Analysis of Stereotactic Accuracy in Patients Undergoing Deep Brain Stimulation Using Nexframe and the Leksell Frame

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Key Words
Frameless stereotaxy · Frame-based stereotaxy · Deep brain stimulation · Stereotactic neurosurgery · Movement disorders

Abstract
Objective: To determine and compare the accuracy of Nexframe and the Leksell stereotactic frame in deep brain stimulation (DBS) procedures. Background: The ‘frameless’ Nexframe uses bone fiducials rather than a head-mounted frame, which offers potential benefits for both the patient and the surgical team. Accuracy of lead implantation and factors affecting this accuracy are of crucial importance but have not been extensively studied for the frameless system.
Design/Methods: The location of 194 (Leksell frame, \(n = 116\); Nexframe, \(n = 78\)) DBS leads was determined on postoperative MRI. Obtained stereotactic coordinates were compared with expected intraoperative target coordinates. Resulting absolute errors in the X (medial-lateral), Y (anterior-posterior), and Z (dorsal-ventral) coordinates (\(\Delta X\), \(\Delta Y\), and \(\Delta Z\)) were then used to calculate the vector error (VE). The vector error describes the total error in 3-D space and represents our main outcome measure.
Results: The vector error (mean ± SD) was 2.8 ± 1.3 for Nexframe and 2.5 ± 1.2 for the Leksell frame (\(p = 0.43\)). For Nexframe, absolute X, Y, and Z errors were 1.4 ± 1.3, 1.7 ± 1.2, and 1.0 ± 0.9 mm. For the Leksell frame, the absolute X, Y, and Z errors were 1.4 ± 1.0, 1.2 ± 1.0, and 1.3 ± 0.9 mm. On the anterior-posterior plane (Y coordinate), the Leksell frame was more accurate than Nexframe (\(p = 0.04\)). In contrast, Nexframe was more accurate on the dorsal-ventral plane (Z coordinate) (\(p = 0.04\)). There was no difference in accuracy between the two methods on the medial-lateral plane (X coordinate).

Conclusion: This comparison of Nexframe and the Leksell frame shows that both techniques have equivalent overall 3-D accuracy.

Introduction
Neurosurgical interventions to alleviate symptoms of movement disorders have their origin in the last part of the nineteenth century, when superficial and readily ac-

We dedicate this article to the memory of our longtime collaborator and friend, Dr. Roy Bakay, who passed away when the manuscript was in preparation.
cessible cortical areas were considered as targets for ablation and resection [1]. With increasing knowledge of, and surgical experience with, the extra-pyramidal system, subcortical structures gained interest as potential surgical targets [2]. Therefore, a method had to be designed to reach structures in the diencephalon and mesencephalon with maximal accuracy and minimal disturbance of the surrounding brain tissue. This led to the development of the stereotactic frame more than 60 years ago and hence to the introduction of stereotactic surgery in humans [3, 4]. To date, the stereotactic frame continues to be the worldwide gold standard for stereotactic procedures, including lesioning and neuromodulation [5]. The frame provides a stable platform and offers a high degree of accuracy [6, 7]. Both features are of utmost importance during functional stereotactic procedures and are the main reasons for its continued widespread use in this specialized field of neurosurgery.

It is evident that the histories of the frame and stereotactic surgery are deeply interwoven. However, the ability to generate a Cartesian coordinate system is not unique to the frame. Adhesive fiducial markers, anatomical landmarks, and surface matching are methods currently applied in frameless image-guided neurosurgery. Registration errors in the euclidean distance noted during tumor resection or biopsy procedures were found to be 2.5 to 5.0 mm [8]. While this may provide sufficient accuracy during these neurosurgical procedures, it is inferior compared to frame-based stereotaxy and insufficient for targeting structures whose dimensions are measured in cubic millimeters, as is the case in deep brain stimulation (DBS) procedures for movement disorders.

Potential advantages of frameless functional surgery systems have been summarized in recent literature [9–12]. From the patient’s perspective, not having a frame bolted to their head and the operating table will minimize discomfort and exhaustion during these lengthy awake procedures. From the surgeon’s perspective, frameless procedures may allow a more efficient work flow on the day of surgery. In contrast to the stereotactic frame, fiducial markers used in frameless procedures can be placed 1 or more days prior to surgery, which enables completion of stereotactic imaging, targeting, and trajectory planning at that time. On the day of surgery, the surgical team will then be able to start the actual DBS procedure without delay. An earlier start and a shorter procedure time will benefit the patient, the surgical team, and the operating room utilization process.

For the past 9 years, the frameless Nexframe (Medtronic, Inc.) stereotactic system has been available for DBS surgery. Nexframe is a small disposable, skull-mounted, trajectory guidance system used in conjunction with an image-guided surgery system employing bone fiducials and a small reference arc with infrared-reflective spheres (fig. 1). During surgery the stereotactic planning station uses the exact fixed relationship between fiducials and spheres so that Cartesian coordinates can be calculated. Both fiducials and the arc must provide sufficient rigidity to obtain and maintain accuracy comparable to that of conventional stereotactic frames. Throughout the procedure the patient is able to change head positions within a reasonable range.

Previous studies on accuracy of frame-based and Nexframe systems have shown variable results [9–14]. Comparison between studies is limited due to differences in sample sizes and methods used to determine lead location. This may be one of the reasons that frameless stereotaxy has not found more widespread acceptance. Our current study is the largest to date comparing the accuracy of the frameless (Nexframe) and frame-based (Leksell) systems.

Methods

Patients

During the period from January 2009 to March 2012, one hundred two patients underwent microelectrode recording (MER)-guided placement of DBS electrodes at Rush University Medical Center (RUMC) using the Leksell frame. From 2004 to 2012, seventy-one patients underwent MER-guided DBS at RUMC and Rockford Memorial Hospital (RMH) using the Nexframe system. In that period, 22 patients underwent frameless DBS at RUMC and 49 patients at RMH. Patients who underwent reimplantation of DBS electrodes due to a hardware-related infection or a suboptimal therapy effect where not included. This study was approved by the institutional review board of each study center.

Surgical Procedure

Leksell Frame

DBS procedures were performed by the same team of movement disorder neurologist (L.V.M.) and neurosurgeon (R.B.). On the day of surgery, the Leksell frame was placed perpendicular to the facial plane and patients underwent a preoperative 1.5-Tesla stereotactic MRI using noncontrast sagittal T1-weighted, axial and coronal T2-weighted, and postgadolinium (Gd) volumetric axial T1-weighted sequences. The imaging was reviewed for quality and targets were identified. All images were transferred in Digital Imaging and Communications in Medicine (DICOM) format to the StealthStation (FrameLink 5.1; Medtronic) where after 3-D reconstruction the anterior commissure, the posterior commissure, the target, and the entry point were determined. Trajectories were planned from an entry point at the vertex of a suitable precoronal...
gyrus, 3–4 cm lateral from the midline. All patients were operated under minimal sedation, with the head frame secured to the operation table. Patients were placed in the supine position with the head elevated 20–30° to minimize the outflow of cerebrospinal fluid through the burr hole during surgery. In bilateral cases, the surgery started on the side of the brain contralateral to the most affected side of the body. One to 3 steel cannula(s) and microelectrodes were inserted through a 12-mm-diameter burr hole. Single or multitract MER was then performed and kinesthetic responses were sought. Therapeutic and possible side effects were evaluated by monopolar electrical stimulation through the microelectrode(s). Microelectrode movements were made based on the MER and stimulation findings while monitoring of the electrode movement and location was performed with fluoroscopy, anteroposterior (AP) radiography, or intraoperative computer tomography (iCT). After the final MER pass had been made, the DBS lead (model 3389 or 3387; Medtronic) was implanted. The DBS electrode was secured by a Stimloc system (ImageGuided Neurologics). Therapeutic effects and possible side effects were evaluated with intraoperative macrostimulation through at least 1 of the 4 DBS electrode contacts. On postoperative day 1, volumetric noncontrast axial T1-weighted MR imaging was performed. This was routinely done to evaluate the lead position, assess postoperative pneumocephalus, and rule out asymptomatic hemorrhage. Two to 7 days after electrode implantation, 1 or 2 pulse generators were implanted in a subcutaneous pocket in the infraclavicular region under general anesthesia.

Nexframe

The frameless DBS procedures were completed by the same team of movement disorder neurologist (L.V.M.) and neurosurgeon (R.B.) at RUMC and neurologist (L.V.M.) and neurosurgeon (D.S.) at RMH.

All patients underwent preoperative 1.5-Tesla MRI 2–30 days prior to the procedure, using noncontrast sagittal T1-weighted, axial and coronal T2 weighted, and post-Gd volumetric axial T1-weighted sequences. Either on the day of or the day before surgery, 5 cranial bone fiducials were placed and a volumetric noncontrast CT scan (axial 1-mm-thick slices) was obtained. All images were transferred in DICOM format to the StealthStation where MRI and stereotactic CT images were fused. After 3-D reconstruction the anterior commissure, the posterior commissure, the target, and the entry points were determined on MRI. Trajectories were planned from an entry point at the vertex of a suitable precoronal

Fig. 1. a The Nexframe system. A: base of the Nexframe attached to the Stim-Lock system and therefore in line with the placed burr hole. The base makes 2 types of possible movement: 360° rotation and 25° angling in 2 directions (note that in this illustration Nexframe is angled 25° upward). B: Nexdrive, used for lowering the micro electrode and lead. The Z-stage is displayed on the side and steps of 0.1 mm can be made by turning the drive knob (asterix).

C: reference arc with infrared reflecting spheres enables neuronavigation software to calculate Cartesian coordinates. The bone fiducials are not visible in this illustration. b The Leksell stereotactic system. A: bone screws are used to fixate the system to the patient’s head. B: ring, C: arc, D: microdrive. The ring and arc are used for positioning the micro drive that holds the microelectrode and lead.
gyrus, 3–4 cm lateral from the midline. In bilateral cases, the surgery started on the side of the brain contralateral to the most affected side of the body. After nonsterile registration and entry point determination, a 12-mm-diameter burr hole was made. The Stimloc was placed and served as fixation for the ring of Nexframe. After draping and sterile registration, the Nexprobe was aligned to the target and the Nexdrive was affixed to the top of the ring. Single-channel MER was then performed and patients were examined for kinesthetic responses and effects of microstimulation. The remainder of the procedure was the same as described for the Leksell frame.

**Lead Tip Measurements**
During surgery the tip of the most ventral electrode, i.e. contact 0, was placed at the final target. The X, Y, and Z coordinates of this point most accurately reflected the intended coordinates of lead placement. In vitro and in vivo MRI DBS lead measurements have shown that the ellipsoid-shaped artifact extends 1.4 mm over the proximal limits of the most ventral contact. This contact artifact is the most clearly identifiable and is the preferred contact to perform DBS lead measurements on [15]. The actual beginning of contact 0 is characterized by a discrete round signal void [6]. Combining 3 different imaging planes (axial, sagittal, and coronal) and the ‘trajectory view’ enables an accurate geometric approximation of the actual electrode tip. By using the trajectory view on the Framelink software, the beginning of the lead can be determined by slowly sliding into the artifact with steps of tenths of a millimeter. The center point of the artifact was chosen because in the vast majority of cases the artifact is concentrically shaped [15].

The DBS electrode tip coordinates (X, Y, and Z) were obtained from postoperative T1-weighted imaging merged with preoperative stereotactic imaging on the StealthStation. Initially, 20 cases were analyzed by 1 investigator (M.B.) and discussed with coinvestigators to reach a consensus regarding when the tip of the electrode was first seen on imaging. This consensus was then applied to the 20 cases already completed and, when needed, adjustments in choosing the electrode tip were made. Subsequently this consensus was applied to all remaining cases. The obtained stereotactic coordinates were compared with the expected coordinates of the leads based on the starting target location adjusted by subsequent intended moves on all 3 planes. Both absolute and directional errors in X (medial-lateral), Y (anterior-posterior), and Z (dorsal-ventral) coordinates (ΔX, ΔY, and ΔZ) were calculated. These errors were used to calculate the euclidean distance:

$$\sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2}.$$  

The euclidean distance describes the total error in 3-D space and represents our main outcome measure (fig. 2). Absolute errors measure the total distance from the intended target to the actual lead artifact for all 3 individual stereotactic coordinates. Small absolute errors indicate that the DBS lead is placed close to the intended target, thus representing a high accuracy. Directional errors are calculated to examine whether a system has directional bias on each of the individual planes. This allows identification of a systematic error. Factors that could influence the accuracy of both systems were evaluated (brain atrophy using Evans’ index, age, disease duration, number of MER tracks, sagittal angle/coronal angle, left/right sides, and width and length of the (mid)brain).

**Statistical Analysis**
Euclidian, absolute, and directional errors were compared with nonparametric statistics using the Mann-Whitney U test. After the 2-group comparison the Leksell group was divided into multitract and single-tract MER groups. A subanalysis was performed comparing errors (euclidian, absolute, and directional) between Nexframe and the 2 separate Leksell groups and between the Leksell groups.

The euclidian errors were analyzed for association with the number of MER tracks, the distance of intraoperative intended moves on all 3 planes, the length/width of the (mid)brain, and Evans’ index. Midbrain measurements were performed using the same software used for lead tip measurements. The width and length were determined at the level of the maximum diameter of the red nucleus. Evans’ index was determined based on the ratio of
maximum width of the frontal horns of the lateral ventricles and the maximal internal diameter of the skull.

To better understand the differences in distance measures, a principal coordinate analysis was conducted. Principal coordinate analysis is a multivariate data visualization tool that reduces the position vectors of the leads and the target location to a common dimension that can then be projected onto a 2-D coordinate grid from which euclidean distances can be measured. Mean values are presented ± standard deviation (SD).

### Results

**Patient Population**

A total of 252 leads were implanted in 173 patients. Using the Leksell frame, 163 leads were placed in 102 patients at RUMC: 71 leads were placed in 41 patients using single-tract MER, and 92 leads were placed in 61 patients using multitract MER. Using Nexframe, 60 leads were implanted in 49 patients at RMH and 29 leads were implanted in 22 patients at RUMC. A total of 10 patients (11 leads) in the Nexframe group and 29 patients (47 leads) in the Leksell group were excluded from this study. The reasons for exclusion were: missing initial coordinates (n = 11), poor quality of postoperative imaging (n = 21), missing postoperative imaging (n = 14), and inability to load imaging onto the StealthStation (n = 9). The demographics and target structures of the remaining patients are presented in table 1.

**Nexframe and Leksell Frame Comparison**

Mean euclidean errors for Nexframe and the Leksell frame were 2.71 ±1.23 and 2.63 ±1.07 mm, respectively (p = 0.82). For Nexframe absolute X, Y, and Z errors were 1.4 ± 1.3, 1.7 ± 1.2, and 1.0 ± 0.9 mm. For the Leksell frame absolute X, Y, and Z errors were 1.4 ± 1.0, 1.2 ± 1.0, and 1.3 ± 0.9 mm. The difference in errors between the 2 techniques was statistically significant on the anterior-posterior plane with superior accuracy using the Leksell frame (p = 0.03) and on the dorsal-ventral plane with superior accuracy using Nexframe (p < 0.01). There was no difference in absolute errors between the 2 techniques on the medial-lateral plane (p = 0.78).

The Leksell surgeries were subdivided into multitract and single-tract MER groups and then compared to Nexframe. Superior accuracy was demonstrated on the anterior-posterior plane for the multitract group but not for the single-tract group (p = 0.011 and p = 0.19). The dorsal-ventral plane demonstrated inferior accuracy in both the multitract and the single-tract groups (p = 0.002 and p = 0.02). There was no difference between groups on the medial-lateral planes. When comparing all 3 planes, there was no significant difference in absolute errors between the 2 Leksell procedures.

Directional errors demonstrated deviation of lead placement in the medial, posterior, and ventral direction irrespectively of the technique used (fig. 3). Nexframe showed more posterior displacement than the Leksell frame (1.5 ± 1.3 vs 0.4 ± 1.6 mm, p < 0.01), whereas the Leksell frame showed more ventral displacement (1.0 ± 1.4 vs 0.3 ± 1.62 mm, p < 0.01). There was no difference in medial deviation between groups (p = 0.10). Results in directional errors on the anterior-posterior and medial-lateral planes did not change after subdividing the Leksell surgical group into multi- and single-tract procedures. On the dorsal-ventral plane, Nexframe and Leksell single-tract showed equivalent directional errors; however, Leksell multitract demonstrated a more ventral placement (p = 0.08 and

### Table 1. Overview of patient and surgical characteristics

|                  | Patients, n | Leads, n | Mean sagittal angle, degrees | Mean coronal angle, degrees | Males, n | Age at surgery, years | Age at onset, years | Disease duration, years | Bilateral cases, n | Disease, n | Target, n |
|------------------|-------------|----------|-----------------------------|-----------------------------|----------|----------------------|---------------------|-----------------------|---------------------|------------|----------|
| Nexframe         | 61          | 78       | 57.1                        | 14.3                        |          |                      | 60.2 ± 13.9         | 47.6 ± 16.7           | 12.7 ± 5.3         | 6          | 14       | 1        | 1        | 3          | 13       | 2       | 0        | 4        |
| RUSH             | 19          | 24       | 9                           | 61.2 ± 13.9                 | 45.5 ± 19.2 | 9                     | 27 ± 12             | 12 ± 2               | 1                   | 25         | 15       | 2        | 0        |           |
| RMH              | 42          | 54       | 52.5                        | 11.7                        |          |                      | 56.7 ± 14.6         | 42.6 ± 18.1           | 14.7 ± 12.5         | 27         | 24       | 6        | 9        | 0          | 24       | 6       | 9        | 0        |
| Leksell          | 73          | 116      | 52.5                        | 11.7                        |          |                      | 58.2 ± 12.0         | 43.3 ± 14.8           | 14.3 ± 10.4         | 29         | 27       | 3        | 4        | 0          | 27       | 3       | 4        | 0        |
| RUSH multitract  | 39          | 58       | 30                          | 56.7 ± 14.6                 | 42.6 ± 18.1 | 27                    | 24 ± 6              | 9 ± 0                | 0                   | 24         | 6        | 9        | 0        |           |
| RUSH single tract| 34          | 58       | 21                          | 58.2 ± 12.0                 | 43.3 ± 14.8 | 29                    | 27 ± 3              | 4 ± 0                | 0                   | 27         | 3        | 4        | 0        |           |

Values are presented as means ± SD unless otherwise stated. PD = Parkinson’s disease; ET = essential tremor; Dys = dystonia; MS = multiple sclerosis; STN = subthalamic nucleus; Vim = ventral intermediate nucleus of the thalamus; GPi = globus pallidus internus; ZI = zona incerta.
p < 0.01). On all 3 planes there was no significant difference in directional errors between single- and multi-tract Leksell procedures.

For both the Leksell and Nexframe groups the SD were small, indicating highly clustered absolute errors, which are a result of high precision. Principal coordinate analysis confirmed this by demonstrating a high similarity of intended targets and lead positions for both Nexframe ($R^2 = 0.99$) and the Leksell frame ($R^2 = 0.98$).

**Discussion**

**Euclidean Error**

The direct comparison between the Leksell frame and Nexframe demonstrated that both techniques have equivalent accuracy in DBS surgery. Four other studies have reported on the accuracy of both systems and only 1 study found a statistically significant difference between the 2 frames when comparing euclidean errors. The euclidean distance between the intended surgical target and the lead location measured on postoperative imaging served as the main outcome measurement in 3 of the 4 studies comparing accuracy. Holloway et al. [10] was the first group to report on the accuracy of the Nexframe system and found a euclidean error of 3.15 mm based on 47 placed DBS leads. This group used a previous report on the accuracy of the Leksell frame for comparison and showed no difference in euclidean errors. Bjartmarz and Rehncrona [13] reported a superior accuracy of the Leksell frame with 1.2-mm (Leksell) and 2.5-mm (Nexframe) euclidean errors; however, the sample size was small, with 13 placed leads in both groups. Kelman et al. [9] compared Nexframe to the Cosman-Roberts-Wells (CRW) frame and found no significant difference in euclidean errors. They reported a 2.65-mm (CRW) euclidean error with 70 leads and a 2.78-mm (Nexframe) euclidean error with 69 placed leads. Finally, the study by Fukaya et al. [14] did not calculate euclidean errors. They only reported absolute errors due to the small number of evaluated lead placements (10 placed leads with Nexframe). Our results in euclidean errors are in line with the results of Holloway et al. [10] and Kelman et al. [9], with 2.71 mm for Nexframe and 2.63 mm for the Leksell frame. With a Nexframe sample size of 78

![Fig. 3. Plots of directional errors. The Leksell frame is represented by green circles. Nexframe is represented by red circles. On the left, directional errors in the medial-lateral direction (horizontal axis) and in the anterior-posterior direction (vertical axis) are shown. Each circle represents a directional error in the medial-lateral (X coordinate) direction with its corresponding error in the anterior-posterior (Y coordinate) direction. The right plot shows directional errors in the dorsal-ventral direction (vertical axis). Each circle represents an individual directional error in medial-lateral (X coordinate) direction with its corresponding error in the dorsal-ventral (Z coordinate) direction. The figure illustrates that both the Leksell frame and Nexframe have a tendency for lead deviation in the medial, posterior, and ventral direction. Nexframe showed a significant more posterior deviation in comparison with the Leksell frame.](image-url)
placed leads, our study is the largest reported for this ‘frameless’ method and the only large study directly comparing Nexframe with the Leksell frame.

In addition to sample size and group comparison, our study also differed in terms of the postoperative imaging modality used to calculate the euclidean errors. Bjartmarz and Rehncrona [13] used intraoperative X-ray imaging and Holloway et al. [10] and Kelman et al. [9] used postoperative CT, whereas we used postoperative MRI to determine electrode positioning. A well-taken X-ray image displays the lead with a high resolution and low distortion, with all 4 contacts (Medtronic DBS leads 3389 and 3387) clearly visible [16, 17]. However, most operating rooms are no longer equipped with stereotactic X-ray systems and therefore dedicated software and equipment are needed to translate X-ray imaging to a Cartesian coordinate system [13]. Postoperative CT and MRI are currently the most commonly applied imaging modalities for verification of lead location. Literature describes both CT and MRI as being sufficiently accurate for postoperative determination of DBS lead location [18, 19]. MRI has no radiation exposure and offers a higher resolution of surrounding anatomical structures but is more sensitive to image distortion compared to CT [20]. Comparison of electrode artifact centers between CT and MRI led to both incongruent and congruent localization findings. The electrode artifact is found to be smaller and more concentric on CT in comparison with MRI, but mean differences in all 3 stereotactic coordinates were found to be less than 1 mm, an error small enough to not be considered clinically relevant [21]. When applying correct window levels, CT offers a sharp and highly contrasted lead artifact which facilitates localization of the lead tip. When using MRI, correct sequencing, phase shift, slice thickness, and angulation must be applied and metallic distortion corrected in order to acquire electrode visualization with a clarity comparable to that of CT [22, 23].

The X-ray system used by Bjartmarz and Rehncrona [13] offered the advantage of intraoperative rather than postoperative verification of the lead location. Ideally, 3-D imaging should be completed after each DBS lead placement while the patient is still in the OR, so that any necessary electrode repositioning can be performed immediately. Recent studies have reported on the use of intraoperative MRI and CT for localization of DBS electrodes [24, 25]. Movable intraoperative CT devices are fairly easy to implement in DBS surgery and offer fast imaging of MER and DBS electrodes. After merging intraoperative CT to preoperative stereotactic MRI, the lead location in the euclidean space can be determined. We are currently applying intraoperative CT during all DBS surgeries to compare lead location according to intraoperative CT with that on postoperative MRI.

**Absolute and Directional Errors**

Euclidean errors provide the most useful information when measuring stereotactic accuracy. Absolute and directional errors provide valuable additional information if correctly interpreted. Absolute errors measure total distance from intended target to actual lead artifact for all 3 individual stereotactic coordinates. Small errors resemble close placement of the DBS lead to intended target and indicate a high accuracy. The individual errors have no directional component, so information about the spread of these points around their intended target cannot be derived. Calculated means of absolute errors should be

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**Fig. 4.** Concept of accuracy and precision. The upper left image indicates both accurate and precise placement, hence the markings (representing electrode placement) are close to the intended target (most inner circle) and clustered. The upper right image indicates inaccurate but precise placement, with markings off the intended target but clustered. The lower left image indicates accurate but imprecise placement, with markings close to the target but scattered around it. The lower right image shows both inaccurate and imprecise placement, with markings off target as well as scattered. Accuracy is used to describe the distance from the intended target in relation to the final placement. Precision describes the amount of variation in distances between the final placements. Greater precision represents less variation, which results in clustered targets.
used to address the accuracy on each plane. SD of mean absolute errors show whether all errors are of comparable magnitude. If individual errors reveal a high resemblance in magnitude, they will be clustered together, i.e. demonstrating a high precision. Directional errors are calculated to demonstrate whether a system error has a directional component on each of the individual planes. Once calculated, a systematic error, such as a systematic medial placement, could then be exposed (fig. 4).

Comparisons of absolute errors showed a high accuracy for both systems, with statistical differences on the anterior-posterior and dorsal-ventral planes but not on the medial-lateral plane. The superior accuracy of the Leksell frame on the anterior-posterior plane was mainly driven by the multitract group. This suggests that this accuracy difference could have been due to having used multiple tracts rather than being due to differences between Nexframe and the Leksell frame. Identifying the target with MER using a single probe demands a different approach than using multiple probes. There are significantly more MER tracts when using the multitract technique. When using the Leksell multitract technique, we typically descend with 3 probes (a central, a medial, and a lateral microelectrode). When an additional MER track is needed, one or more of the original 3 probes are left in place. Leaving a probe in place could decrease displacement on the anterior-posterior plane due to brain shift. It is proposed that brain shift affects especially the anterior-posterior plane more due to intraoperative posterior shifting of the brain [26–29]. Most literature describes brain shift during single-tract MER, and it is unclear whether the effect of pneumocephalus on brain shift is comparable when using multitract MER. Nexframe demonstrated superior accuracy on the dorsal-ventral plane compared to both multi- and single-tract Leksell surgeries. This could have been due to usage of the integrated lead calibration during Nexframe procedures, which eliminates manual Z-depth calculations and the need for rulers. However, of all 3 planes the dorsal-ventral one is probably the most subjected to error due to manual measuring of the electrode length just before placement. In addition, the exact Z-coordinate of the electrode tip is more difficult to determine on MRI and CT than its corresponding X- and Y-coordinates.

Directional errors demonstrated a tendency of the lead placement to deviate in the medial, posterior, and ventral direction, irrespectively of the technique used. Nexframe showed significantly more posterior displacement than the Leksell frame. Other studies have demonstrated similar results with equivalent medial deviation of both surgical techniques and significantly more posterior deviation when using Nexframe [9, 10]. Though posterior deviation is less than 1.1 mm compared to the Leksell frame, it seems justified to take this repeated finding into account during the planning phase.

**Nexframe in Practice**

Using a standard stereotactic frame requires completion of stereotactic imaging on the day of surgery. In contrast, the bone fiducials of Nexframe can be placed prior to the day of surgery, at which time stereotactic imaging can be obtained as well. This allows planning of target and trajectory prior to the day of surgery and, as a result, an early start in the OR on the day of surgery. The absence of a frame during the procedure facilitates evaluation of the patient during MER and test stimulation and improves communication between the patient and the neurologist.

From a patient’s perspective, separation of stereotactic imaging and the surgical procedure may also offer advantages. The day of frameless surgery will not start with placement of the stereotactic frame, which many patients find to be an uncomfortable procedure. In contrast, placement of bone fiducials is well tolerated by most patients. After completion of preoperative imaging the day before surgery, the fiducials can be protected with a head bandage, which presents few restrictions for patients during movement or sleep. The procedure can start the following morning shortly after awakening, thus reducing time spent in the off-medication state. This will lower the possibility of exhaustion during lengthy DBS surgeries and increase the ability of patients to cooperate. The stereotactic frame frequently causes discomfort throughout the procedure, which may necessitate more sedation than required in a frameless procedure. Less sedation allows better cooperation during the MER and test stimulation.

The Nexframe system is comprised of disposable components, which offer advantages over the nondisposable stereotactic frame. Due to repeated use, the stereotactic frame is required to be periodically recalibrated to detect and correct systematic errors that can develop over time. Nexframe equipment comes calibrated out of packaging and is disposed of after surgery, which eliminates any systematic errors due to repeated usage. Because many centers own 1 stereotactic frame, they are limited to 1 DBS procedure per day due to sterilization of the equipment postoperatively. With Nexframe more procedures could be completed per day.
Study Strengths and Limitations

This is a retrospective study which has known limitations. In addition, lead tip measurements could not be performed under blinded conditions because the software automatically lists specific patient characteristics including the type of frame used. Finally, one could argue that the accuracy analysis should be limited to 1 specific target; however, the targeting method is identical for each target and lowering the sample size would reduce the power of the analyses. Strengths of the study include the largest sample size to date, the direct comparison of the most frequently used stereotactic frame with the novel Nexframe, and the similar techniques used in the 2 centers due to the established collaborations of study staff.

Conclusion

This comparison between Nexframe and the Leksell frame demonstrates that both techniques have equivalent euclidean accuracies. Nexframe offers advantages for the surgical team by increasing the time for stereotactic planning. In addition, patients may be more comfortable without the stereotactic frame, which could increase their endurance and cooperation on the day of surgery.

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