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Deviation of DBS Recording Microelectrodes during Insertion Assessed by Intraoperative CT

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Keywords
Deep brain stimulation · Microelectrode recording · Subthalamic nucleus · Targeting accuracy · Targeting error

Abstract
Introduction: Intraoperative microelectrodes recording with the Ben Gun microdrive system are often used during DBS surgery. An accurate location of these microelectrodes will directly influence the interest of this recording. We have studied the imprecision of implantation of these microelectrodes. ***Methods:*** We have analyzed the stereotactic position of 135 microelectrodes implanted with the Ben Gun microdrive during DBS surgery of 16 patients with advanced Parkinson's disease. An intracranial CT was obtained and integrated to a stereotactic planification system. We recorded the stereotactic coordinates of the 5 microelectrodes inserted simultaneously in a cross-shape. The coordinates of each microelectrode were compared with coordinates of the other 4 electrodes inserted simultaneously with the Ben Gun and visible on the same iCT image. Thus, this procedure avoids errors from image fusion and from brain shift. We calculate (1) the three-dimensional Euclidian deviation of microelectrodes, (2) the deviation in X- and Y-axes on reconstructed probe's eye view MR images, and (3) the deviation from the 2-mm theoretical distance between the central electrode and 4 satellite microelectrodes. ***Results:*** The median deviation was 0.64 mm in 3-D and 0.58 mm in 2-D probe's eye view. Satellite electrodes were located from the central electrode theoretically at 2.0 mm and practically within the range 1.9–2.1 mm, 1.5–2.5 mm, 1.0–3.0 mm, and 0.5–3.5 mm for, respectively, 9.3%, 53.7%, 88.0%, and 98.1%, thus highlighting the significant deviation from the theoretical distance. Position imprecisions were similar for the 4 satellite microelectrodes. The imprecision was similar in X-axis and Y-axes and statistically less in Z-axis. For bilateral implantation, the second implantation of the same patient was not associated with a greater risk of deviation of the microelectrodes than for the first side implanted. ***Conclusion:*** A significant percentage of microelectrodes for MER can deviate substantially from their theoretical target during DBS procedures. An iCT can be used to estimate the potential deviation of microelectrodes and improve the interpretation of MER during the procedure.

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Introduction

Deep brain stimulation (DBS) of the subthalamic nucleus (STN) has become an evidence-based treatment option in Parkinson's disease [1]. Efficacy of DBS therapy is critically influenced by the anatomic location of implanted electrodes [2]. Microelectrode recording (MER) prior to implantation of the final DBS electrodes is often used and has shown to provide some benefits [1]. Intraoperative MER of the STN along the trajectory of the target is recommended to ensure three-dimensional disbandment of the proposed target area [1]. The "Ben Gun" microdrive system, which facilitates the insertion of up to five microelectrodes with an interspace of 2 mm (Fig. 1, image 1), is one of the microdrive systems designed for multichannel recording [1]. The use of parallel multichannel recording enables parallel testing of different trajectories along the z-axis to define the optimal target [1].

Correct lead location in the desired target has been proven to be a strong influential factor for good clinical outcome [1, 3]. Intraoperative CT (iCT) can now be used as a method of three-dimensional confirmation of electrodes placement in DBS surgery [1, 3, 4]. Although used essentially for confirmation of good placement of the final electrode before closure, iCT can easily be performed at any point during the implantation procedure, including the placement of microelectrodes used for MER. Comparison between coordinates of the target from the initial stereotactic planning and coordinates of the final electrode, or difference between coordinates of the position of the optimal microelectrode and of the final electrode, has already been studied [1, 3, 4]. In these studies, some imprecision exists in the comparison of these coordinates that are related to merging errors issued from image fusion, and brain shift since images to be compared are taken at different time periods. The current study will estimate the imprecision of implantation of the microelectrodes used for MER only due to the microdrive system and independently of other sources of imprecision.

Materials and Methods

Patients' Selection

We have analyzed retrospectively the stereotactic position of 135 microelectrodes used for MER during the DBS surgery procedures of 16 patients with advanced Parkinson's disease. All patients were recruited from the Department of Neurology and Neurosurgery of the University Hospital Tivoli at La Louvière, Belgium. All patients have had a preoperative MRI performed a few days before surgery and a preoperative stereotactic planning performed on the stereotactic planification software Leksell SurgiPlan (SPS) 11.0 (Elekta Instruments®, Stockholm, Sweden). All patients received bilateral STN-DBS; for 5 patients, the iCT parameters we have used were not accurate enough to define with high precision the microelectrodes during implantation in one of the 2 sides.

Surgical Procedure

The day of the surgery, the Leksell stereotactic frame (Brainlab Inc., München, Germany), was attached to the patient's head under local anesthesia with mild intravenous sedation in a standard manner. A cerebral CT scan was performed and was integrated in the stereotactic planning to give stereotactic coordinates. During surgery, the patient remained awake and was only mildly sedated during some parts of the procedure. The Medtronic O-arm portable image acquisition system (Medtronic Inc., Minneapolis, MN, USA) was placed before surgery, after the patient had been correctly positioned for surgery. Cutaneous incision was performed along the stereotactic trajectories on both sides. A burr hole was made in one side first, and the dura was opened. The stereotactic arch was positioned, and 5 guide tubes (D.ZAP™, FHC Inc., Bucharest, Romania) were introduced with the Ben Gun system (Stardrive STar™, Medtronic Inc., Minneapolis, MN, USA) through the cortex under iCT control (Fig. 1, image 2); the Ben Gun was positioned orthogonally. Fibrin sealant glue (Tisseel®, Baxter Inc.) is placed to reduce pneumocephalus. Five microelectrodes (D.ZAP™, FHC Inc., Bucharest, Romania) for MER were inserted in the guide tubes. An iCT was then performed with the O-arm. The MER started at 10 mm before the theoretical target; recording was made by increments of 0.5 mm until 5 mm after the theoretical target. The microelectrodes that were supposed to have passed optimally through the STN were selected, and clinical testing was made at selected levels to define the optimal targeting for implantation of the final electrode. An iCT was performed before removing the microelectrodes (Fig. 1, images 3–4). The microelectrodes were removed, and the guide tube selected for implantation of the final electrode was removed and replaced by the final electrode. The guide tubes were removed and an iCT was performed with the final electrode in place. These imaging were integrated in the stereotactic planning to verify the position accuracy of the final electrode.

The same procedure was then performed on the contralateral side. The cannulas and microelectrodes are reused on the other side only when no significant deviation of these cannulas and microelectrodes was found during implantation of the first side. For the cannulas and microelectrodes for which we had a deviation on iCT during implantation of the first side, we change these cannulas and microelectrodes for implantation on the second side. When they are reused for the second side, the cannulas and micrelectrodes are placed at the same position on the Ben Gun for the second side.

The Ben Gun Microdrive System

A MER was performed systematically with five microelectrodes inserted with the Ben Gun system. This commercially available microdrive system enables the parallel insertion of up to five microelectrodes in a cross-shape with an interspace of 2 mm [2, 5] (Fig. 1, images 1–4). The probing of the target area reflects for each electrode a certain depth profile, allowing the generation of a reliable electrophysiological mapping of targeted brain structures with different activity patterns. Among five MER, the one that strains the target at the longest distance and possesses the highest rate of neuronal discharge patterns must be chosen for clinical testing [2].

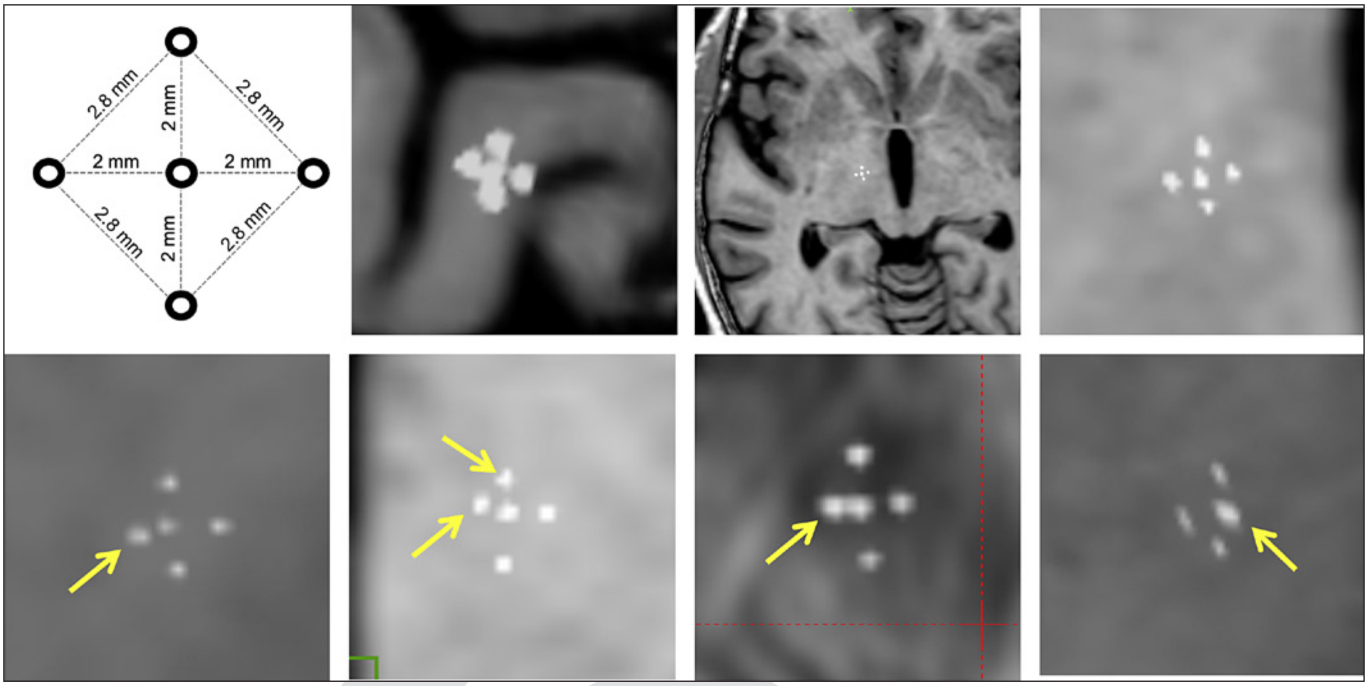

Fig. 1. Implantation of 5 microelectrodes with the Ben Gun. Image 1: theoretical distances of the 5 holes of the Ben Gun. Image 2: view of the cross-shaped microelectrodes tube guides within the 5 holes of the Ben Gun. Images 3–4: 5 microelectrodes inserted without deviation. Images 5–8: different examples of the 5 microelectrodes inserted with the Ben Gun with some of them (yellow arrow) implanted with a significant deviation from their trajectory.

Image Acquisition and Analysis

During surgery, iCT images were obtained using the Medtronic O-arm portable image acquisition system (Medtronic Inc., Minneapolis, MN, USA). Widely used in spinal instrumentation surgery, the O-arm has also been used for DBS surgery [2–4]. The O-arm allowed us to obtain iCT images immediately after microelectrode placement. We incorporated the iCT image series into SPS. We fused the iCT images with the stereotactic preoperative CT scan. We observed the five microelectrodes inserted in a probe's eye view in SPS, and we recorded the stereotactic coordinates of the five microelectrodes.

Data Analysis

We analyzed the data of 27 stereotactic procedures of implantation of 5 microelectrodes performed with the Ben Gun system. The stereotactic coordinates of the 135 microelectrodes were recorded. The real-time position of the electrode's tip was not compared to the planned position of the electrode on the stereotactic planification to avoid errors from image fusion and from brain shift. The stereotactic coordinates of each electrode were directly compared with the coordinates of the other electrodes inserted simultaneously with the Ben Gun in a cross-shaped design (Fig. 1, image 1). This procedure does not necessitate any image fusion and is not affected by any source of electrode's shift since the electrodes are located on the same iCT image.

Analysis of the inaccuracy in targeting of the microelectrodes was assessed by three different methods of calculation. The first method analyzes, for each electrode, the three-dimensional Euclidian deviation of the microelectrode's tip from the theoretical target assessed by the 2 mm or 2.8 mm distance of this electrode from the other microelectrodes of the cross-shape on the 3-D MR-images. To do this, we project and adjust the theoretical Ben Gun cross-shaped distribution of the 5 microelectrodes shown in Figure 1, image 1, on the iCT image of the electrodes in place. So, for each electrode, the theoretical position was defined by the distance from the positions of the other electrodes of the cross-shape. The difference between the theoretical position and the real location of the microelectrode was calculated following the formula $\Delta d = \sqrt{(\Delta x^2+\Delta y^2+\Delta z^2)}$ and analyzed statistically.

The Ben Gun system is designed to theoretically position the anterior, posterior, lateral, and medial electrodes at a distance of 2 mm from the central electrode and separated to each other by 2.8 mm (Fig. 1, image 1). The second method of estimation of the inaccuracy in targeting is borne out by the fact that the Ben Gun creates a MER in a 2-mm cylindrical area around the central electrode and oriented along the trajectory of the MER placement trajectory. Therefore, it is important during surgery to evaluate the differences between the Ben Gun's related theoretical values of position of the microelectrodes and the calculated distances of them in X- and Y-axis coordinates on reconstructed probe's eye view MR images. Actually, to determine the optimal DBS target, the deviation of microelectrodes in the Z-axis is not really important because it has been compensated by the recording at multiple 0.5 mm steps along the Z-axis during MER. So, our second method analyzes the two-dimensional deviations of each of the five microelectrodes from its theoretical cross-shaped target on the reconstructed probe's eye view MR images perpendicular to the implantation trajectory.

Table 1. Vectorial distance from the target

Variable	Values
Microelectrodes, *n*	135
Mean	0.73 mm
Median	0.64 mm
SD	0.48 mm
Max	2.41 mm
<0.1 mm	7 (5.2%)
<0.5 mm	48 (35.6%)
<1.0 mm	99 (73.3%)
<1.5 mm	127 (94.1%)
<2.0 mm	134 (99.2%)
<2.5 mm	135 (100%)

Table 2. 2-D distance from the target

Variable	Values
Microelectrodes, *n*	135
Mean	0.68 mm
Median	0.58 mm
SD	0.48 mm
Max	2.28 mm
<0.1 mm	8 (5.9%)
<0.5 mm	54 (40.0%)
<1.0 mm	101 (74.8%)
<1.5 mm	129 (95.6%)
<2.0 mm	134 (99.2%)
<2.5 mm	135 (100%)

The third method of calculation of the targeting inaccuracy refers to the aim of the Ben Gun system, which is to obtain a three-dimensional cartography at the 2 mm area around the target. This method assesses the difference between the theoretical 2 mm distances between the central electrode and the 4 peripheral electrodes (anterior, posterior, lateral, and medial electrodes), and the real distances. As the central electrode is our target and the 4 surrounding electrodes will analyze the periphery of it, it seems crucial to have a direct evaluation of the imprecision of the surrounding electrodes in comparison of the central electrode. This method will consequently provide some information complementary to the one of the methods 1 and 2.

Statistical Analysis

Statistics were performed with the commercially available software GraphPad Instat® 3.10 (GraphPad©, San Diego, USA). Comparison of continuous variables was performed with the Mann-Whitney two-sample *t* test. Correlations between groups were assessed with the χ^2 test for trend. The results were considered significant for *p* values <0.05.

We have made some statistical analysis of the data recorded on the deviation of microelectrodes. We have checked, for the 135 electrodes implantations, if the imprecision of targeting of 1 of the 5 microelectrodes of the Ben Gun implantation was associated with a higher risk of deviation of the 4 other electrodes in comparison with the other 26 Ben Gun implantations. We have analyzed if some of the 5 microelectrodes in the Ben Gun had more imprecision of implantation than the others, and which had the greatest or least risk of deviation. We checked for bilateral implantation if the second implantation of the same patient was associated with a greater risk of deviation of the microelectrodes than for the first side implanted.

Results

Euclidian Distance from Target

The mean and median 3-D deviations of the 135 inserted microelectrodes were 0.73 and 0.64 mm, respectively (standard deviation 0.48 mm) (Table 1). The maximal deviation observed was 2.41 mm. The deviation was <0.1 mm for 7 electrodes (5.2%), <0.5 mm for 48 electrodes (35.6%), <1.0 mm for 99 electrodes (73.3%), <1.5 mm for 127 electrodes (94.1%), and <2.0 mm for 134 electrodes (99.2%). These results highlight the significant deviation from the theoretical distance we have observed, and the importance of using the real distances measured between microelectrodes for the interpretation of MER.

Two-Dimensional Distance from Target

In the plan perpendicular to the stereotactic trajectory of the microelectrodes, the 2-D deviation of the 135 electrodes was 0.68 and 0.58 mm, respectively (standard deviation 0.48 mm) (Table 2). The maximal deviation observed was 2.28 mm. The deviation was <0.1 mm for only 8 electrodes (5.9%), <0.5 mm for 54 electrodes (40.0%), <1.0 mm for 101 electrodes (74.8%), <1.5 mm for 129 electrodes (95.6%), and <2.0 mm for 134 electrodes (99.2%). Figure 1 (images 5–8) shows some examples of deviation of microelectrodes after insertion with the Ben's Gun, and Figure 2 presents the 2-D deviation of the 135 electrodes from their theoretical position in the Ben Gun system.

Distance of the Lateral Electrodes from the Central Electrode

The distance of the 108 lateral microelectrodes implanted with the Ben's Gun Microdrive system from their respective central microelectrode was measured on the 2-D plan perpendicular to the stereotactic trajectory of the microelectrodes (Tables 3, 4). The mean and median distances were, respectively, 2.09 and 2.10 mm (standard deviation 0.66 mm). The minimum distance was 0.60 mm

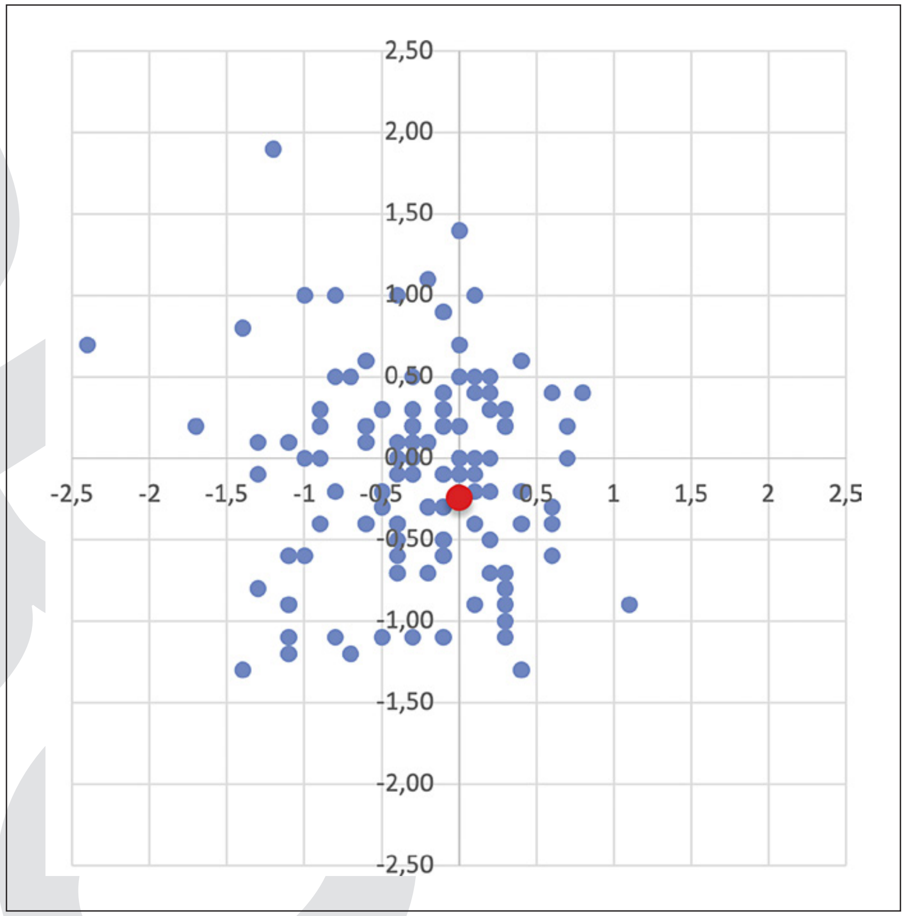

Fig. 2. Probe's eye 2-D view of the cumulated real positions of the microelectrodes studied in comparison with their theoretical positions issued from the Ben Gun design. Red point: theoretical position; blue points: real positions of the microelectrodes.

and the maximum distance 3.79 mm. Ten electrodes (9.3%) were located within the range 1.9–2.1 mm, 58 electrodes (53.7%) in the range 1.5–2.5 mm, 95 electrodes (88.0%) in the range 1.0–3.0 mm, 106 electrodes (98.1%) in the range 0.5–3.5 mm, and all electrodes in the range 0–4 mm. Figure 3 presents the position of the 108 lateral electrodes related to their central electrode. In Table 4, we have presented the results, for all 27 series of 5 microelectrodes inserted with the Ben Gun, the deviation of lateral electrodes from the theoretical 2 mm distance from the central electrode.

Table 3. Distance lateral from central electrode

Variable	Values
Microelectrodes, *n*	108
Mean	2.09 mm
Median	2.10 mm
SD	0.66 mm
Min	0.60 mm
Max	3.79 mm
Range 1.9–2.1 mm	10 (9.3%)
Range 1.5–2.5 mm	58 (53.7%)
Range 1.0–3.0 mm	95 (88.0%)
Range 0.5–3.5 mm	106 (98.1%)
Range 0–4 mm	108 (100%)

Statistical Analysis

The imprecision of targeting of 1 of the 4 satellite microelectrodes of the Ben Gun implantation was not statistically associated with a higher risk of deviation of the 3 other satellite microelectrodes, in comparison with the other 26 implantations ($p = 0.3290$). The 4 satellite microelectrodes of the Ben Gun implantation had a similar range of imprecision: mean Euclidian deviation of 2.09 mm for the anterior electrode, 2.07 mm for the posterior electrode, 2.04 mm for the lateral electrode, and 2.16 mm for the medial electrode. The imprecision was similar in the X-axis (mean 0.70 mm) and Y-axis (mean 0.70 mm): $p = 0.1787$ and statistically less in the Z-axis (mean 0.10 mm): $p = 0.0067$. For bilateral implantation, the second

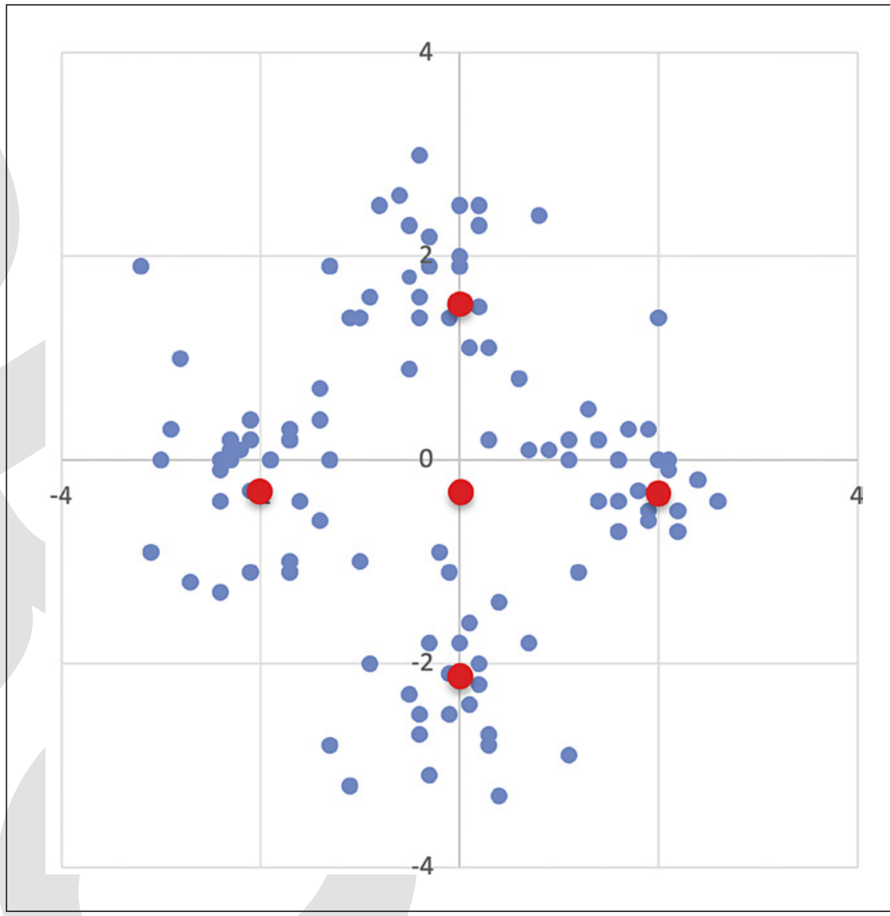

Fig. 3. Graph showing all real positions of the microelectrodes studied. Red points: theoretical positions of the microelectrodes; blue points: real positions of the microelectrodes.

implantation of the same patient was not associated with a greater risk of deviation of the microelectrodes than for the first side implanted ($p = 0.6541$).

Discussion

Multiple MER with the Ben Gun Microdrive System

The efficacy of DBS of the STN in Parkinson's disease is dependent on the accuracy of targeting [1, 6]. Although there is a considerable discussion on the necessity of MER in DBS surgery, many centers still use MER extensively to verify targeting accuracy using physiology [1, 5]. We favor the use of MER in combination with intraoperative testing and iCT imaging to achieve a more precise electrode placement, aiming to ameliorate clinical outcome. Brain environment during surgery is dynamic, and brain shift may occur from cerebrospinal fluid egress, pneumocephalus, or hematoma formation [5–8]. As a result, even with the use of direct localizing techniques, some authors have shown that targeting deep brain structures can have as much as 2 mm of imprecision [5, 6]. This margin of imprecision may be too great to target small nuclei, such as the STN. Electrophysiological mapping is one method to overcome this problem and improve the accuracy of electrode implantation. There are two major advantages of inserting multiple microelectrodes simultaneously rather than serially. The first is that it facilitates the construction of a detailed physiological map of a cylindrical volume of tissue centered on the STN [5, 6]. The second is that by inserting multiple electrodes simultaneously, the parallel guiding tubes may help to fix the brain tissue so that the spatial arrangement between electrodes remains accurate as opposed to several single passes that may have some degree of brain shift, altering the spatial relationship [5, 9].

Different systems have been developed to hold and drive microelectrodes into the brain during MER in a DBS procedure. One multichannel microarray, devised by Dr. Alim-Louis Benabid and called the Ben Gun, is designed to

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Table 4. Position of the 4 satellite electrodes

Series	ANT	POST	LAT	MED
Theory	2.0	2.0	2.0	2.0
1	3.1	0.9	2.9	2.1
2	2.6	2.5	1.8	2.1
3	2.1	3.2	2.8	2.7
4	2.6	3.3	2.3	1.8
5	1.6	2.7	2.4	1.7
6	2.6	2.8	3.2	3.4
7	2.5	1.1	2.0	3.1
8	1.0	2.4	2.4	3.1
9	2.4	2.1	1.6	2.1
10	2.1	1.8	2.4	2.3
11	2.2	2.0	2.1	2.4
12	1.8	2.7	2.3	1.9
13	1.5	1.3	2.2	2.1
14	2.4	1.4	1.7	2.6
15	2.1	3.1	1.6	1.4
16	1.8	2.0	2.1	3.7
17	2.1	2.1	2.4	3.0
18	1.5	2.8	1.3	1.9
19	2.9	2.3	2.6	1.7
20	2.6	2.2	1.7	2.9
21	1.5	1.6	2.4	2.2
22	2.0	1.8	1.4	2.4
23	1.7	1.8	3.3	2.8
24	2.9	2.9	2.1	1.4
25	3.3	1.0	2.7	1.7
26	1.7	2.1	1.9	2.9
27	1.4	2.5	2.0	2.3

Black = range distance 1.9–2.1 mm. Dark grey = range distance 1.5–2.5 mm. White = range distance 1.0–3.0 mm. Very light grey = range distance 0.5–3.5 mm. Light grey = range distance 0–4 mm.

drive up to 5 parallel microelectrodes at one time [5, 6, 10]. This microelectrode holder device has one central channel surrounded by four peripheral channels that are located 2 mm anteriorly, posteriorly, medially, and laterally with respect to the central port. So, the Ben Gun allows recording neuronal activity, for each level studied, theoretically at 5 locations 2.0 mm apart from each other and arranged in a cross-fashion. Sweet et al. [5] have proposed an adaptation for the use of the Ben Gun to optimize efficient mapping by rotating the device by 45°. The interpretation of the results of MER and clinical testing is highly dependent on the relative positions of the microelectrodes.

iCT for DBS Procedures

The Medtronic O-arm image acquisition system is an iCT initially developed for spinal instrumentation surgery. More recently, this technology has been adapted in DBS surgery to increase the accuracy of lead placement [2, 4, 7]. In these studies, the iCT is used to compare the position of the definitive DBS electrode during surgery with the theoretical targeting of the stereotactic planning.

We have used the O-arm system to analyze the position of the 5 microelectrodes implanted for MER with the Ben Gun. With this procedure, we checked the potential deviation of microelectrodes during implantation. Hence, we know that the surgical implantation of electrodes is associated with some sources of targeting inaccuracy, such as the semiflexibility of the microelectrodes, crossing the pia mater, or traversing the brain parenchyma. In most studies, the images acquired from the iCT are fused with preoperative imaging or compared with prior iCT images obtained a few times ago; this nonsimultaneous image acquisition adds a few errors to the comparison of target accuracy. Brain shift may occur during DBS surgery, induced by CSF evacuation, edema formation, pneumocephalus from intracranial air entry at burr holes, microbleedings along the trajectory of electrodes, and so on [5–8]. Our technique for analysis of microelectrode deviation avoids these sources of inaccuracy since we compare the position of the 5 microelectrodes implanted simultaneously with the Ben Gun. Moreover, the procedure of image fusion also creates by itself some imprecision; our procedure does not require fusion of images.

Position Accuracy of Microelectrodes during Implantation

This study highlights the imprecision of positioning of microelectrodes for MER during the DBS procedure. We have recorded that only 5.2% of the electrodes inserted with the Ben Gun has an Euclidian deviation from their theoretical position (based on the 2 mm and 2.8 mm distances from the surrounding electrodes, as in Fig. 1 image 1) by less than 0.1 mm, only 35.6% by less than 0.5 mm, and 26.7% by more than 1 mm (Table 1). So, to be accurate, the interpretation of MER must consider the real distances between the microelectrodes and not the theoretical 2 mm or 2.8 mm distances between them (Fig. 1, image 1). Our experience shows that the actual distances between microelectrodes during MER can easily be measured with an iCT.

During MER, we record the neuronal activity by increments of 0.5 mm from 10 mm before the theoretical target to 5 mm after this target to obtain a three-dimensional cartography of the 2 mm area around the target. Therefore, it is important to estimate the 2-D distance between microelectrodes in a probe's eye view. The results of our analyses detailed in Tables 2–4 confirm that many microelectrodes have distances between them significantly different from theoretical distances. Figure 1 shows some examples of malposition of some microelectrodes (images 5–8). Figures 2, 3 exhibit the cumulative positions of all electrodes analyzed in this study.

The guide cannula inserted via the Ben Gun can be the source of this imprecision. It is therefore important to check these electrodes before use to verify that they are straight. We use systematically the "trick of the trade" described in the technical manual of use of the StarDrive system: we roll the cannulas of a flat surface as soon as they come out of the package, before insertion. With this technique, we can verify that cannulas are straight and do not use those that are obviously not straight.

To our knowledge, no specific study has been focused so far on this source of imprecision during DBS procedures. We experienced that a significant number of microelectrodes can deviate significantly from their Ben Gun's theoretical target. Since the interpretation of results of MER and clinical testing are related to the position of microelectrodes, knowing the exact position of these microelectrodes is crucial.

Optimization of Placement of Microelectrodes for MER

Our experience shows that implantation of MER microelectrodes with the Ben Gun microdrive system may be associated with significant imprecision in targeting. The neurosurgeon must be aware of this and be very cautious during the implantation process to avoid any source of deviation of the microelectrodes. One very risky step is the passage of microelectrodes through the pia mater. We recommend checking the electrodes before use to verify that they are straight with the trick described above.

We also strongly recommend using systematically an iCT to check for the real position of the microelectrodes after implantation of the electrodes and before MER. Electrodes with a significant deviation from their theoretical target can be repositioned. If it is not possible to reach the target with a sufficient precision, the interpretation of results of MER of this electrode must be adapted consequently.

In the future, the Ben Gun system could perhaps be improved in an engineer matter. Using a Ben Gun manufactured with fixed cannulas could help in the precision of implantation of the microelectrodes. Cannulas could be made in a nondeformable alloy. A device could be engineered to check for the inframillimetric accuracy of the cannulas and the microelectrodes, as we have for accuracy in radiosurgery by instance.

Limitations of the Current Study

Our study carries several limitations. This study is monocentric. The procedure described in this study has been applied only for the Ben Gun system for multichannel positioning of microelectrodes. It would be interesting to analyze the target deviation of microelectrodes on other systems of multiple guide tube holders. A comparison between the results from different guide tube holders would be helpful.

We have analyzed the relative position of a limited number of microelectrodes. This surgical protocol is still ongoing in our department; our future DBS procedures will increase the cohort of microelectrodes implanted to have more experience in optimization of microelectrodes targeting for MER.

We have measured manually on SPS the position of the microelectrodes studied. A computerized automation for localization of microelectrodes tip could be developed and used to improve the precision of measurement of the stereotactic distances.

Conclusions

We experienced that a significant percentage of microelectrodes for MER can deviate substantially from their theoretical target during DBS procedures. Due to some sources of minimal deviations of the microelectrodes, the distance between the 5 microelectrodes' tip can vary significantly from the theoretical 2 mm distance and the theoretical cross-arrangement of microelectrodes with the Ben Gun. An iCT can be used to estimate the potential deviation of microelectrodes and improve the interpretation of MER during the procedure.

Statement of Ethics

The current research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki. The patients have given their written informed consent. The study protocol was approved by the Institute's Committee on Human Research (Belgian Institutional Review Board of the Ethical Committee of CHU Tivoli ULB, ref. 1360/2020).

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Nicolas Massager and Sophie Dethy are the authors based on the ICMJE Criteria for Authorship: they have (1) made substantial contributions to the conception and design of the work and the acquisition, analysis, and interpretation of data for the work; (2) drafted the work for important intellectual content; (3) made the final approval of the version to be published; and (4) made agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Anthony Nguyen is an author based on the ICMJE Criteria for Authorship: she has (1) made substantial contributions to the acquisition, analysis, and interpretation of data for the work; (2) revised it critically for important intellectual content; (3) made the final approval of the version to be published; and (4) made agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Henri-Benjamin Pouleau and Daniele Morelli are the authors based on the ICMJE Criteria for Authorship: they have (1) made substantial contributions to the acquisition, analysis, and interpretation of data for the work; (2) drafted the work for important intellectual content; (3) made the final approval of the version to be published; and (4) made agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

References

1 Kinfe TM, Vesper J. The impact of multichannel microelectrode recording (MER) in deep brain stimulation of the basal ganglia. Acta Neurochir Suppl. 2013;117:27–33.
2 Shahlaie K, Larson PS, Starr PA. Intraoperative computed tomography for deep brain stimulation surgery: technique and accuracy assessment. Neurosurgery. 2011;68(1 Suppl Operative):114–24; discussion 124.
3 Smith AP, Bakay RAE. Frameless deep brain stimulation using intraoperative O-arm technology. Clinical article. J Neurosurg. 2011;115(2):301–9.
4 Atsumi H, Matsumae M. Fusing of preoperative magnetic resonance and intraoperative O-arm images in deep brain stimulation enhance intuitive surgical planning and increase accuracy of lead placement. Neurol Med Chir. 2021;61(5):341–6.
5 Sweet JA, Walter BL, Munyon C, Miller JP. Multitract orthogonal microelectrode localization of the subthalamic nucleus: description of a novel technique. Neurosurgery. 2014;10(Suppl 2):240–5; discussion 245.
6 Limousin P, Krack P, Pollak P, Benazzouz A, Ardouin C, Hoffmann D, et al. Electrical stimulation of the subthalamic nucleus in advanced Parkinson's disease. N Engl J Med. 1998;339(16):1105–11.
7 Hemm S, Wardell K. Stereotactic implantation of deep brain stimulation electrodes: a review of technical systems, methods and emerging tools. Med Biol Eng Comput. 2010;48(7):611–24.
8 Li Z, Zhang JG, Ye Y, Li X. Review of factors affecting targeting accuracy of deep brain stimulation: electrode implantation between 2001 and 2015. Stereotact Funct Neurosurg. 2016;94(6):351–62.
9 Gross RE, Krack P, Rodriguez-Oroz MC, Rezai AR, Benabid AL. Electrophysiological mapping for the implantation of deep brain stimulators for Parkinson's disease and tremor. Mov Disord. 2006;21(Suppl 14):S259–S283.
10 Tamma F, Caputo E, Chiesa V, Egidi M, Locatelli M, Rampini P, et al. Anatomo-clinical correlation of intraoperative stimulation-induced side-effects during HF-DBS of the subthalamic nucleus. Neurol Sci. 2002;23(Suppl 2):S109–S110.