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TECHNICAL NOTE

The impact of brain shift in deep brain stimulation surgery: observation and obviation

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Abstract
Background The impact of brain shift on deep brain stimulation surgery is considerable. In DBS surgery, brain shift is mainly caused by CSF loss. CSF loss can be estimated by post-surgical intracranial air. Different approaches and techniques exist to minimize CSF loss and hence brain shift. The aim of this survey was to investigate the extent and dynamics of CSF loss during DBS surgery, analyze its impact on final electrode position, and describe a simple and inexpensive method of burr hole closure.
Methods Sixty-six patients being treated with deep brain stimulation were retrospectively analyzed for this treatise. During surgery, CSF loss was minimized using bone wax as a burr hole closure. Intracranial air volume was calculated based on early post-surgery stereotactic 3D CT and correlated with duration of surgery and electrode deviations derived from post-surgery image fusion.
Results Median early post-surgery intracranial air was 2.1 cm^3 (range 0–35.7 cm^3, SD 8.53 cm^3). No correlation was found between duration of surgery and CSF-loss (R=0.078, p=0.534), indicating that CSF loss mainly occurs early during surgery. Linear regression analysis revealed no significant correlations regarding volume of intracranial air and electrode displacement in any of the three principal axes. No significant difference regarding electrode deviations between first and second side of surgery were observed.
Conclusions CSF loss mainly occurs during the early phase of DBS surgery. CSF loss during a later phase of surgery can be effectively averted by burr hole closure. Postoperative intracranial air volumes up to 35 cm^3 did not result in significant electrode displacement in our series. Comparing our results to studies previously published on this subject, burr hole closure using bone wax is highly effective.

Keywords Brain shift · Deep brain stimulation · Movement disorder · CSF loss

Abbreviations

DBS	Deep brain stimulation
MER	Microelectrode recording
CSF	Cerebrospinal fluid
SD	Standard deviation
PD	Parkinson's disease
AC	Anterior commissure
PC	Posterior commissure
STN	Subthalamic nucleus
SNr	Substantia nigra pars reticulate
VIM	Ventro intermediate nucleus of the thalamus
GPi	Globus pallidus pars interna

Introduction

The term brain shift describes movement and deformation of the brain in terms of its anatomical and physiological position in the skull. Its impact predominantly on deep brain stimulation surgery is considerable, as efficacy in stereotactic surgery mainly depends on meticulous surgical planning and accurate electrode placement. Single aspects of brain shift during stereotactic procedures and deep brain stimulation electrode implantation have been investigated in the past [4, 5, 8, 10]. Post-surgery intracranial air volume has early been identified as a reliable surrogate for CSF loss and hence is used as an indicator in comparing different DBS surgery techniques [2].

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Several factors are likely to influence the amount of CSF loss: patient position, brain atrophy, duration of surgery, burr hole localization, size of CSF space opening, and method of temporary burr hole closure [6].

Due to the brain's complex design, deformation cannot be predicted by the amount of CSF loss alone. Brain viscosity, brain atrophy, and changes in ventricular morphology due to CSF redistribution are additional aspects that are likely to influence the degree and direction of brain shift [3].

In this retrospective study, we investigate the amount of intracranial air as a surrogate for CSF loss subsequent to DBS surgery and analyze its influence on surgical outcome with respect to electrode position. Different means are used to reduce CSF loss during stereotactic surgery. Our results applying a simple and inexpensive burr hole closure technique are compared to previously published studies using different approaches.

Materials and methods

Patient population

Sixty-six patients being treated in our institution between January 2008 and May 2010 were retrospectively analyzed for this survey. All patients received first-time surgery. The median age was 59.3 years (SD 13.3 years), 39 patients were male and 27 were female (59 vs. 41 %). Underlying pathologies and stimulation targets are summarized in Table 1. Out of the total of 66 patients, 62 (94 %) received bilateral electrode implantation. Exclusion criteria were not evaluable or delayed (more than 90 min post-surgery) CT imaging or major complications like bleeding resulting in additional electrode shift.

Stereotactic procedure

Preoperative MR imaging was conducted the day before surgery in all patients. Depending on the underlying condition, analgesic sedation or general anesthesia was induced. Following placement of the stereotactic frame (Riechert-Mundinger), a thin-cut native CT was administered and fused to MRI using STP 3.0 software (Stryker-Leibinger, Freiburg, Germany). Target points were based on the AC-PC line calculations and refined in T2 imaging. Entry points were chosen avoiding the lateral ventricles and cortical veins. Targeting accuracy was checked using a phantom. Patient position was supine with the neck approximately 20° flexed. Burr holes (11 mm) were created coaxial with the trajectory; surgery started on the left side in all patients. The dural opening was performed using a pointed bipolar forceps and a small incision. Bipolar arachnoidal opening was performed directly prior to microelectrode placement to avoid CSF loss during this phase of surgery. In all cases of this series, MER was used with respect to individual anatomy (Inomed MicroMacro electrode, Inomed GmbH, Freiburg, Germany) applying the MicroDrive device (Inomed). Immediately following the microelectrode placement, the burr hole was air- and fluid-tight closed using warmed bone wax, which was compacted between the microelectrode tubes (Fig. 1).

Table 1 Synopsis of surgical targets and underlying conditions

Diagnosis	DBS target	Number of patients
Parkinson's disease	STN	43
Myoclonus epilepsy	SNr/STN	2
Multiple sclerosis	VIM	1
Locked-in syndrome	Lamina intermedialis thalami	1
Huntington's chorea	GPi	3
Holmes tremor	VIM	1
Bilateral essential tremor	VIM	6
Tardive dystonia	GPi	3
Idiopathic dystonia	GPi	6

Microrecording started 5 mm above the target point and 1-mm steps were taken. The exact implantation site was chosen on the basis of microrecording and, if available, awake microstimulation testing for motor symptoms and adverse side-effects.

Final electrodes (DBS Lead 3389 or 3387, Medtronic Inc., Minneapolis, MN, USA) were implanted under fluoroscopic control and the bone wax closure was removed

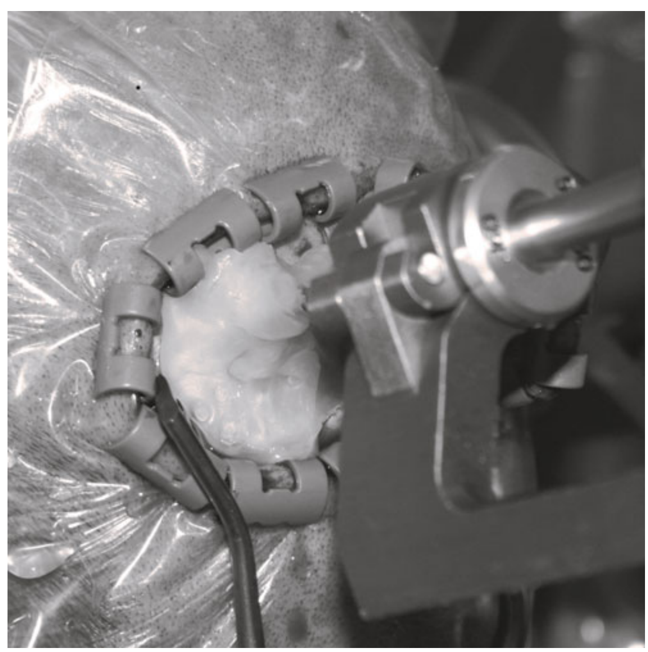

Fig. 1 Temporary burr hole closure using bone wax compacted between the microelectrode tubes, left side, with five microelectrodes in MicroDrive, Riechert-Mundinger device

subsequent to fixation. Mini fragment fixation plates (Synthes® GmbH, Germany) were used for macroelectrode fixation. Definitive burr hole closure was achieved using bone cement (Palacos®, Heraeus GmbH, Germany). Stimulator implantation was performed the following day under general anesthesia. In our study population, no transventricular electrode placement was observed.

Assessment of intracranial air

Post-surgery 2-mm stereotactic CT scans were obtained. In contrast to intraoperative positioning, patient positioning in the CT scanner is rather plain and imaging only roughly reflects the anatomical situation in a late stage of surgery being one reason to choose a volumetric approach rather than a calculating frontal cortical displacement as done in prior studies.

As automated measurements did not provide satisfying results regarding accuracy, intracranial air was tagged manually in a slice-by-slice manner using Osirix v.3.6.1 software.

3D reconstructions and volumes were calculated using Osirix "Power Crust" region of interest analyzer plug-in.

Electrode deviations were calculated from re-fusion of post-surgery CT scans and stereotactic planning imaging for each of the three principal axes using the STP Workstation. Deliberate changes derived from MER were included in this calculation and taken into account in re-fusion. Information was derived from the geometric specifications of the Micro-Drive, depth information obtained in MER and tract used for final electrode implantation. Analogous to pre-surgical planning, the lowest electrode contact was chosen as the target point and taken as final electrode position in post-surgery image sets.

Statistical analysis

Statistical analysis was performed using *t* test, Pearson's correlation, and linear regression analysis. Software used was IBM SPSS Version 19. Level of significance stipulated was 5 % (0.05).

Results

No surgical complications were observed in the study group and no adverse stimulation effects were observed during surgery. The trajectory for final electrode placement was guided by intraoperative microrecording in all cases.

Duration of surgery varied (range 80–355 min, median 183 min, SD 49.2 min). Fifty-one patients had surgery in total intravenous anesthesia (TIVA) with intra-operative awake testing and 15 patients had general anesthesia (GA). Duration of surgery and amount of post-surgery intracranial air did not significantly differ between TIVA and GA patients. Interval to post-surgery CT-scan was less than 90 min in all patients.

Median early post-surgery intracranial air was 2.1 cm^3 (range 0–35.7 cm^3, SD 8.53 cm^3) (Fig. 2).

Duration of surgery and intracranial air volume were normally distributed in Shapiro–Wilk testing. Duration of surgery did not significantly influence post-surgery intracranial air volume (p=0.534, R=0.078) (Figs. 3 and 4).

Electrode deviations were calculated in all 66 patients from fusion of planning to post-surgery CT imaging. As expected, the highest median deviation was observed in the z-(cranial-caudal) axis as this axis is subject to the largest changes derived from the results of microrecording.

The axis most likely to show deviations due to CSF loss in supine position is the y-(anterior-posterior) axis. Median electrode displacement in the anterior-posterior axis on the left side (first side of surgery) was 0.18 mm (SD 2.0 mm, range −4.9–6.7 mm) and 0.07 mm on the right side (SD 2.03, range −4.0–8.5). Linear regression analysis revealed no significant correlations regarding volume of intracranial air and electrode displacement in any of the three principal axes (Table 2).

No significant differences were found between first and second side of surgery regarding electrode deviations using the *t* test. Air distribution was not calculated discretely for each side but tends to show symmetrical distribution.

The underlying disease widely influences the operative setting including patient positioning, duration of surgery, and target point. Therefore, linear regression analysis was repeated including only the STN-PD patients group as these display the largest homogenous group in the study population. No significant correlation was found regarding intracranial air volume and electrode displacement (Table 3).

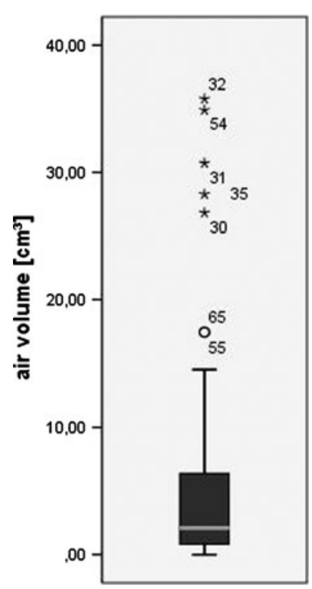

Fig. 2 Box plot showing the distribution of early post-surgery intracranial air, median 2.1 cm^3 (range 0–35.7 cm^3, SD 8.53 cm^3)

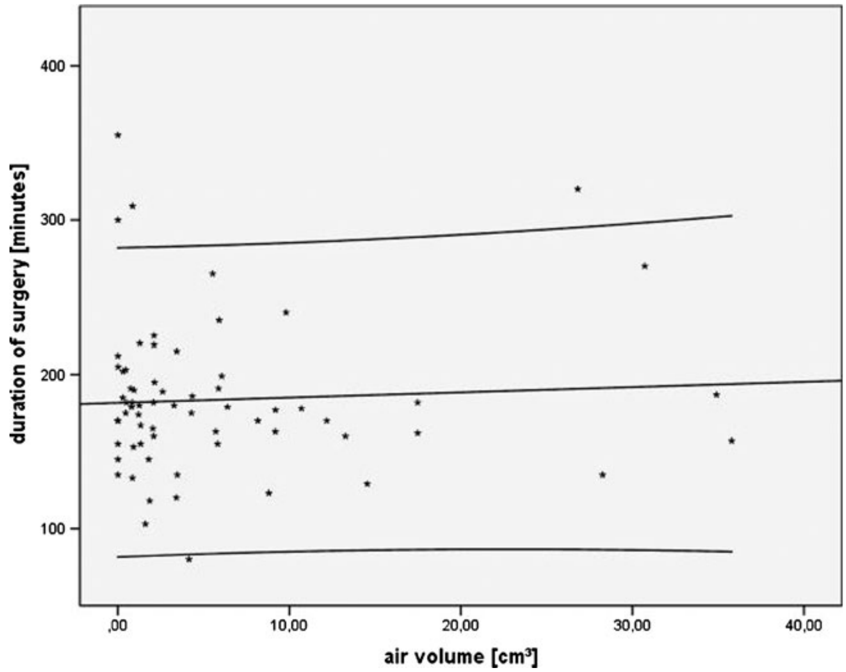

Fig. 3 Scatter plot with line of best fit and 95 % CI displaying the relation between duration of surgery and intracranial air volume (R=0.78, p=0.534)

Discussion

Brain shift due to CSF loss has early been recognized as an important source of error in deep brain stimulation surgery. Different approaches have been used to identify brain shift during these procedures and compensate for it [2, 7]. A comprehensive overview on the studies published so far is given by Petersen [8].

Given that no intentional changes are applied to brain volume and intracranial blood volume during DBS surgery, CSF loss is the main contributor to brain shift in these procedures.

As no correlation could be found in our study regarding duration of surgery and amount of postsurgery intracranial air, one can assume that the major portion of CSF is lost in the early stage of surgery during microelectrode placement. This confirms our intraoperative observations. For the same reason,

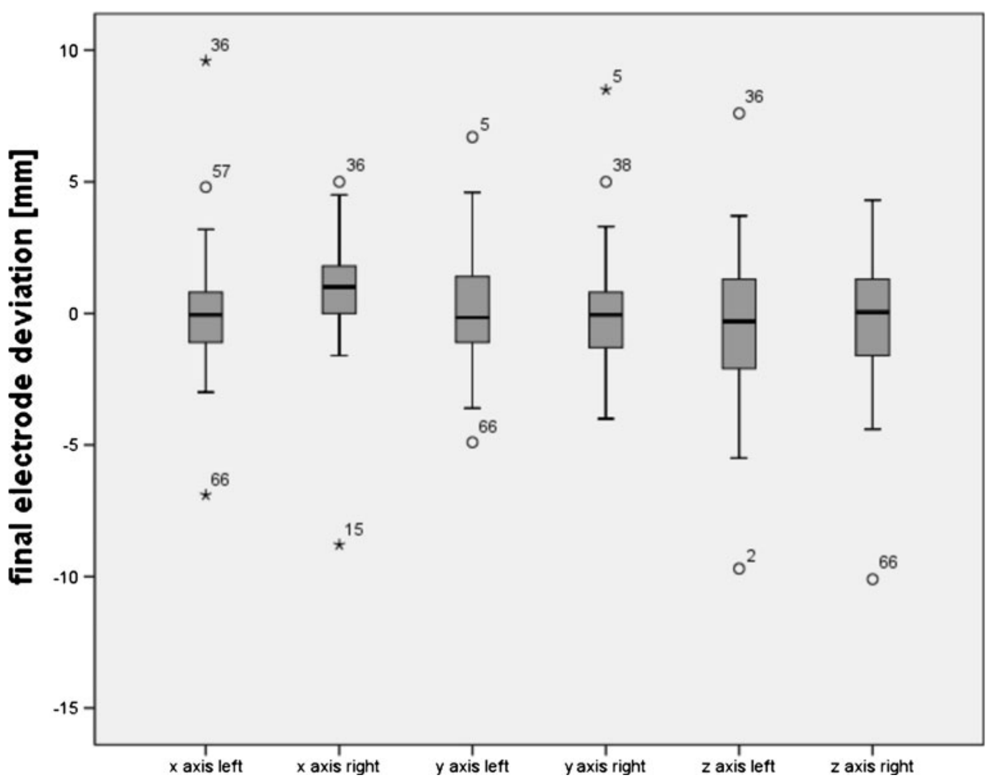

Fig. 4 Box plots analyzing the displacement between calculated and final electrode position, discrete for each side and each of the principal axes; no significant differences were observed between first and second side of surgery

Table 2 Linear regression analysis applying intracranial air as independent variable; *n.s.* not significant

Displacement (mm)	Regression coefficient (*R*)	*p* value	95 % CI
x axis left	−0.066	0.929[n.s.]	(−1.543)–1.410
y axis left	−0.094	0.890[n.s.]	(−1.438)–1.251
z axis left	0.391	0.464 [n.s.]	(−.669)–1.450
x axis right	−0.165	0.816 [n.s.]	(−1.583)–1.252
y axis right	0.311	0.662 [n.s.]	(−1.104)–1.726
z axis right	0.227	0.703 [n.s.]	(−.960)–1.414

we conclude that burr hole closure can be achieved that sufficiently reduces further CSF loss during ongoing surgery. This conclusion is consolidated by the fact that no significant difference, esp. no increase in air volume, was observed between the first and second side of surgery.

We conclude that the method of burr hole closure during MER and electrode placement is the makeshift step in preventing CSF loss and hence brain shift.

Techniques of burr hole closure applied vary. The method used in our department utilizing bone wax is described above.

In most studies, fronto-cortical displacement was used as a surrogate for brain shift and correlated with changes in AC-PC line length reducing a three-dimensional problem to one dimension.

Volumetric measurements comparable to our study were conducted by Elias [3] and most recently by Coenen [2]. The author describes a significant correlation between volume of postoperative pneumocephalus and posterior shift of the AC. Comparable results were not seen in our study. This might result from the lower amount of intracranial air observed in our study (2.1 vs. 5.8 cm^3 and 4.86 cm^3 resp.). On the other hand, the rostral position of the AC might render it prone to posterior shift more likely than the electrodes investigated in our study.

Brain shift not only restrains electrode implantation during surgery. Air resorption, and therefore brain shift remission, can result in an upward dislocation as the electrode is fixed to the skull and therefore bent as the brain regains its original position and anatomy. This was shown by van den Munckhof [9] in a retrospective study of 14 patients being treated for PD.

Table 3 Linear regression analysis applying intracranial air as independent variable in the PD-STN subgroup, *n*=43

Displacement (mm)	Regression coefficient (*R*)	*p* value	95 % CI
x axis left	0.022	0.923[n.s.]	(−2.106)–2.319
y axis left	−0.028	0.897[n.s.]	(−2.073)–1.822
z axis left	0.047	0.834[n.s.]	(−1.717)–2.116
x axis right	−0.008	0.969[n.s.]	(−1.841)–1.772
y axis right	−0.102	0.690[n.s.]	(−2.562)–1.714
z axis right	−0.156	0.493[n.s.]	(−2.750)–1.349

n.s. not significant

The authors also described a statistically significant correlation between post-operative intracranial air and electrode deviation in all principal axes. This again is contrary to our findings. This might again be explained by the much lower amount of intracranial air observed in our population. The method used for burr hole closure during surgery, which in our opinion plays a significant role in the extent of CSF loss, is not described by Munckhof at all.

Azmi [1] recently analyzed the influence of intracranial air on the number of MER tracks needed to securely identify their target structures. In their population of 32 patients being treated for PD, an increase in post-surgery intracranial air correlated with an increase in MER measurements required on the second side of surgery and an increase in target point deviation.

These results are likewise in contrast to our findings. The duration of surgery does not significantly influence the amount of intracranial air in our study. We conclude, in contrary to Azmi, that CSF leakage mainly occurs early between arachnoidal opening and microelectrode placement as the burr hole closure technique applied plays a major role in CSF leakage reduction. This is indicated by the missing correlation of duration of surgery and amount of intracranial air in our investigation.

Concerns have been raised over MER using multiple parallel tracks due to the wider arachnoidal and dural opening required and therefore its increased risk of CSF loss.

In our study, bone wax was used for a temporary burr hole closing. Simultaneous MER with five microelectrodes was realized in all patients in our study.

The authors of this study do not share these concerns. We rather agree with van den Munckhof that the rigid microelectrode cannulas staying in place during the procedure might add to implantation accuracy by providing a certain degree of brain fixation especially in anterior-posterior direction and may potentially stabilize macroelectrode placement.

As a flaw of our study, it has to be taken into account that this is a retrospective survey and no control group can be presented to evaluate the influence of higher intracranial air volumes on electrode shift or to evaluate different techniques of temporary burr hole closure. The patient population includes different indications for treatment and hence different target points. The overall result with a missing correlation between amount of intracranial air and electrode deviation can be in reproduced in the homogenous PD-STN subgroup.

Conclusions

Brain shift can compromise the success of DBS surgery by impeding exact electrode placement and therefore should be minimized. Despite inevitable CSF leakage during microelectrode placement, CSF leakage can be effectively reduced to a safe amount during microrecording and in the later phase of surgery. Postoperative intracranial air volumes up to 35 cm^3 did not result in significant electrode deviations in our series. Compared to other techniques published, burr hole closure using bone wax yields excellent results regarding CSF loss.

Acknowledgments None.

Conflicts of interest None.

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Comment

The study by Slotty and colleagues must be commended for some of the information provided. Although other studies on the topic are available, the authors correctly measured the shift of the target points instead of using surrogate measures such as the shift of the intercommisural line. The authors demonstrate that the shift was clinically irrelevant. Brain shift due to CSF loss has early been recognized as an important source of error in deep brain stimulation surgery. Even though a negative effect on the precision of the procedure is undeniable, its real clinical importance is, in my opinion, relative. This is demonstrated by the high rate of efficacy of deep brain stimulation (DBS) for movement disorders with failures mainly ascribable to errors in patients' selection. With the current technique, it is possible to quickly insert cannulas along the selected trajectory immediately after a burr hole has been performed. Cannulas that serve to guide the microelectrode rigidly fix the brain, at least in the zone close to the target. More importantly, minimal shift due to CSF leakage are easily and reliably corrected using microelectrode recordings. This is an invaluable tool in confirming the target. This technique has contributed to the dramatic improvements that many patients have experienced with a wide array of stereotactic procedures. Nevertheless, postoperative pneumocephalus is a possible troubling complication of bilateral and long-lasting procedure such as DBS. Using burr hole sealants is a smart solution to avoid excessive CSF loss.

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