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Neurosurgical Techniques

Impact of Brain Shift on Intraoperative Neurophysiological Monitoring with Cortical Strip Electrodes

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Summary

Background. Intraoperative neurophysiological monitoring has become the standard procedure for locating eloquent regions of the brain. Such continuous electrical stimulation of motor pathways is usually applied by means of flat silicon-embedded electrodes placed directly on the motor cortex. However, shifting of the silicon strip on the cortical surface as well as electrode displacement due to brain shift underneath the electrode can lead to inaccurate recordings not directly caused by intraoperative impairment of the motor cortex or the motor pathways.

Method. This prospective study was conducted to quantify cortical brain shift during open cranial surgery and to assess its impact on electrode positioning in 31 procedures near the precentral gyrus. Three groups of different lesion volumes were distinguished. Movement of the cortex between opening of the dura and completion of tumor removal as well as cortical electrode shifting were digitally measured and analyzed.

Findings. Cortical surface structures evidenced a significantly larger shift (up to 23.4 mm) in comparison to the electrode strips (up to 4.2 mm) in lesions with a volume of over 20 ml. Cortex shifting highly correlated with lesion volume, whereas strip electrode movement was almost unidirectional and did not differ significantly among the three groups. However, the way they were placed (completely on the cortex vs. partly underlying or overlapping the craniotomy borders) affected the magnitude of their intraoperative displacement. As a consequence, 3 of the 31 cases (9.3%) showed a significant change in the recorded motor responses due to intraoperative dislocation of the stimulating electrode.

Interpretation. Changes in the location of cerebral structures due to intraoperative brain shift may exert a marked influence on intraoperative neurophysiological monitoring if cortical strip electrodes are used. Therefore, long-term monitoring of the central region requires continuous checking of the position of stimulating electrodes and, if necessary, correction of their location.

Keywords: Brain shift; functional neurosurgery; neuronavigation; neurophysiological monitoring.

Introduction

Intraoperative functional mapping and monitoring techniques have proven to be useful complementary techniques for localizing functionally relevant areas of the brain. They allow for removing intracranial lesions with a maximum of safety and efficacy and with a minimum of invasiveness. Under general anesthesia motor function can be tested best by direct stimulation of the motor cortex [1, 9, 10, 25]. This technique provides real-time monitoring with frequent feedback to the surgeon and is preferably performed using flat silicon strips with embedded steel or platinum electrodes which are placed directly on the brain surface after opening of the dura. Changes in the latency and amplitude of compound muscle action potentials (CMAPs) generated in contralateral extremity muscles serve as warning signals against surgical maneuvers potentially producing functional damage. However, experience with this procedure in the routine clinical setting shows that intermittent or permanent changes in the generated CMAPs may be caused not only by actual deviations in potential but also by misplacement or dislocation of the strip electrode [9, 10, 23]. This failure may be due to several factors: (a) misplacement of the electrode strip in relation to the anatomical location of the sensorimotor cortex; (b) intraoperative shifting of cortical structures underneath the electrode, or (c) mechanical displacement of the electrode by the operator. The extent of such intraoperative cortical

movement (so-called "brain shift" or "brain distortion") and its impact on neurosurgical procedures, stereotactical interventions, and neuronavigation have already been investigated by several authors [2, 5, 21]. However, the causes, magnitude, and biomechanical processes underlying such distortion as well as the influence of tumor type and the imaging characteristics are still poorly understood as brain shift is a continuous dynamic process which is difficult to predict. The aim of the present study therefore was to determine the causes and extent of the cortical displacement of commercially available strip electrodes and to investigate the impact of electrode displacement on intraoperative neurophysiological monitoring (IOM) in patients undergoing removal of masses near the central region.

Methods and Patients

Patients

Measurements were performed in 31 intracranial procedures carried out between November 1998 and August 2001. There were 18 males and 13 females with a mean age of 56.3 years (range: 30–78 years). Patients with a space-occupying lesion in or around the central region were included in the study. Patients undergoing burr hole biopsy as well as patients previously operated on were excluded from the study. The lesions were located in the frontal lobe anterior to the precentral gyrus in 15 patients, in the precentral gyrus in 6, and in the parietal lobe in 10 patients. Histological diagnosis was cerebral metastases in 14 cases, glioblastoma in 13, and WHO grade III astrocytoma in another 4 cases. The patients were operated on either in the supine position with the head oriented approx. 60 degrees to the contralateral side of the tumor (12 cases) or strictly on either left or right side (19 cases). Intraoperatively, the head was fixed in a Mayfield^{TM} clamp in all cases.

Anesthesia

All operations were performed under total intravenous anesthesia (TIVA) using a standard anesthesia regimen: Anesthesia was induced with propofol (1–2 mg/kg) and fentanyl (5–10 μg/kg). Propofol (75–125 μg/kg/h) was continuously applied during surgery. Analgesia was achieved by alfentanyl or fentanyl. Dexamethasone (20 mg, i.m.) was administered 2 hours before surgery and was continued perioperatively at doses of 8 mg every 4 hours. Intraoperative administration of mannitol was required in 6 of the 31 cases. Muscle relaxants were administered only for intubation and not during surgery.

Imaging and Image Analysis

All patients underwent preoperative gadolinium-enhanced magnetic resonance imaging (MRI) with acquisition of a three-dimensional volume data set consisting of contiguous sagittal MR images. In order to obtain isotropic voxels of 1 mm length, MRI was performed using T1-weighted 3D GE sequences (3D MP RAGE, magnetization prepared rapid gradient echo) with the following parameters: TR 9.7 msec, TE 4 msec, FA 12°, TI 300 msec, TD 0 sec, FOV 256 mm, matrix 256 × 256, 256 partitions, slice thickness 1 mm, acquisition time 11 min 54 sec. Lesion volume and the distance from the center of the lesion to the nearest cortical surface were measured in millimeters using the FITWare 1.0®-3D software tool (Functional Imaging Technologies, Waltersdorf, Land Brandenburg, Germany). Lesion volume was calculated from the perpendicular radii in the axial, coronal, and sagittal views using the formula for calculating the volume of an ellipsoid (volume $= 4/3\ \pi r_a r_b r_c$). Based on their size, the lesions were subdivided into three groups: Group A (volume < 20 ml), Group B (volume 20 ml to 40 ml), and Group C (volume > 40 ml).

Brain Shift Measurement Technique

The extent of brain shift and its effect on the cortical surface and on the strip electrode were measured with the aid of an electromagnetic navigation system (NEN-NeuroGuard^{TM}, Nicolet Biomedical Inc., Madison, WI, USA), a frameless, intraoperative image-guided navigation system comprising the hardware and software necessary to generate and sense a magnetic field for computing the position and orientation of miniature sensors [24], and additionally documented by digital photography. Technical details of the NEN system used have been described elsewhere [24].

Following successful adjustment of the system (registration error < 3 mm; algorithmic plausibility; no electromagnetic noise; sensor linearity) and completion of the craniotomy, two fiducials located directly at the margin of the craniotomy (burr hole for suturing up the dura) were registered and their positions stored as Cartesian data (X, Y, Z). The coordinates of these points were checked intraoperatively by repeat registration. A localization error of 1 mm in all three spatial directions was accepted as being within the system's tolerated inaccuracy while all measuring results showing a greater deviation were not used for the present study. Upon placement of the strip electrode, the coordinates of the geometric centers of the stimulating electrodes as well as those of at least 4 cortical landmarks such as sulci, cortical vessels and vessel intersections, or superficially visible tumor borders distributed symmetrically over the craniotomy were recorded (Fig. 1). The spatial positions are indicated by colored points on the 3D brain model of the navigation system. After complete removal of the tumor or whenever significant changes in potential occurred, the initially defined fiducials and the coordinates of the landmarks were registered again for comparison of the new positional data (X*, Y*, Z*) with the initially recorded data (X, Y, Z) with "X*" describing the coronal position or displacement in an anteroposterior direction, "Y*" the sagittal position or displacement in a mediolateral direction, and "Z*" the axial position or infalling or bulging of the cortext (Fig. 2).

In addition to the use of the NEN system, the surgical field was documented by digital techniques (photography, videoprint, or videotape), providing an additional means for later analysis of the spatial positions of the anatomic landmarks and of the strip electrode (angulation α relative to the craniotomy margins) using a two-dimensional overlay technique (Fig. 3).

Neurophysiological Monitoring Techniques

After dura opening, the central sulcus was identified in all 31 cases by routine recording of somatosensory evoked potential phase reversal (SEP-PR) upon stimulation of the median or tibial nerve contralateral to the lesion by means of a five- or six-contact stainless steal silicon strip electrode (Ad-Tech®-strip electrode, Ad Technic, WI, USA or PMT Cortac®-Cortical electrode, Chanhassen, USA). Once the precentral gyrus had been localized, the motor pathways were monitored by repetitive monopolar cortex stimulation (MCS) throughout the surgical procedure using the same strip electrode. For direct cortical stimulation, a short train of monopolar, anodal,

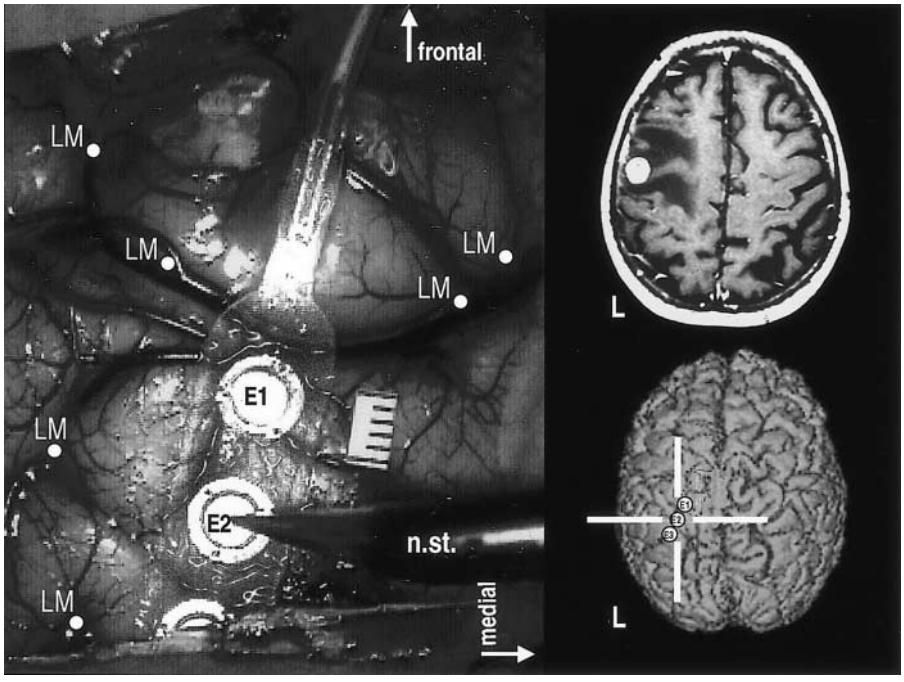

Fig. 1. Following placement of the strip electrode, the Cartesian coordinates of both the stimulating electrodes (*E1, E2* . . .) and of superficial cortical landmarks (*LM*) are registered. The spatial positions are indicated by colored points on the 3D brain model of the navigation system. Axial CT, vertically mirrored for better orientation relative to the 3D model. *L* Left *n.st.* navigation stylus

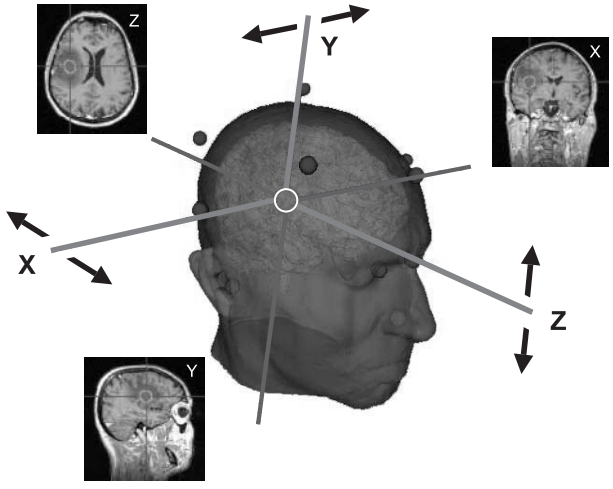

Fig. 2. (a) 3D model of the skull and brain generated from a 3D MRI data set showing the measuring axes: *X* coronal – anteroposterior displacement (b); *Y* sagittal – mediolateral displacement (c); *Z* infalling or bulging of the cortical surface (d)

rectangular pulses of high frequency (duration: 0.2–0.4 msec, frequency: 400–500 Hz, train of 3–7 impulses, intensity: 6–25 mA) was used as described in detail elsewhere [9, 10]. Electromyographic responses were recorded by pairs of needle electrodes placed subcutaneously and overlying the contralateral thenar muscle, forearm flexors, and quadriceps muscle. All studies were conducted using a Viking IV^{TM} (Nicolet Biomedical Inc., Madison, WI, USA).

Statistics

Statistical significance was determined using the unpaired two-tailed t-test for normally distributed data and chi-square tests for noncontinuous data (significance established at $p < 0.05$). The amount of shifting was calculated as the distance between two points of a pair (after dura opening and end of tumor removal) and given as mean and standard deviation (SD). Correlation was accepted when the sample correlation coefficient r exceeded 0.4.

Results

Lesion volume, distance from the cortical surface, and presence of edema were determined from the preoperative MR images. The quality of the imaged 3D brain surface was virtually identical to the intraoperative view as demonstrated by intraoperative photographic documentation. The reliability of the images and the spatial resolution of 1 mm in each dimension as well as the strict use of Cartesian co-ordinates are excellent prerequisites for neuronavigation and allow for shift calculation with the PC workstation. Accuracy of registration as well as the geometrical matrix were calculated by the navigation system and electronically registered in an individualized study protocol. If the computed error was significant (e.g., registration error of more than 3.0 mm), the registration process was interrupted and had to be repeated. The

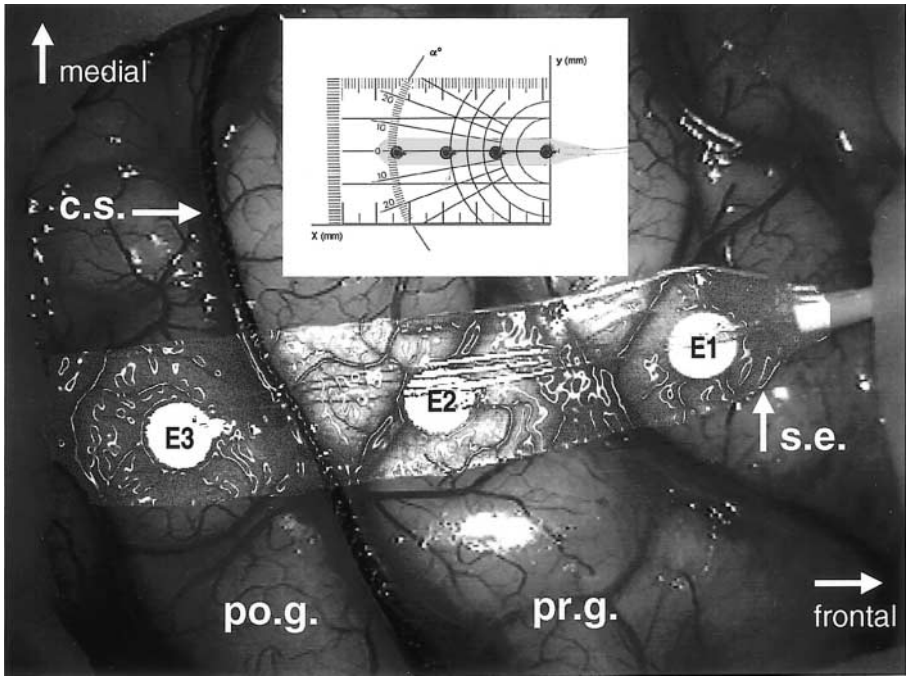

Fig. 3. Intraoperative photography showing the surgical field after opening of the dura and placement of the strip electrode on the cortex. Gauge for digitally measuring the position of the strip electrode relative to the stationary craniotomy margins. *po.g.* Postcentral gyrus; *pr.g.* precentral gyrus; *c.s.* central sulcus; *s.e.* strip electrode; *E1–E3* embedded steel electrodes

registration error was expressed as a root mean square error (RMS error) based on the distance between the predefined centers of the fiducials and the corresponding position of the stylus tip in real space. The mean fiducial registration error associated with the 3D MRI protocol was 1.6 mm (RMS error) in the 31 cases investigated.

The patients were subdivided into 3 groups according to tumor volumes calculated from the preoperative MR images. Group A (small tumor size < 20 ml) had a mean tumor volume of 15.6 ml (range 2.7 to 19.8 ml), group B (intermediate tumor size 20–40 ml) of 34.6 ml (range 22.8 to 39.4 ml), and group C (large tumor size > 40 ml) of 78.9 ml (range 42.3 to 139.7 ml). The mean distance of the tumor center from the cortical surface was 18.4 mm with a rather narrow range of 9.3 to 28.6 mm, which made it seem unsuitable to establish subgroups for statistical analysis. There was no statistically significant correlation between tumor depth and shifting (Table 1).

After craniotomy and opening of the dura, the cortical surface exhibited constant sinking in the direction of gravity in 25 cases. In the other 6 cases, initial outward bulging of the surface with compression of the surrounding sulci was observed. However, this only happened in large tumors with a volume of more than 40 ml and may be attributable to either vasogenic edema or expansion of parenchyma compressed before dural opening. In all of these cases edema was already present on the preoperative MR images. Upon completion of the procedure the direction of cortical shifting was bulging in only 1 case, infalling in 27, and level in 3 cases. The falx cerebri as a fixed dural duplicature showed only minimal shifting which was independent of tumor size or location.

Shift of the cortex between opening of the dura and

Table 1. *Correlations Found Between the Magnitude of Cortical Sideward Shifting (X- and Y-Axes) and Different Surgical Parameters and Maneuvers*

	Correlations
Patient positioning (supine position with head tilted 60–90 ° vs. strict left or right horizontal pos.)	r = 0.11; n.c.
Size of craniotomy	r = 0.32; n.c.
Size of dura opening	r = 0.29; n.c.
Volume of lesion	r = 0.83; *c
Depth of lesion center below cortex surface	r = 0.19; n.c.
Edema visible at preoperative MRI	r = 0.65; *c
Intraoperative use of diuretics (e.g., mannitol)	r = 0.68; *c

r Correlation coefficient; *n.c.* no correlation; **c* high correlation.

Table 2. *Magnitude of Maximal Intraoperative Brain Shift and Strip Electrode Movement in the Anteroposterior and Mediolateral Direction Between Opening of the Dura and Complete Tumor Removal*

	Shift (in mm) ± SD until complete tumor resection					
	Anteroposterior (X-axis)			Mediolateral (Y-axis)		
	Electrode	Cortex		Electrode	Cortex	
Group A lesions (n = 8) volume < 20 ml	2.7 ± 0.8 SD	4.2 ± 1.2 SD	n.s.	3.5 ± 1.3 SD	5.3 ± 3.2 SD	n.s.
Group B lesions (n = 17) volume 20 ml–40 ml	2.9 ± 1.0 SD	7.8 ± 4.3 SD	$p < 0.05$	3.3 ± 1.2 SD	9.5 ± 6.4 SD	$p < 0.05$
Group C lesions (n = 6) volume > 40 ml	2.8 ± 1.1 SD	12.1 ± 8.4 SD	$p < 0.05$	4.2 ± 1.7 SD	15.3 ± 9.5 SD	$p < 0.05$
Σ = 31						

Mean and standard deviation in millimeters (mm); *n.s.* statistically not significant; $p < 0.05$ = statistically significant.

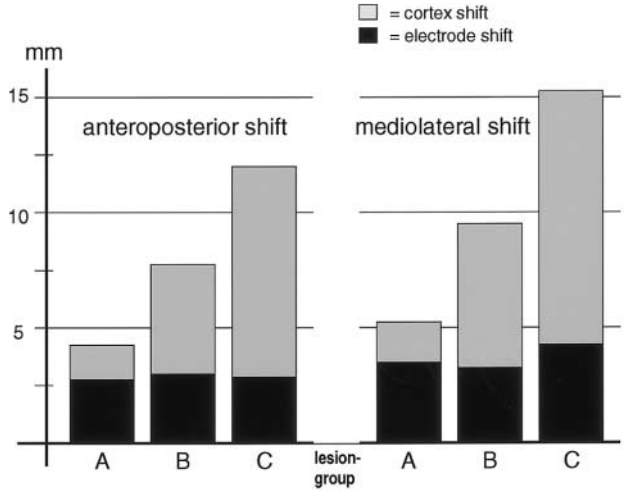

Fig. 4. Anteroposterior and mediolateral shift of cortical surface structures and strip electrodes in relation to lesion volume

complete tumor resection was calculated (a) in the anteroposterior and (b) in the mediolateral direction (Table 2). The mean anteroposterior shift was 4.2 mm (±1.2) in group A, 7.8 mm (±4.3) in group B, and 12.1 mm (±8.4) in group C. The mean mediolateral shift was 5.3 mm (±3.2) in group A, 9.5 mm (±6.4) in group B, and 15.3 mm (±9.5) in group C. Altogether, intraoperative brain distortion increased as the operation proceeded. Calculation of correlation coefficients showed a high correlation between cortical shifting and tumor volume at r = 0.83. Additional correlations were calculated for cortical shifting and patient positioning (r = 0.11), size of craniotomy (r = 0.32), size of dura opening (r = 0.29), lesion volume (r = 0.83), distance of lesion center from cortical surface (r = 0.19), edema (r = 0.65), and intraoperative use of diuretics (r = 0.68). Correlation was found to be significant only for lesion volume, edema, and use of diuretics (Table 1).

Displacement of the strip electrodes as measured in the geometric center of the stimulation electrode used for MCS was as follows: Mean anteroposterior displacement was 2.7 mm (±0.8) in group A, 2.9 mm (±1.0) in group B, and 2.8 mm (±1.1) in group C. Mean mediolateral displacement was 3.5 mm (±1.3) in group A, 3.3 mm (±1.2) in group B, and 4.2 mm (±1.7) in group C. In contrast to cortical shifting, there was no statistical correlation (r = 0.17) between the extent of electrode displacement and tumor volume (Table 2; Fig. 4).

In addition, electrode displacement was investigated in relation to electrode positioning. Three different positions were distinguished (Fig. 5): (I) strip electrode completely on cortex (n = 14), (II) partly subdural in location (n = 11), and (III) partly positioned over craniotomy margin (n = 6). Two types of movement were observed: (1) surface movement of the active stimulating electrode relative to the fixed craniotomy margins – given as mm shift and (2) deviation of the longitudinal axis of the strip electrode – given as α° angulation. The largest mean electrode shift was seen for electrodes in position I (3.2 mm, range 0–5.8 mm), followed by position III (2.8 mm, range 0–6.4 mm) and position II (1.9 mm, range 0–3.3 mm). One explanation for the observed differences is the adhesive behavior of the strip electrodes that may vary in different positions. Electrodes in partly subdural location (pos. II) appear to be most stable whereas electrodes in completely cortical location (pos. I) or partly extending over the craniotomy margin (pos. III) appear to be most susceptible to intraoperative dislocation. However, these observations show mere tendencies since the differences were not statistically significant. The same holds true for the deviation of the longitudinal axis of the strip electrode relative to the adjacent craniotomy margin. The mean angular devi-

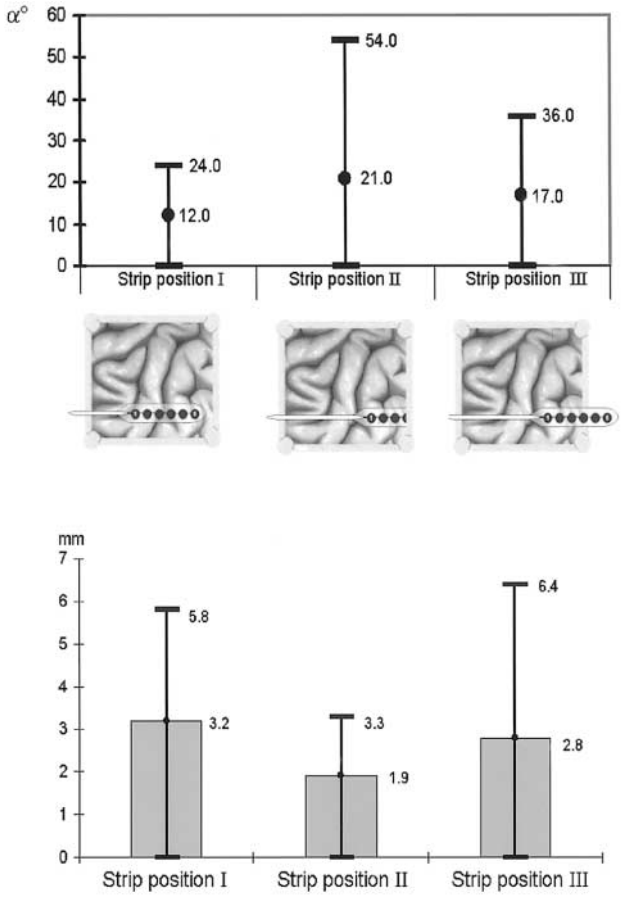

Fig. 5. Influence of different electrode positions on electrode displacement. (Strip position I) strip completely on cortex, (II) partly subdural in location, and (III) partly positioned over craniotomy margin: angulation in α° and shift in mm; mean value, minimum and maximum

ations determined were 12° (range 0°–24°) for strips completely on the cortex (pos. I), 17° (range 0°–36°) in position III, and 21° (range 0°–54°) in position II. The differences were again not significant. The fact that electrodes in partly subdural position showed the greatest tendency for intraoperative longitudinal displacement is probably also due to the adhesive forces existing between the electrode strips and the dura, which appear to be stronger than between the strips and the cortex due to flexibility of the thin and mobile dura.

In 3 of the 31 cases (9.3%) a significant change in the recorded motor responses was due to an intraoperative dislocation of the stimulating electrode:

Case 1 (Fig. 6)

A 32-year-old male with a right frontal tumor (PNET) near the precentral gyrus underwent right frontoparietal osteplastic craniotomy for tumor removal. SEP-PR identified the central sulcus parietal to the tumor. Mapping and monitoring of the motor cortex were performed by MCS, indicating that the site of stimulation was located within the somatotopic hand and arm area of the precentral gyrus. Sudden complete loss of potentials during tumor resection could not be attributed to technical causes and was regarded as warning signal. Manipulation at the dorsal tumor margin was immediately discontinued in order to avoid damage to motor pathways. After further volume reduction more frontally, however, CMAPs could suddenly be recorded through needle electrodes overlying the contralateral quadriceps. Checking of the surgical field showed that the position of the strip electrode was nearly unchanged in relation to the craniotomy margins. However, the cortex underneath the strip electrode had shifted laterally (21 mm) due to volume reduction. Thus, by the end of surgery, the stimuling electrode had moved closer to the interhemispheric fissure and was situated in the somatotopic leg area of the precentral gyrus [23].

Case 2 (Fig. 7)

A 57-year-old man with slight right-sided paresis that was more pronounced in the leg was operated on for a metastasis from bronchial carcinoma. The metastasis was located in the left frontal area near the midline and was removed through a left frontoparietal craniotomy. After incision of the dura, a strip electrode was positioned on the cortex near the lateral craniotomy margin with its frontal part (about 15 mm) extending subdurally beneath the frontal craniotomy margin. Following removal of the necrotic tumor contents by suction, infalling of the cortex by 8 mm was observed. The strip electrode got detached from the cortex, resulting in the immediate complete loss of potentials. Angulation relative to the initial electrode position was 12°. The contact of the stimulating electrode E1 to the precentral gyrus was interrupted as a result of lateral displacement by 5 mm and parietal movement in the direction of the cable by 13 mm. Adhesion of the strip electrode to the underside of the dura appeared to be stronger than to the cortical surface. Following repositioning of the strip electrode under visual control, intraoperative monitoring could be continued without complications.

Case 3 (Fig. 1)

A 61-year-old woman underwent left frontoparietal craniotomy for removal of a left frontal metastasis from papillary thyroid carcinoma. Recording of SEP-PR with a strip electrode revealed the central sulcus to be located immediately parietal to the craniotomy. The somatotopic arm area of the precentral gyrus was identified underneath the stimulating electrode E3 by means of MCS prior to corticotomy. In the course of tumor removal, a gradual amplitude reduction was noted, finally resulting in a complete loss of potentials. The intervention was discontinued. Inspection of the site and checking of the initially registered landmark data suggested that frontal volume reduction had led to a cortical shift of 10 mm in an anterior direction. In contrast, the position of the strip electrode was found to be almost unchanged compared to its initial location (1.5 mm lateral shift, 1 mm posterior shift, 2° angulation). Upon stimulation of all electrodes of the strip electrode, a muscle response with a latency and amplitude comparable to the initial potential could be generated via electrode E2, demonstrating that the motor cortex had shifted in an anterior direction relative to the unchanged position of the stimulating electrode. Using electrode E2, the intervention and intraoperative monitoring were continued without complications.

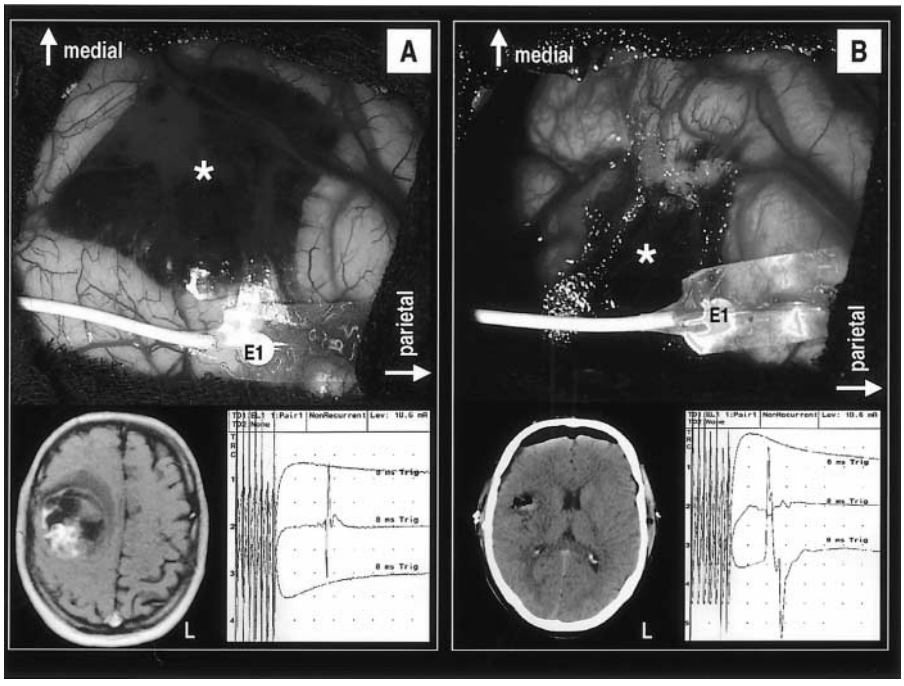

Fig. 6. Case 1 – 32-year-old male with right frontal tumor (*PNET*). Intraoperative photography showing the strip electrode placed parietal to the tumor, partly located under the dorsal craniotomy borders and overlying the precentral gyrus. (A) before and (B) after tumor removal. Corresponding preoperative MR image and postoperative CT scan are shown below. The CMAPs elicited demonstrate lateral movement of the cortex underneath the unchanged electrode strip. *L* Left; *pr.g.* precentral gyrus; * tumor; *E1* electrode No. 1

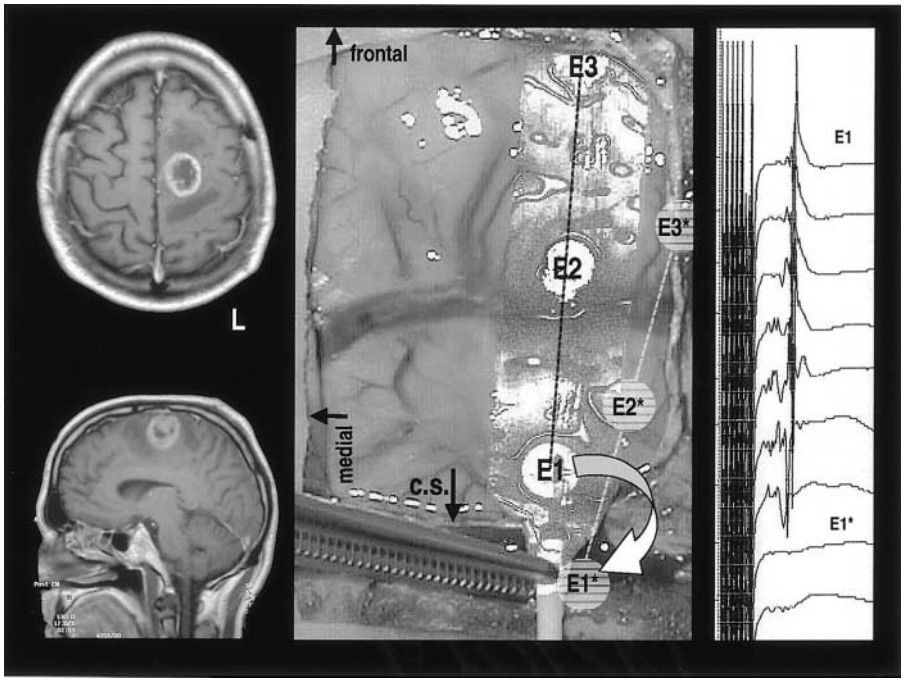

Fig. 7. Case 2 – Axial and sagittal MR images showing a left frontal lung cancer metastasis in a 57-year-old male. CMAPs were recorded from the right thenar muscle after stimulating electrode E1. Electrode shift occurring during tumor resection is demonstrated on the intraoperative image. Immediate loss of potentials was due to displacement of electrode E1 towards its new position E1*. *L* Left; *c.s.* central sulcus

Discussion

Damage to neural structures during brain tumor surgery can only be prevented if appropriate measures are taken while functional changes are reversible. Although modern techniques of pre- and intraoperative diagnostic imaging such as functional MRI or intraoperative image guidance allow for precisely localizing lesions and their relationship to functionally relevant areas like the motor cortex, they may not suffice for intraoperative functional orientation alone. On the one hand, motor areas spread over wider zones than the anatomically well-described neural bank just anterior to the central sulcus. On the other hand, there may be marked individual variations in the functional organization of the brain, particularly in patients with intracranial lesions [11]. Intraoperative neurophysiological mapping and monitoring techniques may therefore aid in the early detection of functional changes and hence in preventing postoperative neurological deficits. However, all factors affecting the reliability of IOM may thus increase the risk of misinterpreting the monitoring results. Therefore, in addition to various technical problems, shifting of cortical structures or of the stimulating electrode itself must be taken into account in trouble shooting.

Intraoperative Mapping and Monitoring Techniques

Intraoperative SEP phase reversal using cortical strip electrodes has proved to be a reliable method for identifying the central sulcus [26, 27]. A common success rate of more than 90% is reported in the literature [1, 8, 10, 26, 27]. This procedure reliably localizes the central sulcus but yields no functional information. Only direct stimulation of corticospinal tract neurons ensures intraoperative identification of motor areas.

Motor function can be tested under general anesthesia by means of direct motor cortex stimulation. Bipolar stimulation is the ''traditional'' method for cortical mapping originally described by Fritsch and Hitzig [3] whereas high frequency MCS is suitable not only for mapping but also for continuous intraoperative monitoring of motor pathways [9, 10, 23]. Repetitive monopolar cortical stimulation is performed by using the same cortical strip electrodes as for SEP-PR. The CMAPs recorded can be analyzed with regard to their latency, amplitude, and duration, thus providing an objective measure of the motor response. Our own series of 70 patients demonstrated a reliable correlation between intraoperative changes in recorded CMAPs and clinical outcome [9, 10]. However, false alarms usually prolong surgery, thereby increasing the patient's exposure to anesthesia or the likelihood of complications and incomplete tumor resection. The reported cases illustrate that intraoperative electrode displacement may be an important source of error affecting the use of strip electrodes in intraoperative neurophysiological monitoring techniques. However, a distinction must be made between cortical shift underneath the stationary electrode and mechanical displacement of the strip electrode on the cortex.

Brain Shift

Cortical shifting during open cranial surgery (known as ''brain shift'', ''postimaging brain distortion'' or ''brain deformation'') is a continuous dynamic process with great variability that results from either relapse or bulging of the cerebral cortex. Kelly *et al.* [7] were the first to describe brain shifting occurring during volumetric stereotaxy in 1986, when they observed dislocation of small steel balls placed in the surgical field. Since then, different techniques have been used to identify this phenomenon, including the use of neuronavigation techniques, optical scanning of the surgical field, or comparison of intraoperatively acquired images.

Brain shifting has been attributed to different causes, which can be subdivided into three groups. These are surgical maneuvers, pathophysiological responses, and metabolic changes, which interact with each other (Fig. 8). Many authors have demonstrated that shifting and its spatial direction seem to be influenced primarily by patient positioning and gravity forces [2, 5, 15, 16, 17, 18, 21]. Additionally, changes in intracranial pressure due to mechanical manipulations or cerebrospinal fluid loss have been shown to be highly correlated with intraoperative brain distortion [5, 17]. Nevertheless, there seem to be many different pathophysiological mechanisms that may directly or indirectly influence the intraoperative behavior of the cortex such as parenchymal swelling due to disturbances in the fluid and electrolyte balance, anesthetics, diuretics, or ventilation. Poncelet *et al.* [20] reported a physiological pulsatile motion of the brain having the same frequency as the cardiac cycle. With an amplitude of up to 0.5 mm, this motion might affect the spatial accuracy of surface structures.

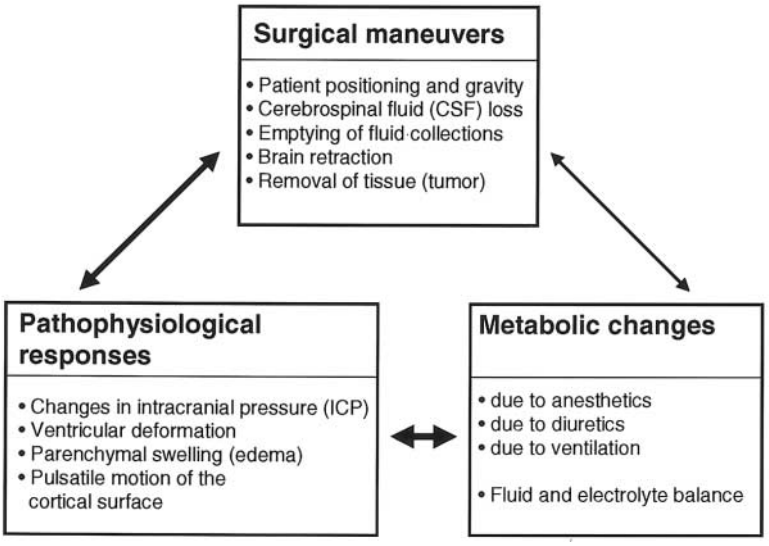

Fig. 8. Causes of brain shift and their interaction

Intraoperative Electrode Shifting|Displacement

Silicon-embedded strip electrodes are typically placed on the cortex, where they are covered and weighed down by brain cotton to protect the surrounding brain surface, on the one hand, and to make the strips heavier and to thus improve their positional stability by increasing their adhesion to the underlying cortex, on the other. Slight shearing movements between the brain surface and the electrode strips can thus be compensated for. This is reflected by the relatively slight effective movement between the cortex and strip in patients with small tumors in group A as opposed to groups B and C with an exponentially increasing relative electrode displacement (Table 2, Fig. 5). However, when there is intraoperative infalling of the brain surface, the tendency for electrode displacement is crucially affected by the position of the strip. In particular the strong adhesion to the dura leads to rotational movement around the point of strongest adhesion when strip electrodes are partly subdural in location, resulting in axial displacement of up to 54° (Fig. 5). In contrast, electrodes partly positioned over the craniotomy margin turned out to be less prone to this type of displacement but were most susceptible to horizontal displacement. Thus, the results of the present study suggest that strict cortical placement and adequate stabilization by covering with moist brain cotton make electrodes least prone to displacement.

Compensation for Shifting Phenomena

To overcome the problem of brain shift and to visualize its intraoperative magnitude, several approaches are currently being evaluated. These comprise surgical techniques, intraoperative imaging, and mathematical models.

Kelly [7] described the use of a cylindrical retractor during volumetric stereotactic mass lesion resection to guide the procedure and to stabilize the intracranial tissue relation. Other surgeons use stereotactically implanted catheters (tumor fencing) for guidance during the microsurgical procedure [12]. In 1999, Roberts *et al.* [22] introduced the method of so-called "sparse data" to modify and update imaging data by matching specific points during the surgical procedure with the aid of optical scanning or ultrasonography.

Intraoperative CT has been used for intraoperative monitoring by some institutions since its introduction by Lunsford [13] in 1982. However, mobile CT scanners have the drawback of involving radiation exposure, still exhibit a poor soft-tissue contrast, and do not enable online detection of brain shift because they do not provide real-time "continuous" visualization of the brain. Intraoperative ultrasonography may be an alternative, as it is capable of rapidly collecting multiplanar three-dimensional data. It is widely used during intracranial operations to access a lesion but it is useless for evaluating geometrical shift unless it is combined with three-dimensional orientation, so-called

3D ultrasonography [6]. With this additional option, ultrasonography allows for estimating shifting not only of the cortex but also of deeper structures. Intraoperative MRI seems to be the most reliable imaging modality for shift compensation and is currently undergoing clinical evaluation [16, 17, 18]. MRI yields information not only on the shifting of the brain surface but also on the deformation of structures beneath the surface. Nevertheless, use of this modality may be limited to few centers only because of its high costs and the necessity of reorganizing the operating theater. Additionally, most intraoperative neurophysiological monitoring techniques are not compatible with intraoperative MRI because they are affected by the electromagnetic field.

Other researchers have developed different mathematical models to describe the shift phenomenon. However, none of the mathematical approaches for calculating and predicting possible cortical movement (B-spline [14], optical flow [4] or the finite element model [19]) that have been proposed so far are able to adequately describe the phenomenon of brain shift since intraoperative deformation follows a variable rather than a unidirectional course and may even inverse direction. This follows from the fact that, physically, the brain parenchyma must be considered an inhomogeneous and highly structured mass with unpredictable responses to the surgical manipulation itself. According to Miga *et al.* [15], intraoperative brain movement varies nonuniformly, suggesting that fixed transformation solutions to intraoperative motion should be avoided. Instead, they promote "model-updated image guidance" as a promising method for correcting intraoperative tissue deformation.

Conclusion

The authors are of the opinion that intraoperative cortical mapping and monitoring should be part of routine management in the surgical removal of lesions located in eloquent areas of the brain. However, one must be aware that brain shift may be a crucial factor resulting in inaccurate recording if the localization of the strip electrodes used as well as of the cortical structures surrounding them are not controlled throughout the intervention. There are still many unknown interindividual differences in shift behavior, and brain tissue properties may change due to various metabolic processes. Therefore, it still seems nearly impossible to describe and characterize intraoperative deformation adequately and even more so to develop models accurately predicting such processes.

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Comments

Dr. Olaf Suess insists on his favourite subject: intraoperative monitoring for tailoring tumor resection on eloquent brain areas. This time is a prospective study (31 cases) to quantify the effect of cortical brain shift on electrode positioning during open surgery. A recent and short case report by the same author (2001, Acta Neurochir, 143: 621–623) had an identical theme. In the current study, intraoperative displacement of cortical strip electrodes due to brain shift, with alterations in the recorded motor responses (9.3% of the studied cases), are correlated to the way they were placed (under the craniotomy borders versus clear cortical surface) rather than to the volume of resection. Therefore, they conclude that continuous evaluation of the position of the stimulating strips is absolutely mandatory. Brain shift and cortical electrode movement, from the beginning to the end of surgery, are nicely measured digitally and analysed.

F. Isamat

This paper deals with the important and current problem of the accuracy of localization of brain structures, and particularly of cortical structures in eloquent areas during surgery, and particularly resective surgery, using functional methods, such as recording of cortical activities, and evoked potentials with subdural strip electrodes.

The study is done on a significant number of patients (31), using a variety of methods to evaluate the change in localization of the electrodes versus the brain cortical structures they are supposed to monitor during the operative process, particularly the first steps of opening the envelopes.

The methods used are sound, the results which are provided are precise and correctly analysed. The correlation with the different factors is interestingly analysed, and the conclusions are seriously based on the results of this study.

As it appears to the referee, the main conclusion of the authors is that, although the recorded changes are rather small as compared to what could be expected, they still are significant in terms of precise localization of the cortical structures. They discuss extensively the possibilities to compensate those imprecisions using reformation of images and mathematical "modelization".

Their final conclusion seems to be pessimistic, saying that there is currently no perfect way to correct the imprecisions introduced by the opening of the skull on the localization methods used before resective surgery. It would be interesting to have a statement from the authors about the perspective of using intraoperative magnetic resonance imaging, which would counteract all the factors which have been investigated in this paper, and should be, in theory at least, the solution for these distortions of the data.

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