological department. As demonstrated in fewer studies, the slice thickness of the neuro-images plays an important role for high accuracy in both, frame based and frameless stereotaxy [6, 9, 26]. In our study we have used a reliable protocol for CT/MRI using 3 mm thick CT slices with 1 mm reconstruction index and 1.5 mm thick MR images, similar to other investigators [6, 11, 35]. The location of the fiducial markers on certain head areas might also play a role for accuracy. In our experience, the skin over the mastoid, the frontal and parietal bones and the forehead appeared less moveable than in other locations. No data concerning this problem are available in the literature. The number of fiducial markers (5–10 in our study) used was found not to influence the accuracy in this study significantly, nor in a smaller, experimental study with another navigation system [29]. A critical step seems to be the fixation of the patient in the head clamp. During this manoeuvre, remarkable distortion of the scalp and shift of the fiducials might occur.

All sources of error together contribute to application accuracy and might explain a continuous improvement of accuracy as was detected during our study. Application accuracy values improved up to <2 mm in 87.5% of the patients during Cases 21–40. This might also explain the reported higher accuracy levels in studies with higher patient numbers [11].

Clinical Usefulness

The detected millimetric registration and application accuracy levels of the system during clinical use resulted in a clinically sufficient targeting and resection guidance in the brain tumour surgery cases. In meningioma surgery the application accuracy was sufficient to determine the extent of the bone flap, exact tumour margins as well as determination of the extent of exophytic tumour parts during resection, thereby aiding complete resection and potentially lowering the risk of recurrence.

According to studies with prolonged survival in glioma patients with rigorous debulking of contrast enhanced solid tumour tissue in high grade gliomas and extensive surgical resection in low-grade gliomas [1, 5, 21, 25, 30–32], border definition and resection guidance allowed this approach avoiding lesions in risk areas.

In metastasis and cavernoma surgery the system allowed lesion targeting and removal by planning the safest, minimally traumatic approach without missing the target by the provided application accuracy.

Thus, in agreement with other clinical reports, targeting of cavernomas, neuro-image guided localisation and resection of supratentorial gliomas, meningiomas and metastases were the most useful indications for the system [2, 3, 6, 11, 26, 32–34]. At this time, the provided accuracy levels were of limited value for other investigated applications like transsphenoidal surgery, vascular neurosurgery, brain stem surgery, surgery around the floor of the 4th ventricle and insufficient for spinal surgery (Table 2).

Intra-Operative Brain/Lesion Shift

Although a slight brain shift due to loss of cerebrospinal fluid, tumour removal or anaesthesiological factors was detected, successful targeting of lesions was possible in every investigated case, but resection guidance lost importance during the operation as a result of the detected shift. As reported in the literature [15, 16], the following measures were considered: The patient positioning was performed in a way to place the craniotomy at the uppermost point of the head to avoid cerebrospinal fluid loss. Additionally, the blood pressure and pCO_2 were kept constant during the whole procedure. Brain retraction was avoided.

Conclusions

In conclusion, the system provided a sufficiently accurate lesion localisation, definition of lesion boundaries and target trajectories in our series for brain tumour surgery in meningiomas, gliomas and metastases as well as cavernomas. Accuracy degradation during surgery mainly due to brain/lesion shift limited the advantage of image guidance during or at the end of resection. Studies with intra-operative registration refreshment using ultrasound and intra-operative CT are under way.

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Investment Disclosure

The authors do not have any financial interest in the investigated system and will derive no monetary benefit from the publication of the article.

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Comments

The reported accuracy levels and description of the method, by which they have been determined, is the useful information in this paper. The authors should not use too much effort to try to convince us about the clinical usefulness or futility. It is basically enough to give the figures and a short opinion; the reader will judge for himself whether the accuracy and additional effort and investment appeals to him.

The determined application accuracy is anyway only an approximate indicator, and does not have scientific power. Indeed, the authors use intra-operative determination of the target contours as one of the measures for application accuracy; that means that these borders are visible to the eye during the operation. On the other hand, they state that the system was useful to determine the exact tumour margins. This, of course, is a scientifically dangerous inversion; if the contours are visible and can be used for calibration, then the system is not useful for boundary determination, and vice versa.

I also think that the authors underestimate problems of brain shift, especially during resection of hemispheric tumours with poor delimitation.

H. Fankhauser

The paper by Roessler *et al.* deals with the preliminary intraoperative evaluation of an infrared image-guided neuronavigation commercially available system. 29 surgical procedures, intentionally covering the average field of neurosurgical practice were performed and accuracy data as well as surgeon evaluation usefulness are provided.

The study has been correctly performed, from the methodological point of view. The figures are well done and correctly describe the method on practical grounds. The hardware and the software are not described in detail, as they are considered as commercially available for everyone.

The results show that accuracy is within acceptable limits for the considered surgical applications, that the system does not bring a significantly increased complexity of the operating set up and that usefulness (considered as an additional help brought by the system) is considered by the surgeon as worthy.

The discussion highlights the advantages of this method as compared to other published equivalent reports.

Although this paper does not bring real scientific knowledge or data, it is interesting to inform the neurosurgical world of the performances of the commercially available guidance systems, for which they start to have to make a choice when they want to acquire such a system. Under these circumstances, this type of preliminary report can be published, to contribute building up a set of data on which further choices should be made.

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