Review

Stereotactic and Functional Neurosurgery

Stereotact Funct Neurosurg 2016;94:351–362
DOI: 10.1159/000449206

Received: September 29, 2015
Accepted after revision: August 16, 2016
Published online: October 27, 2016

Review on Factors Affecting Targeting Accuracy of Deep Brain Stimulation Electrode Implantation between 2001 and 2015

Zhe Li[a] Jian-Guo Zhang[c] Yan Ye[b] Xiaoping Li[b]

Departments of [a]Biomedical Engineering and [b]Mechanical Engineering, National University of Singapore, Singapore, Singapore; [c]Department of Neurosurgery, Beijing Tiantan Hospital, Capital Medical University, Beijing, China

Key Words

Accuracy · Deep brain stimulation · Depth electrodes · Stereotactic surgery · Targeting · Electrode implantation · Error

Abstract

Background: Accurate implantation of a depth electrode into the brain is of the greatest importance in deep brain stimulation (DBS), and various stereotactic systems have been developed for electrode implantation. However, an updated analysis of depth electrode implantation in the modern era of DBS is lacking. ***Objective:*** This study aims at providing an updated review on targeting accuracy of DBS electrode implantation by analyzing contemporary DBS electrode implantation operations from the perspective of precision engineering. ***Methods:*** Eligible articles with information on targeting accuracy of DBS electrode implantation were searched in the PubMed database. ***Results:*** An average targeting error of DBS electrode implantation is reported to decrease toward 1 mm; the standard deviation of targeting error is decreasing toward 0.5 mm. Targeting accuracy is not only found to be affected by individual surgical steps, but also systematically affected by the architecture of the implantation operation. ***Conclusion:*** A systematic strategy should be adopted to further improve the targeting accuracy of depth electrode implantation. Attention should be paid to optimizing the whole electrode implantation operation, which can help minimize error accumulation or amplification throughout the serially connected procedures for DBS electrode implantation.

Introduction

Deep brain stimulation (DBS) is an established therapy for the treatment of medication-refractory movement disorders like Parkinson's disease. In this treatment, programmed electrical pulses sent from the implanted electrode are used to modulate the activities of target neurons located deep in the brain [1]. The modern era of DBS was thought to be inaugurated by Benabid and his colleagues' pioneering work published in 1987, in which chronic high-frequency electrical stimulation was found to be effective in treating tremor [2–4]. Afterwards, DBS was approved by the Food and Drug Administration for the treatment of essential tremor and Parkinson's disease in 1997 and 2002, respectively [5]. Because of its evident effectiveness, reversibility and nonablative nature, DBS is now being attempted for many other neuropsychiatric or neurodegenerative disorders such as medication-refractory depression and Alzheimer's disease [6–11].

KARGER

E-Mail karger@karger.com
www.karger.com/sfn

1011–6125/16/0946–0351$39.50/0

Zhe Li
Department of Biomedical Engineering, National University of Singapore
E3A-07-01A, 7 Engineering Drive 1, Singapore 117574 (Singapore)
E-Mail: zhelidut@gmail.com

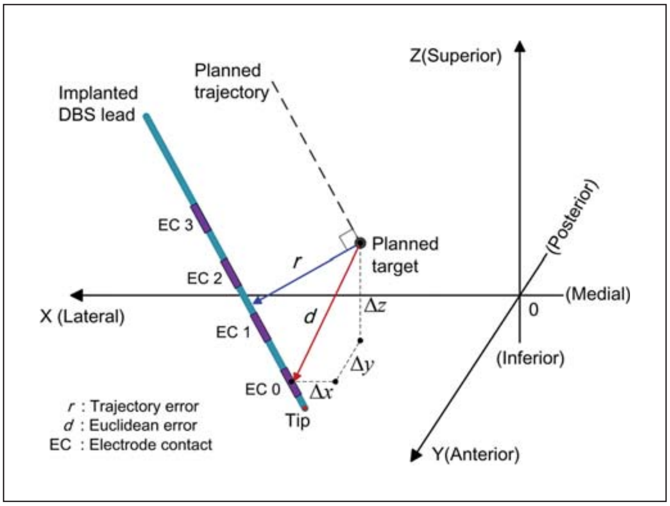

Fig. 1. Different definitions of TE.

Effective stimulation of deep brain targets depends on the accurate implantation of the DBS electrode (model 3387/3389, Medtronic Inc., Minneapolis, Minn., USA) with the assistance of a stereotactic system [12–16], and targeting accuracy of depth electrode implantation is of cardinal importance in this operation. To help improve targeting accuracy, new techniques such as rapid prototyping, image fusion and advanced robotics are developed. In the early days, only frame-based stereotactic systems were used for electrode implantation [17–20]. Nowadays, various newly developed systems integrated with novel techniques such as optical navigation and interventional magnetic resonance imaging (iMRI) have entered the clinical theater, making the electrode implantation operation increasingly diverse [15, 21–23], but the information on the targeting accuracy of different stereotactic systems is fragmented and mainly appears in various clinical reports [24–27]. An early systematic study on this topic is that published in 1994 by Maciunas et al. [24]. In that paper, the targeting accuracy of different frame-based systems was investigated. Another recent review article only systematically described the procedures for DBS electrode implantation [28].

However, a systematic study comparing the performance of various stereotactic systems in the modern era of DBS is lacking. This makes it hard to understand how the landscape of DBS has been changed with the adoption of new stereotactic systems in the last two decades. Without an updated and systematic literature study, it is difficult to answer some vital questions regarding DBS. For example, what is the state-of-the-art average targeting accuracy of DBS electrode implantation? What is the lowest targeting error (TE) ever achieved? Is the frequently cited notion 'DBS has an average targeting accuracy of 2–3 mm' which appeared many years ago still correct? In fact, this notion keeps appearing in some of the latest publications [29, 30]. Furthermore, it is not clear how targeting accuracy is differently affected in the electrode implantation operation assisted by diverse stereotactic systems.

This paper intends to fill this knowledge gap by providing the latest information on targeting accuracy of electrode implantation in the modern era of DBS based on a systematic literature study. Findings from this paper not only help answer the previously mentioned questions, but also provide guidance on improving the targeting accuracy of depth electrode implantation for scientists and engineers working in this dynamic area of DBS.

Methods

Original articles published in PubMed were searched using the following key words: deep brain stimulation, accuracy, error and electrode. Different combinations of these key words were tried. The first report on targeting accuracy was found to appear in 2002; thus, articles published after 2001 were searched. Returned articles were prechecked to exclude unrelated and duplicated articles; the remaining papers were rechecked to only include original articles published in English with information on targeting accuracy of at least 5 patients. Reports on animal experiments were excluded.

As for targeting accuracy, it means how accurately and precisely the electrode is delivered into the brain [24]. It can be represented by TE in 3 different ways, the Euclidean error d, the vector error Δ and the trajectory error r (fig. 1) [20, 22, 31–36]. d is the distance between the target and a specific position (commonly the clinically effective electrode contact) on the DBS lead; vector errors Δx, Δy and Δz are, respectively, the projections of d in the x- (lateral-medial), y- (anterior-posterior) and z-directions (superior-inferior); r is the shortest distance between the target and the DBS lead. Besides, standard deviation (SD) of the average TE is another important parameter to represent the repeatability of electrode implantation. A smaller SD means higher implantation repeatability.

In published articles, TE was reported in different manners. To compare the targeting accuracy, the Euclidean error d and its standard deviation SD_d are adopted in this study. In some articles, only vector errors were reported [17, 19, 37–40]. In this situation, d was acquired with vector errors using equation 1 [18, 29, 31]. Because vector error is the projection of d onto a given axis, equation 1 reveals the inherent relationship between Euclidean error and vector errors. In this computation process, no additional error would be incurred to Euclidean error d. As for the standard deviation SD_d, if there were no evident difference among the SD for vector errors, SD_d could be estimated using equation 2. If an evident difference exists between SD_x, SD_y and SD_z, the calculated SD_d would be un-

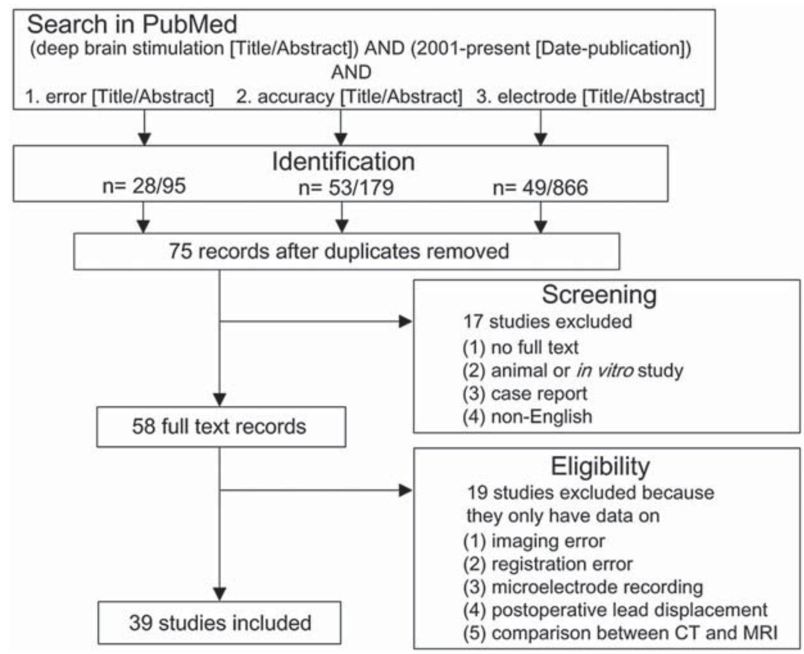

Fig. 2. Strategy for searching studies with information on targeting accuracy of DBS electrode implantation.

derestimated. Due to the lack of raw data on TE, calculation error for SD_d cannot be avoided. To highlight this effect, SD_d acquired by equation 2 would be denoted by a superscript c in the following:

$$d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \quad (1)$$

$$SD_d = \sqrt{SD_x^2 + SD_y^2 + SD_z^2}, \quad (2)$$

where SD_x, SD_y and SD_z are the SDs of Δx, Δy and Δz, respectively.

Results

A total of 75 articles were preliminarily found, and the procedures used for a systematic literature search are summarized in figure 2. After screening and eligibility checking, 39 full-text clinical articles with data on targeting accuracy were finally included as shown in table 1. Eight different stereotactic systems were found in the 39 finally included articles for DBS electrode implantation. These systems can be classified into 3 groups, the frame-based, the frameless and the iMRI-guided systems. The frame-based systems include the Leksell system (Elekta Instruments Inc., Sweden) [18, 31, 41], the Zamorano-Dujovny system (Stryker-Leibinger Inc., Germany) [19], the Riechert-Mundinger system (Innomed Pte Ltd., Germany) [20], the Cosman-Roberts-Wells system (Radionics Inc., USA) [17, 39, 42] and the Neuromate robot (Renishaw Inc., UK) [43]. The frameless systems include NexFrame (Image-Guided Neurologics Inc., USA) [21, 26, 32] and the STarFix microTargeting Platform (FHC Inc., USA) [22, 27, 44]. The iMRI-guided system means the ClearPoint SmartFrame (MRI Interventions Inc., USA) [35].

Percentage of DBS Leads Implanted by Different Systems

A total of 2,931 DBS leads were implanted in 1,765 patients as summarized in table 1. In order to reveal change in adoption rate of different systems over time, percentages of DBS leads implanted by various systems were calculated before and after 2007, respectively. The results summarized in figure 3 indicate that most DBS leads were implanted by frame-based systems. The usage of frame-based systems generally experienced a decline. Take the Leksell system for example. DBS leads implanted by this system declined from 73.54% (2001–2007) to 51.75% (2008–2015). At the same time, frameless systems have been increasingly used over time. DBS leads implanted by

Table 1. TE of DBS electrode implantation reported in articles published from 2001 to 2015

Study [Ref.], year	Number of		MER (Y/N)	Vector error, mm			Euclidean error, mm	Stereotactic system
	leads	patients		Δx	Δy	Δz		
Schrader et al. [19], 2002	85	43	Y	Left: 0.48±0.71 Right: 1.00±0.74	1.8±1.66 1.8±1.39	1.87±2.63 2.23±1.67	2.64±3.19[c] 3.03±2.29[c]	ZD
Starr et al. [45], 2002	76	44	Y	1.40 (0–4.7)	1.62 (0–5.1)	1.72 (8.8)	3.2±1.41	Leksell
Duffner et al. [17], 2002	17	10	Y	1.2 (0–2.7)	1.0 (0–2.1)	0.7 (0–3.2)	1.71[c]	CRW
Cuny et al. [18], 2002	28	14	Y	1.3	3.7	1.2	4.1	Leksell
Patel et al. [25], 2002	37	19	N	0.3±0.4	0.4±0.4	–	–	Leksell
De Salles et al. [46], 2004	72/76	54	Y	0.97±0.09	1.15±0.12	1.35±0.12	2.33±0.14	Leksell
Ferroli et al. [37], 2004	17	10	Y[a]	0.65±0.27	0.61±0.22	0.82±0.31	1.21±0.47[c]	Leksell
Fitzpatrick et al. [22], 2005	20	13	Y	1.4 (up to 4.0)	1.4 (up to 3.2)	1.1 (up to 2.9)	2.7	STarFix
Andrade-Souza et al. [47], 2005	28	14	Y	–	–	–	3.19±1.16, 3.42±1.34, 4.66±1.33	Leksell
Lee et al. [48], 2005	10 25 82	74	Y	–	–	–	4.8±3.16 2.64±1.26 2.23±1.15	Leksell
Holloway et al. [21], 2005	47	38	Y	1.6±1.0	1.3±1.0	2.0±1.3	3.2±1.4	NexFrame
Martin et al. [12], 2005	8	5	N	–	–	–	1.0±0.88	NexFrame
Hamid et al. [38], 2005	54	27	Y	0.48±0.38	0.69±0.58	2.9±1.95	3.02±2.07[c]	Leksell
Bjartmarz and Rehncrona [26], 2007	14 14	14	Y[a]	1.9±1.3 0.5±0.5	0.9±0.8 0.4±0.4	1.0±0.7 0.9±0.8	2.5±1.4 1.2±0.6	NexFrame Leksell
Patel et al. [13], 2007	205	101	N	–	–	–	1.5	Leksell
Guo et al. [49], 2007	55	28	Y	–	–	–	1.7–3.0	Leksell
Pollo et al. [39], 2007	62	31	Y	1.03±0.76	1.34±1.02	0.21	1.70[c]	CRW
Fiegele et al. [20], 2008	46	23	Y	1.34	0.63	1.18	3.15±1.69	RM
Daniluk et al. [42], 2009	22	11	Y	–	–	–	1.7	CRW
Zrinzo et al. [34], 2009	162	109	Y[b]	–	–	–	1.5±1.0	Leksell
Kelman et al. [29], 2010	70 69	90	Y	–	–	–	2.65±0.22 2.78±0.25	CRW NexFrame
Shin et al. [14], 2010	32	16	Y	0.2±0.5	0.9±1.3	0.5±1.1	1.05±1.77[c]	Leksell
D'Haese et al. [27], 2010	104	75	Y	–	–	–	1.99±0.92	STarFix
Holl et al. [33], 2010	312	165	N	0.6	0.7	0.4	1.4±0.9	Leksell
Fukaya et al. [40], 2010	10 40	5 20	Y	1.3±0.3 1.5±0.9	1.0±0.9 1.1±0.7	0.5±0.6 0.8±0.6	1.71±1.12[c] 2.02±1.29[c]	NexFrame Leksell
Starr et al. [15], 2010	53	29	N	0.73±0.62	0.85±0.7	1.54±1.05	2.18±0.92	NexFrame
Pezeshkian et al. [50], 2011	46 50	26 26	Y	1.09±1.04 1.52±1.26	1.46±1.14 1.62±1.35	1.44±0.96 2.1±1.62	2.32±1.82[c] 3.06±2.46[c]	Leksell
Chang et al. [51], 2011	46	23	Y	0.61 (0–2.9)	0.55 (0–1.7)	–	0.92	Leksell
Konrad et al. [44], 2011	284	263	Y	–	–	–	1.99±0.9	STarFix
Smith and Bakay [23], 2011	15	12	Y	–	–	–	3.04±1.45, 2.62±1.5	NexFrame
Foltynie et al. [52], 2011	158	79	Y[a]	–	–	–	1.3±0.6	Leksell
Shahlaie et al. [16], 2011	24	15	Y	0.72±0.10	1.03±0.17	0.84±0.14	1.65±0.19 [30]	Leksell
Thani et al. [41], 2012	16	12	N	1.4	1.4	–	1.8	Leksell
Holloway and Docef [30], 2013	44 29	33 21	Y	–	–	–	2.16±0.92 2.04±0.8	NexFrame
Burchiel et al. [32], 2013	119	60	N	–	–	–	1.59±1.11	NexFrame
Lumsden et al. [31], 2013	88	42	Y	Left: 1.05 (0–4) Right: 1.28 (0.1–4.1)	0.85 (0–2.2) 0.7 (0–5.5)	0.94 (0–7.8) 0.7 (0–8.6)	2.45	Leksell
Starr et al. [35], 2014	12	6[d]	N	–	–	–	0.6±0.5	SmartFrame
Mirzadeh et al. [53], 2014	46 48	48	N	–	–	–	1.1±0.7 1.6±0.7	NexFrame Leksell
Von Langsdorff et al. [43], 2015	30	17	–	0.37±0.34	0.32±0.24	0.58±0.31	0.86±0.32	Neuromate
Total	2,931	1,765						

MER = Microelectrode recording; Y = yes; N = no; ZD = Zamorano-Dujovny; CRW = Cosman-Roberts-Wells; RM = Riechert-Mundinger.
[a] Macrostimulation. [b] Semimicrostimulation and macrostimulation. [c] Using equations 1 and 2. [d] Pediatric patients.

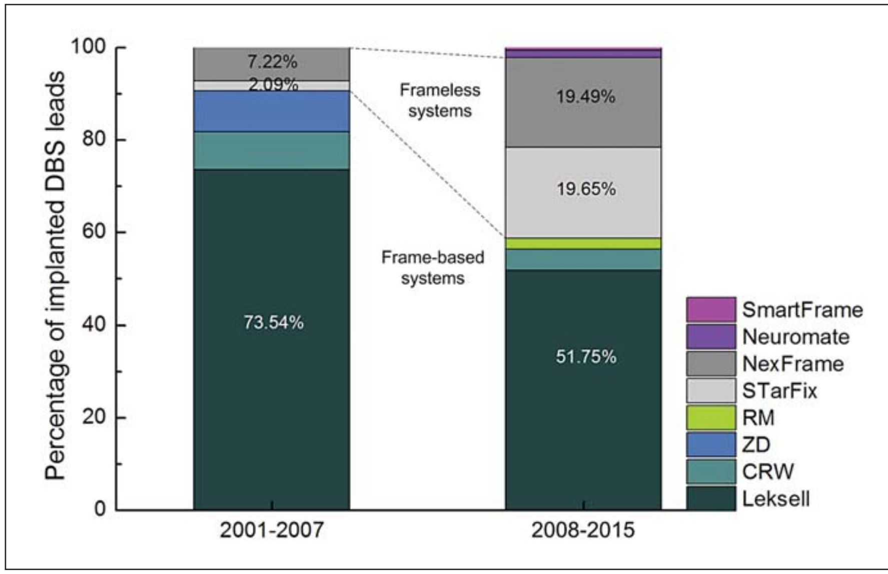

Fig. 3. Percentage of DBS leads implanted by different stereotactic systems. RM = Riechert-Mundinger; ZD = Zamorano-Dujovny; CRW = Cosman-Roberts-Wells.

NexFrame increased from 7.22% (2001–2007) to 19.49% (2008–2015). Another fact worth noting is that the stereotactic systems have become more diverse over time. Two new systems, the robotic Neuromate [43] and the iMRI-guided ClearPoint SmartFrame [35], have entered the clinical theater after 2007, making the depth electrode implantation operation more complex.

Development of Targeting Accuracy over Time

The TE of electrode implantation by different systems is summarized in figure 4a. The data on TE are available in the 39 finally included articles. Among these articles, 8 do not have information on Euclidean error, but they all have data on vector errors; thus, Euclidean errors d for these articles are calculated using equation 1. Euclidean error acquired via computation is clearly labeled with superscript c in table 1. In order to reveal the development of TE over time, weighted average TE is calculated with equation 3. For the calculation of weighted TE in a given year, TE and the corresponding number of leads reported in that article are both considered:

$$WTE_j = \sum_{i=1}^{n}\left(TE_{ij} \times P_{ij}\right) / \sum_{i=1}^{n} P_{ij}, \tag{3}$$

where WTE_j and n are the weighted average TE and the number of published articles on TE in year j, respectively; TE_{ij} and P_{ij} are the TE and the number of leads reported in article i published in year j; only the year in which 2 or more articles on targeting accuracy were published ($n \geq 2$) is considered.

It is shown that the TE is generally decreasing over time. In the early 2000s, TEs larger than 4 mm were occasionally reported. From 2006 onwards, TEs are generally smaller than 3 mm, and the weighted average TE is smaller than 2 mm. In the last few years, TE is decreasing toward 1 mm (fig. 4a). Besides, the corresponding SDs are shown in figure 4b. The SD of TE for articles without information on Euclidean error is calculated using equation 2. The data point for SD acquired via calculation is also labeled with superscript c in figure 4b. The calculated SD of d is larger than the SD of its related vector errors as shown in table 1. From figure 4b, a decreasing trend in SD can be observed. In the last few years, SD is even decreasing toward 0.5 mm. This means depth electrode implantation can be performed with higher repeatability.

Comparison of Targeting Accuracy Realized by Different Stereotactic Systems

In order to compare the performance of different systems, TEs of representative frame-based, frameless and iMRI-guided systems are plotted in figure 5. A decreasing trend in TE is observed for electrode implantation by both frame-based and frameless systems. Comparing the data shown in figure 5a and b, the frameless system is shown to have comparable targeting accuracy with the conventionally frame-based system. However, the newly developed robotic frame-based system Neuromate was reported to have a TE of 0.86 ± 0.32 mm [43], which is much smaller than that of electrode implantation operations by most frame-based or frameless systems (fig. 5).

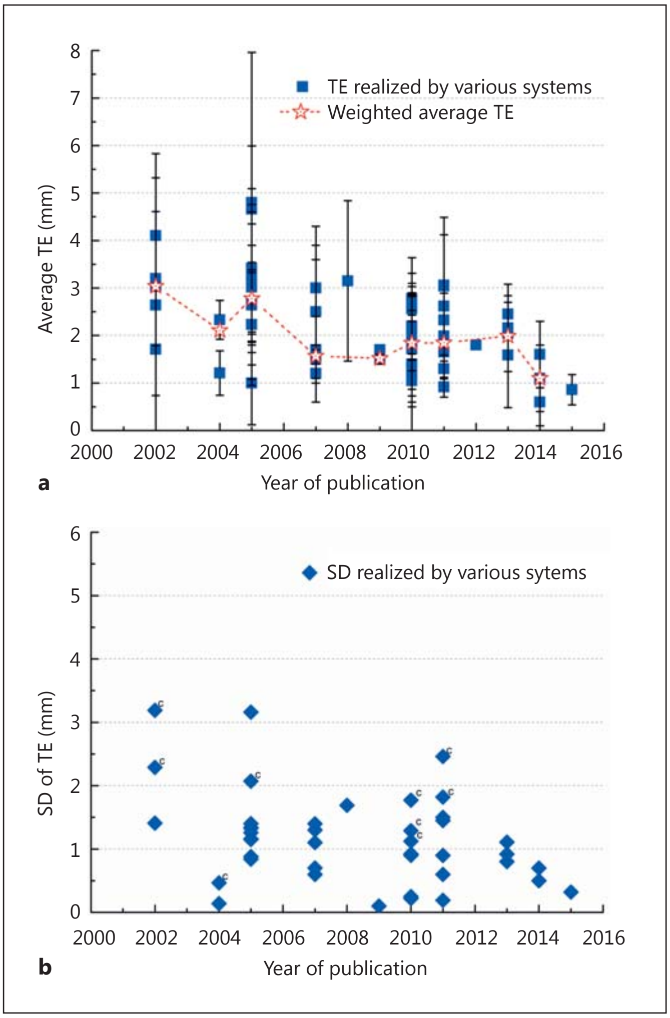

Fig. 4. Targeting accuracy reported in the literature. **a** The average TE. **b** Corresponding SD of the average TE (labeling of points with superscript c means the data at this point are acquired by equation 2).

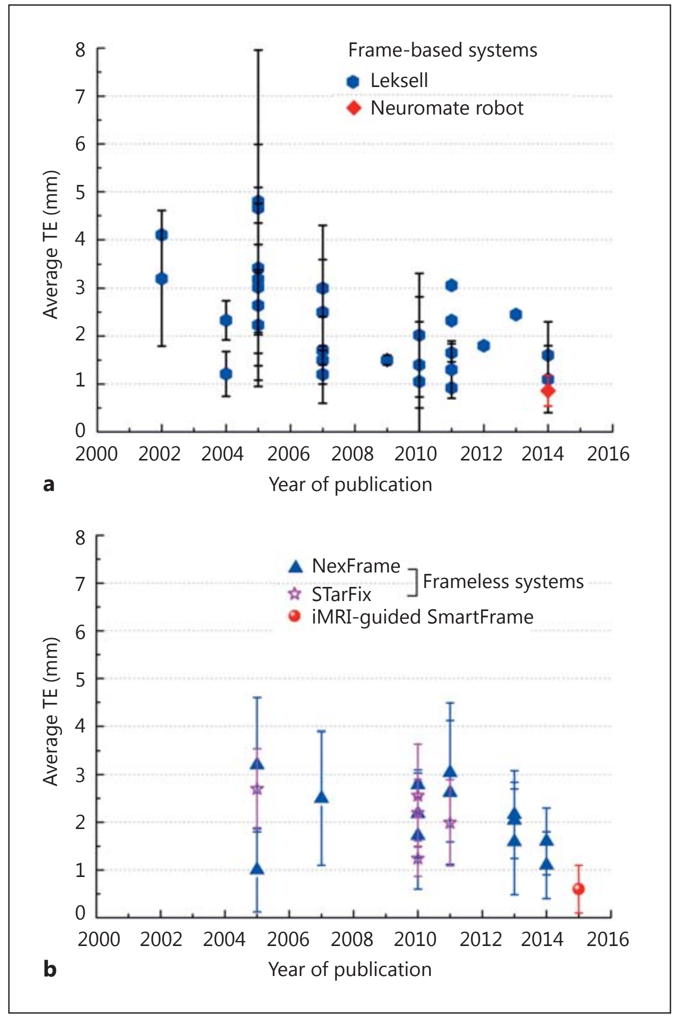

Fig. 5. TE of DBS electrode implantation by the frame-based Leksell system and the newly developed robotic frame-based system Neuromate (**a**) and the frameless and iMRI-guided systems (**b**).

Besides, the iMRI-guided system SmartFrame was reported to have an even smaller TE of about 0.6 mm [35], which is thought to be the smallest TE ever achieved. Due to the reduced TE, a high improvement of 86% in patients' movement performance was reported [35]. However, this system's TE was acquired via operation on pediatric patients. A smaller insertion depth in the nonadult brain may contribute to a smaller TE. Thus, the performance of this system needs to be further evaluated on adult patients by a neutral third party.

Another important fact worth mentioning is the great variance among TEs and SDs reported by different institutions using the same system during the same period of time. Take the electrode implantation by the Leksell system for example. From 2011 to 2014, some institutions reported a TE of about 3 mm [50], while others realized a TE as small as 1.3 mm [52] (fig. 5a), and the corresponding SD also varies from 0.19 to 2.46 mm [16, 31, 41]. The same problem exists for the operation with frameless systems like NexFrame or STarFix. Although peripheral equipment or devices may influence TE, variance in neurosurgeons' proficiency and expertise in performing DBS electrode implantation among different institutions/hospitals would be a significant contributor. Cross-institutional training or communication may help flatten this difference.

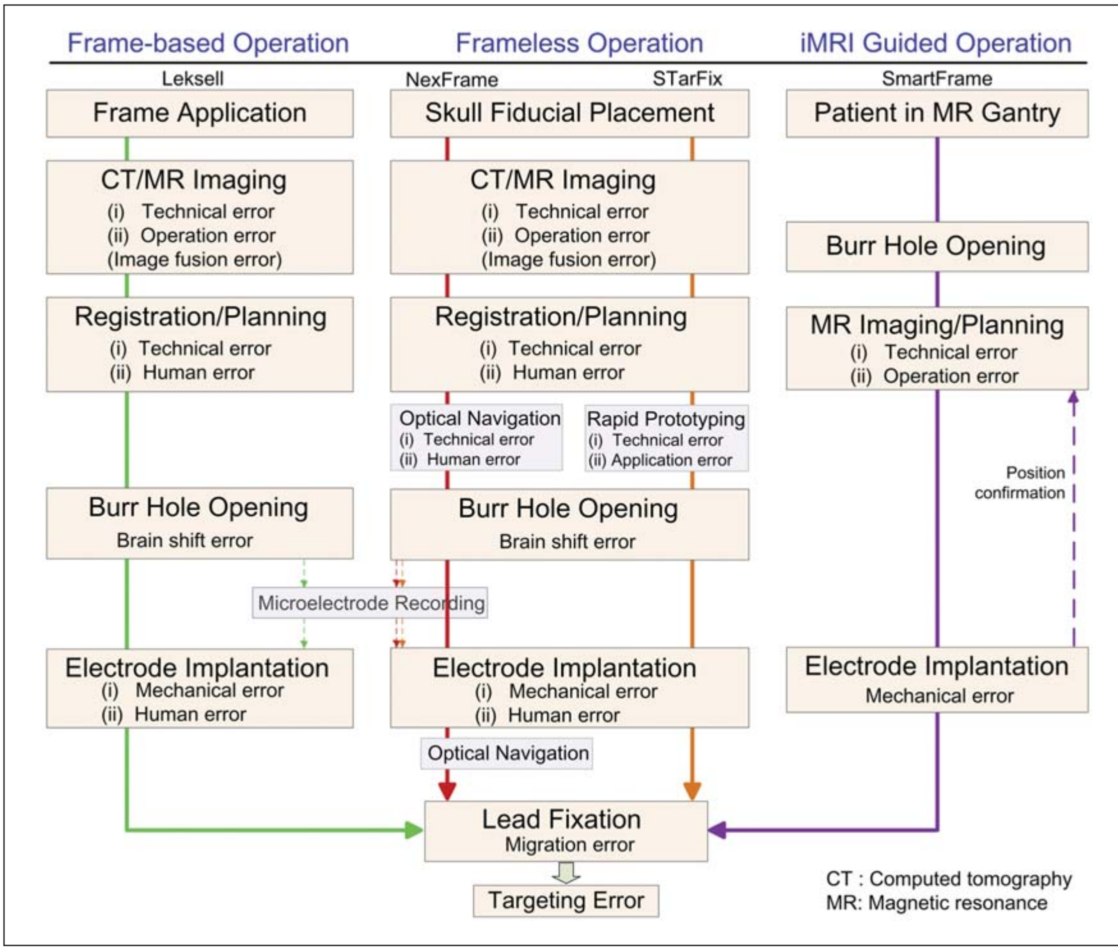

Fig. 6. Architectures of 3 representative electrode implantation operations and error transmission throughout each operation.

Discussion

Targeting accuracy of the DBS electrode implantation operation has greatly improved over time. Findings on WTE indicate that the average targeting accuracy of DBS has increased to about 1–2 mm. The popular statement 'DBS has an average targeting accuracy of about 2–3 mm' [30, 36] appearing in some of the latest publications would be obsolete. Besides, findings acquired in this study can help clarify the debate over the superiority in targeting accuracy between frame-based and frameless systems. The frameless operation was declared to have a better targeting accuracy than the frame-based operation in some articles, while the opposite opinion was also reported [15, 26]. According to the data shown in figure 5, targeting accuracy of the frameless operation is nearly the same as that of the conventional frame-based operation. However, the newly developed Neuromate robotic system and the iMRI system have a much higher targeting accuracy. Since the DBS electrode is implanted by successively carrying out a series of procedures, arrangement of these procedures inside the operation would affect the final targeting accuracy. In the following, electrode implantation operation by different stereotactic systems will be compared from the perspective of implantation architecture.

Architecture of an electrode implantation operation means what procedures are included and how these procedures are arranged in the operation. From the perspective of precision engineering, the architecture affects the targeting accuracy by influencing error transmission or accumulation throughout the operation [33]. Implantation operation encompasses all processes from fiducial/frame application, imaging and planning, burr hole opening, electrode implantation, to lead fixation [28]. In order to investigate error transmission throughout different operations, architectures of 3 representative DBS operations are compared in figure 6.

As shown in figure 6, a serial architecture exists in all operations. The frameless operation is technically and procedurally more complex than the frame-based operation. Frameless operation improves the patient's comfort at the expense of introducing extra procedure(s) such as the optical navigation in NexFrame [15, 29] and the rapid prototyping in STarFix [22, 44]. These extra procedures may increase the chance for error accumulation. However, the targeting accuracy of a frameless operation is not evidently affected by the increased procedural complexity as revealed in figure 5. This may be because the technical accuracy of the introduced procedure is too high to evidently influence the final TE. Yet, the increased procedural complexity does influence neurosurgeons' attitudes toward this operation. It was reported that the frameless system was inconvenient to use and was even left unused in some institutions [23, 26, 40, 44].

Among the 3 representative operations, the iMRI-guided operation has the simplest architecture. The introduction of iMRI eliminates the need for image registration which is crucial in conventional frame-based or frameless operations. The accompanying technical and human errors are also removed [35, 54]. Moreover, the architecture of the iMRI-guided operation has been optimized by rearranging procedures inside this operation. Imaging and planning comes after dura opening, and the brain shift error caused by cerebrospinal fluid (CSF) leakage could be eliminated [35, 54]. This is also different from the frame-based and frameless operations. Procedure simplification and optimization help improve the targeting accuracy by reducing the chance for error accumulation. This partially explains the ultra-high targeting accuracy of the iMRI-guided operation as shown in figure 5. Therefore, from the macroperspective of architecture, a most effective strategy to improve targeting accuracy is to reduce error occurrence/accumulation via architecture simplification and optimization. This philosophy can also be used in developing new devices or techniques for depth electrode implantation.

Electrode implantation is performed based on a few important assumptions, that is, position of the target determined in the image space is the same as that in the physical space, the anatomical target would be 'fixed' to the preoperatively determined position inside the skull, the DBS lead would be delivered into the brain exactly as desired, and the DBS lead would be anchored to the position in the brain after implantation. However, things do not develop as desired in the actual operation. If the real situation deviates from these assumptions, error would occur. These errors would accumulate throughout the operation and be revealed as the final TE. In the following, key factors affecting these important assumptions will be discussed.

Imaging

MRI has superior sensitivity in visualizing anatomical structures and is adopted as the main technique for target determination and trajectory planning [55–57]. A key assumption in the planning stage is that the coordinates of the anatomical target determined in the image space are the same as those in the physical space. However, image distortion and limited resolution of MRI would cause error in determining the position of the anatomical target for stimulation [58]. The technique of fusing MRI and CT images has been adopted to deal with this problem [17, 19, 21, 22, 29, 31, 33, 38, 50]. The fused image inherits MRI's high anatomical resolution and CT's high geometric accuracy, but this method increases technical and procedural complexity and may introduce image fusion error. Advanced image fusion algorithms are needed to minimize this error [56, 57, 59, 60]. Another effective strategy is to develop MRI-compatible devices or high-resolution MRI systems, which has become a trend in recent years [12, 13, 15, 25, 35, 41, 54, 61, 62].

Brain Shift

A second key assumption in DBS is that the target stays at the preoperatively determined position in the skull throughout surgery. However, due to brain shift, the planned target always moves away from the preoperatively determined position. Brain shift refers to the movement and deformation of the brain inside the skull [63, 64]. In DBS, it is mainly caused by CSF leakage after opening of the arachnoid membrane, due to which the target would move away from the preoperatively determined position [27, 65]. Resorption of the subdural air after scalp closure could also incur an inverse brain shift [64, 66]. The error caused by brain shift is hard to control. Methods preventing CSF leakage can help minimize brain shift error. Sealing the burr hole with fibrin glue/wax [18, 32, 33, 51], adjusting the head to make the burr hole at the highest position [13, 20, 50] and irrigating the burr hole with isotonic or saline solution [13, 33, 41] are frequently practiced. A most effective strategy is to eliminate this error by arranging the imaging and planning after dura opening as employed in the iMRI-guided operation with SmartFrame [35].

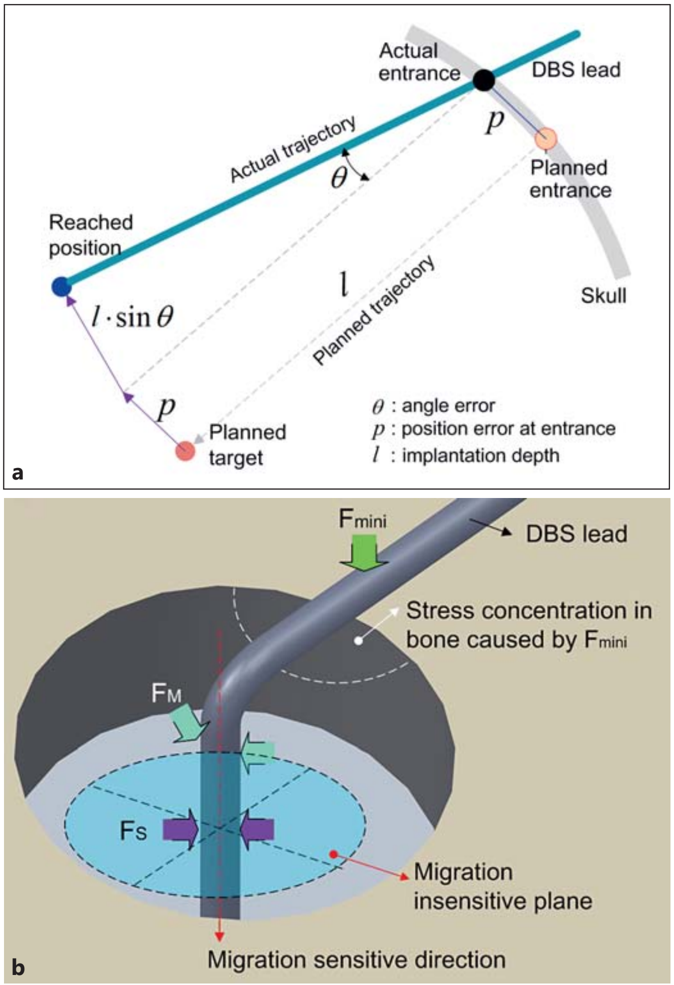

Fig. 7. a Influence of the stereotactic frame's mechanical error on TE. **b** Forces for lead fixation exerted by different anchoring devices.

Mechanical Error of the Stereotactic System

In the electrode insertion stage, it is assumed that the DBS lead would be exactly delivered into brain at the planned entrance and along the planned trajectory. However, implantation accuracy is always impaired by the stereotactic frame's mechanical error. As illustrated in figure 7a, p and θ are the position error and angle/gesture error in an insertion operation, respectively. Position error p at entrance can cause a small position error at the planned implantation depth, while a small θ can incur a large error of $l \cdot \sin\theta$ due to the large implantation depth l (up to about 80 mm or larger). Thus, sufficient attention should be paid to minimize mechanical errors. The higher targeting accuracy of Neuromate shown in figure 5a is partially due to the robotic arm's ultra-small angle and position errors [43]. Besides, the stereotactic frame must be securely applied; otherwise, the mechanical accuracy would be impaired by intraoperative frame loosening [44, 67].

Postimplantation Electrode Migration

The assumption that the implanted electrode does not migrate in the brain is not always valid in practice [65]. Electrode migration can occur due to inadvertent pushing-down of the DBS lead during fixation, as reflected from the relatively larger vertical error [15, 16, 21, 38, 50, 65]. This error is thought to be affected by the force exerted by the anchoring device. According to the principle of precision engineering, one should avoid applying the anchoring force in the direction of lead migration or the migration-sensitive direction. Currently, 3 representative devices for anchoring the DBS lead are the titanium miniplate [19, 65], Medtronic burr hole ring and cap (Medtronic Inc.) supplied in the DBS lead package [68], and Stimloc cranial base and cap (Medtronic Inc., its old commercial name: Navigus; information acquired through personal communication with Medtronic Inc.) [38, 42, 65]. As illustrated in figure 7b, the anchoring forces exerted by the titanium miniplate, Stimloc and Medtronic cap are F_{mini}, F_S and F_M, respectively. F_{mini} is in the migration-sensitive direction, F_S is in the migration-insensitive direction (perpendicular to the insertion trajectory), and F_M is in between. From the perspective of anchoring force, Stimloc (or Navigus) would have the best anchoring performance. Stimloc's superiority has been verified by the smaller vertical error reported in some clinical studies [48, 65, 68]. The force exerted by the miniplate could cause stress concentration to the bone beneath, from which bone erosion and long-term lead migration would result [65]. Besides these 3 representative burr hole caps/covers, a few other devices are commercially available such as the NeuroPace burr hole cover from NeuroPace Inc. (www.neuropace.com), the Guardian burr hole cover (St Jude Medical Inc.) [69] and the SureTek burr hole cover from Boston Scientific Inc. (http://neuromedics.ru/products/brain_fix_suretek). None of these devices was used in the 39 articles summarized in table 1. Although these devices are different in design, their functioning mechanisms are similar to the devices analyzed in figure 7b. For example, the NeuroPace burr hole cover exerts a force onto the lead in the same way as the Medtronic burr hole ring and cap. Thus, it is representative to analyze the anchoring force's effect on lead migration based on the 3 devices shown in figure 7b. For all these lead-anchoring devices, care must be taken to avoid applying the anchoring force in the migration-sensitive direction. Besides, caution should also be taken to prevent pulling the lead upward during lead fixation. Modifying the microtexture of the lead's surface is another method to minimize lead migration [70].

Another factor worth noting is microelectrode recording (MER), a neuropsychological method for target verification before definitive implantation of the DBS lead [51, 71–73]. MER was considered mandatory for target verification in the early days [18, 74, 75]. Nowadays, image-guided operation without MER is being increasingly practiced, and its targeting accuracy and clinical efficacy are comparable to those with MER [15, 32, 33, 35, 41, 53]. Due to the incurred cost and risk issues, the add-on value of MER is now being questioned [32, 76, 77]. However, as shown in table 1, physiological targeting is performed to correct the preoperatively determined target in 29 out of the 38 reports (one report has no information on targeting method). This implies that physiological targeting is regarded as superior over image-based targeting by most surgeons/doctors in the contemporary DBS operations.

Conclusion

Accurate implantation of the DBS electrode into the brain is of greatest importance for effective stimulation. In the modern era, due to the adoption of various newly developed stereotactic systems, the electrode implantation operation has become diverse over time. Based on findings from this systematic literature study, the average targeting accuracy of DBS electrode implantation is shown to have increased to 1–2 mm. The lowest targeting accuracy ever achieved is 0.6 ± 0.5 mm by the iMRI-guided ClearPoint SmartFrame. As for the superiority between frameless systems and frame-based systems, although frameless systems could help improve patient compliance by allowing head movement, the frameless system is not superior over frame-based systems from the perspective of targeting accuracy. Based on the findings in this paper, these two types of systems are shown to have comparable targeting accuracy.

The DBS electrode implantation is found to have a serial architecture. An evident feature of serial operation is that errors occurring in an upstream procedure would transmit downwards and accumulate throughout the operation; in this error transmission process, a small upstream error may lead to an enlarged error in a downstream operation. Simplification of the electrode implantation architecture can help improve targeting accuracy by reducing the chance of error occurrence and accumulation. Architecture optimization is also beneficial for improving the targeting accuracy. A typical demonstration of architecture optimization is the electrode implantation using the iMRI-guided SmartFrame. In this operation, imaging and trajectory planning operations are arranged after burr hole opening. This architecture optimization helps eliminate the brain shift's effect on TE. Another thing worth mentioning is that the depth electrode implantation operation is based on a few important assumptions. These assumptions should be carefully reexamined during the operation. If the actual situation deviates from these assumptions, error would be incurred. A typical assumption is 'the DBS lead would be exactly delivered into the brain as desired'. However, manual operation or mechanical error of the open-loop stereotactic frame would make this assumption invalid. Adoption of advanced robotic systems is helpful to solve this issue as revealed from the low TE of the Neuromate robot system.

Another minor suggestion from this literature study is on future reports of TE. A clear definition of TE is desired in future publications. If possible, vector error, trajectory error, and Euclidean error should be reported in a whole package. This could help other researchers compare the electrode implantation operation performed by different institutions or by different stereotactic systems/frames.

References

1 Delgado JM, Hamlin H, Chapman WP: Technique of intracranial electrode implacement for recording and stimulation and its possible therapeutic value in psychotic patients. Confin Neurol 1952;12:315–319.
2 Benabid AL, Pollak P, Louveau A, Henry S, Derougemont J: Combined (thalamotomy and stimulation) stereotactic surgery of the VIM thalamic nucleus for bilateral Parkinson disease. Appl Neurophysiol 1987;50:344–346.
3 Hariz MI, Blomstedt P, Zrinzo L: Deep brain stimulation between 1947 and 1987: the untold story. Neurosurg Focus 2010;29:E1.
4 Benabid AL, Pollak P, Gervason C, Hoffmann D, Gao DM, Hommel M, Perret JE, de Rougemont J: Long-term suppression of tremor by chronic stimulation of the ventral intermediate thalamic nucleus. Lancet 1991;337:403–406.
5 Gielen FLH: Deep brain stimulation: current practice and challenges for the future. 1st IEEE EMBS Conf Neural Eng, Capri, 2003, pp 489–491.
6 Abelson JL, Curtis GC, Sagher O, Albucher RC, Harrigan M, Taylor SF, Martis B, Giordani B: Deep brain stimulation for refractory obsessive-compulsive disorder. Biol Psychiatry 2005;57:510–516.

7 Mayberg HS, Lozano AM, Voon V, McNeely HE, Seminowicz D, Hamani C, Schwalb JM, Kennedy SH: Deep brain stimulation for treatment-resistant depression. Neuron 2005;45:651–660.
8 Feil J, Zangen A: Brain stimulation in the study and treatment of addiction. Neurosci Biobehav Rev 2010;34:559–574.
9 Anderson RJ, Frye MA, Abulseoud OA, Lee KH, McGillivray JA, Berk M, Tye SJ: Deep brain stimulation for treatment-resistant depression: efficacy, safety and mechanisms of action. Neurosci Biobehav Rev 2012;36:1920–1933.
10 Laxton AW, Tang-Wai DF, McAndrews MP, Zumsteg D, Wennberg R, Keren R, Wherrett J, Naglie G, Hamani C, Smith GS, Lozano AM: A phase I trial of deep brain stimulation of memory circuits in Alzheimer's disease. Ann Neurol 2010;68:521–534.
11 Sankar T, Chakravarty MM, Bescos A, Lara M, Obuchi T, Laxton AW, McAndrews MP, Tang-Wai DF, Workman CI, Smith GS, Lozano AM: Deep brain stimulation influences brain structure in Alzheimer's disease. Brain Stimul 2015;8:645–654.
12 Martin AJ, Larson PS, Ostrem JL, Keith Sootsman W, Talke P, Weber OM, Levesque N, Myers J, Starr PA: Placement of deep brain stimulator electrodes using real-time high-field interventional magnetic resonance imaging. Magn Reson Med 2005;54:1107–1114.
13 Patel NK, Plaha P, Gill SS: Magnetic resonance imaging-directed method for functional neurosurgery using implantable guide tubes. Neurosurgery 2007;61:358–365.
14 Shin M, Penholate MF, Lefaucheur JP, Gurruchaga JM, Brugieres P, Nguyen JP: Assessing accuracy of the magnetic resonance imaging-computed tomography fusion images to evaluate the electrode positions in subthalamic nucleus after deep-brain stimulation. Neurosurgery 2010;66:1193–1202.
15 Starr PA, Martin AJ, Ostrem JL, Talke P, Levesque N, Larson PS: Subthalamic nucleus deep brain stimulator placement using high-field interventional magnetic resonance imaging and a skull-mounted aiming device: technique and application accuracy. J Neurosurg 2010;112:479–490.
16 Shahlaie K, Larson PS, Starr PA: Intraoperative computed tomography for deep brain stimulation surgery: technique and accuracy assessment. Neurosurgery 2011;68:114–124.
17 Duffner F, Schiffbauer H, Breit S, Friese S, Freudenstein D: Relevance of image fusion for target point determination in functional neurosurgery. Acta Neurochir (Wien) 2002;144:445–451.
18 Cuny E, Guehl D, Burbaud P, Gross C, Dousset V, Rougier A: Lack of agreement between direct magnetic resonance imaging and statistical determination of a subthalamic target: the role of electrophysiological guidance. J Neurosurg 2002;97:591–597.
19 Schrader B, Hamel W, Weinert D, Mehdorn HM: Documentation of electrode localization. Mov Disord 2002;17:S167–S174.
20 Fiegele T, Feuchtner G, Sohm F, Bauer R, Anton JV, Gotwald T, Twerdy K, Eisner W: Accuracy of stereotactic electrode placement in deep brain stimulation by intraoperative computed tomography. Parkinsonism Relat Disord 2008;14:595–599.
21 Holloway KL, Gaede SE, Starr PA, Rosenow JM, Ramakrishnan V, Henderson JM: Frameless stereotaxy using bone fiducial markers for deep brain stimulation. J Neurosurg 2005;103:404–413.
22 Fitzpatrick JM, Konrad PE, Nickele C, Cetinkaya E, Kao C: Accuracy of customized miniature stereotactic platforms. Stereotact Funct Neurosurg 2005;83:25–31.
23 Smith AP, Bakay RA: Frameless deep brain stimulation using intraoperative O-arm technology. Clinical article. J Neurosurg 2011;115:301–309.
24 Maciunas RJ, Galloway RL Jr, Latimer JW: The application accuracy of stereotactic frames. Neurosurgery 1994;35:682–694.
25 Patel NK, Heywood P, O'Sullivan K, Love S, Gill SS: MRI-directed subthalamic nucleus surgery for Parkinson's disease. Stereotact Funct Neurosurg 2002;78:132–145.
26 Bjartmarz H, Rehncrona S: Comparison of accuracy and precision between frame-based and frameless stereotactic navigation for deep brain stimulation electrode implantation. Stereotact Funct Neurosurg 2007;85:235–242.
27 D'Haese PF, Pallavaram S, Konrad PE, Neimat J, Fitzpatrick JM, Dawant BM: Clinical accuracy of a customized stereotactic platform for deep brain stimulation after accounting for brain shift. Stereotact Funct Neurosurg 2010;88:81–87.
28 Abosch A, Timmermann L, Bartley S, Rietkerk HG, Whiting D, Connolly PJ, Lanctin D, Hariz MI: An international survey of deep brain stimulation procedural steps. Stereotact Funct Neurosurg 2013;91:1–11.
29 Kelman C, Ramakrishnan V, Davies A, Holloway K: Analysis of stereotactic accuracy of the Cosman-Robert-Wells frame and Nexframe frameless systems in deep brain stimulation surgery. Stereotact Funct Neurosurg 2010;88:288–295.
30 Holloway K, Docef A: A quantitative assessment of the accuracy and reliability of O-arm images for deep brain stimulation surgery. Neurosurgery 2013;72:47–57.
31 Lumsden DE, Ashmore J, Charles-Edwards G, Lin JP, Ashkan K, Selway R: Accuracy of stimulating electrode placement in paediatric pallidal deep brain stimulation for primary and secondary dystonia. Acta Neurochir (Wien) 2013;155:823–836.
32 Burchiel KJ, McCartney S, Lee A, Raslan AM: Accuracy of deep brain stimulation electrode placement using intraoperative computed tomography without microelectrode recording. J Neurosurg 2013;119:301–306.
33 Holl EM, Petersen EA, Foltynie T, Martinez-Torres I, Limousin P, Hariz MI, Zrinzo L: Improving targeting in image-guided frame-based deep brain stimulation. Neurosurgery 2010;67:437–447.
34 Zrinzo L, van Hulzen AL, Gorgulho AA, Limousin P, Staal MJ, De Salles AA, Hariz MI: Avoiding the ventricle: a simple step to improve accuracy of anatomical targeting during deep brain stimulation. J Neurosurg 2009;110:1283–1290.
35 Starr PA, Markun LC, Larson PS, Volz MM, Martin AJ, Ostrem JL: Interventional MRI-guided deep brain stimulation in pediatric dystonia: first experience with the ClearPoint system. J Neurosurg Pediatr 2014;14:400–408.
36 Zrinzo L: Pitfalls in precision stereotactic surgery. Surg Neurol Int 2012;3:S53–S61.
37 Ferroli P, Franzini A, Marras C, Maccagnano E, D'Incerti L, Broggi G: A simple method to assess accuracy of deep brain stimulation electrode placement: pre-operative stereotactic CT+ postoperative MR image fusion. Stereotact Funct Neurosurg 2004;82:14–19.
38 Hamid NA, Mitchell RD, Mocroft P, Westby GW, Milner J, Pall H: Targeting the subthalamic nucleus for deep brain stimulation: technical approach and fusion of pre- and postoperative MR images to define accuracy of lead placement. J Neurol Neurosurg Psychiatry 2005;76:409–414.
39 Pollo C, Vingerhoets F, Pralong E, Ghika J, Maeder P, Meuli R, Thiran JP, Villemure JG: Localization of electrodes in the subthalamic nucleus on magnetic resonance imaging. J Neurosurg 2007;106:36–44.
40 Fukaya C, Sumi K, Otaka T, Obuchi T, Kano T, Kobayashi K, Oshima H, Yamamoto T, Katayama Y: Nexframe frameless stereotaxy with multitract microrecording: accuracy evaluated by frame-based stereotactic X-ray. Stereotact Funct Neurosurg 2010;88:163–168.
41 Thani NB, Bala A, Lind CR: Accuracy of magnetic resonance imaging-directed frame-based stereotaxis. Neurosurgery 2012;70:114–123.
42 Daniluk S, Davies KG, Novak P, Vu T, Nazzaro JM, Ellias SA: Isolation of the brain-related factor of the error between intended and achieved position of deep brain stimulation electrodes implanted into the subthalamic nucleus for the treatment of Parkinson's disease. Neurosurgery 2009;64:374–382.
43 Von Langsdorff D, Paquis P, Fontaine D: In vivo measurement of the frame-based application accuracy of the Neuromate neurosurgical robot. J Neurosurg 2015;122:191–194.
44 Konrad PE, Neimat JS, Yu H, Kao CC, Remple MS, D'Haese PF, Dawant BM: Customized, miniature rapid-prototype stereotactic frames for use in deep brain stimulator surgery: initial clinical methodology and experience from 263 patients from 2002 to 2008. Stereotact Funct Neurosurg 2011;89:34–41.

45 Starr PA, Christine CW, Theodosopoulos PV, Lindsey N, Byrd D, Mosley A, Marks WJ: Implantation of deep brain stimulators into the subthalamic nucleus: technical approach and magnetic resonance imaging-verified lead locations. J Neurosurg 2002;97:370–387.
46 De Salles AAF, Frighetto L, Behnke E, Sinha S, Tseng L, Torres R, Lee M, Cabatan-Awang C, Frysinger R: Functional neurosurgery in the MRI environment. Minim Invas Neurosur 2004;47:284–289.
47 Andrade-Souza YM, Schwalb JM, Hamani C, Eltahawy H, Hoque T, Saint-Cyr J, Lozano AM: Comparison of three methods of targeting the subthalamic nucleus for chronic stimulation in Parkinson's disease. Neurosurgery 2005;56:360–368.
48 Lee MWY, De Salles AAF, Frighetto L, Torres R, Behnke E, Bronstein JM: Deep brain stimulation in intraoperative MRI environment – comparison of imaging techniques and electrode fixation methods. Minim Invas Neurosurg 2005;48:1–6.
49 Guo T, Parrent A, Peters T: Surgical targeting accuracy analysis of six methods for subthalamic nucleus deep brain stimulation. Comput Aided Surg 2007;12:325–334.
50 Pezeshkian P, DeSalles AA, Gorgulho A, Behnke E, McArthur D, Bari A: Accuracy of frame-based stereotactic magnetic resonance imaging vs frame-based stereotactic head computed tomography fused with recent magnetic resonance imaging for postimplantation deep brain stimulator lead localization. Neurosurgery 2011;69:1299–1306.
51 Chang WS, Kim HY, Kim JP, Park YS, Chung SS, Chang JW: Bilateral subthalamic deep brain stimulation using single track microelectrode recording. Acta Neurochir (Wien) 2011;153:1087–1095.
52 Foltynie T, Zrinzo L, Martinez-Torres I, Tripoliti E, Petersen E, Holl E, Aviles-Olmos I, Jahanshahi M, Hariz M, Limousin P: MRI-guided STN DBS in Parkinson's disease without microelectrode recording: efficacy and safety. J Neurol Neurosurg Psychiatry 2011;82:358–363.
53 Mirzadeh Z, Chapple K, Lambert M, Dhall R, Ponce FA: Validation of CT-MRI fusion for intraoperative assessment of stereotactic accuracy in DBS surgery. Mov Disord 2014;29:1788–1795.
54 Larson PS, Starr PA, Bates G, Tansey L, Richardson RM, Martin AJ: An optimized system for interventional magnetic resonance imaging-guided stereotactic surgery: preliminary evaluation of targeting accuracy. Neurosurgery 2012;70:95–103.
55 Simon SL, Douglas P, Baltuch GH, Jaggi JL: Error analysis of MRI and Leksell stereotactic frame target localization in deep brain stimulation surgery. Stereotact Funct Neurosurg 2005;83:1–5.
56 O'Gorman RL, Jarosz JM, Samuel M, Clough C, Selway RP, Ashkan K: CT/MR image fusion in the postoperative assessment of electrodes implanted for deep brain stimulation. Stereotact Funct Neurosurg 2009;87:205–210.
57 Lee JY, Kim JW, Lee JY, Lim YH, Kim C, Kim DG, Jeon BS, Paek SH: Is MRI a reliable tool to locate the electrode after deep brain stimulation surgery? Comparison study of CT and MRI for the localization of electrodes after DBS. Acta Neurochir (Wien) 2010;152:2029–2036.
58 Balachandran R, Welch EB, Dawant BM, Fitzpatrick JM: Effect of MR distortion on targeting for deep-brain stimulation. IEEE Trans Biomed Eng 2010;57:1729–1735.
59 Sauner D, Runge M, Poggenborg J, Maarouf M, Sturm V, Treuer H, Hunsche S: Multimodal localization of electrodes in deep brain stimulation: comparison of stereotactic CT and MRI with teleradiography. Stereotact Funct Neurosurg 2010;88:253–258.
60 Pinsker MO, Herzog J, Falk D, Volkmann J, Deuschl G, Mehdorn M: Accuracy and distortion of deep brain stimulation electrodes on postoperative MRI and CT. Zentralbl Neurochir 2008;69:144–147.
61 Li G, Su H, Cole G, Shang W, Harrington K, Camilo A, Pilitsis J, Fischer G: Robotic system for MRI-guided stereotactic neurosurgery. IEEE Trans Biomed Eng 2015;62:1077–1088.
62 Thani NB, Bala A, Swann GB, Lind CR: Accuracy of postoperative computed tomography and magnetic resonance image fusion for assessing deep brain stimulation electrodes. Neurosurgery 2011;69:207–214.
63 Slotty PJ, Kamp MA, Wille C, Kinfe TM, Steiger HJ, Vesper J: The impact of brain shift in deep brain stimulation surgery: observation and obviation. Acta Neurochir (Wien) 2012;154:2063–2068.
64 Lalys F, Haegelen C, D'Albis T, Jannin P: Analysis of electrode deformations in deep brain stimulation surgery. Int J Comput Assist Radiol Surg 2014;9:107–117.
65 Contarino MF, Bot M, Speelman JD, de Bie RM, Tijssen MA, Denys D, Bour LJ, Schuurman PR, van den Munckhof P: Postoperative displacement of deep brain stimulation electrodes related to lead-anchoring technique. Neurosurgery 2013;73:681–688.
66 van den Munckhof P, Contarino MF, Bour LJ, Speelman JD, de Bie RM, Schuurman PR: Postoperative curving and upward displacement of deep brain stimulation electrodes caused by brain shift. Neurosurgery 2010;67:49–53.
67 Balachandran R, Fritz MA, Dietrich MS, Danilchenko A, Mitchell JE, Oldfield VL, Lipscomb WW, Fitzpatrick JM, Neimat JS, Konrad PE, Labadie RF: Clinical testing of an alternate method of inserting bone-implanted fiducial markers. Int J Comput Assist Radiol Surg 2014;9:913–920.
68 Wharen RE Jr, Putzke JD, Uitti RJ: Deep brain stimulation lead fixation: a comparative study of the Navigus and Medtronic burr hole fixation device. Clin Neurol Neurosurg 2005;107:393–395.
69 Pepper J, Zrinzo L, Mirza B, Foltynie T, Limousin P, Hariz M: The risk of hardware infection in deep brain stimulation surgery is greater at impulse generator replacement than at the primary procedure. Stereotact Funct Neurosurg 2013;91:56–65.
70 Parittotokkaporn T, Thomas DG, Schneider A, Huq E, Davies BL, Degenaar P, Rodriguez y Baena F: Microtextured surfaces for deep-brain stimulation electrodes: a biologically inspired design to reduce lead migration. World Neurosurg 2012;77:569–576.
71 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:S259–S283.
72 Montgomery EB Jr: Microelectrode targeting of the subthalamic nucleus for deep brain stimulation surgery. Mov Disord 2012;27:1387–1391.
73 Shamir RR, Zaidel A, Joskowicz L, Bergman H, Israel Z: Microelectrode recording duration and spatial density constraints for automatic targeting of the subthalamic nucleus. Stereotact Funct Neurosurg 2012;90:325–334.
74 Carlson JD, Iacono RP: Electrophysiological versus image-based targeting in the posteroventral pallidotomy. Comput Aided Surg 1999;4:93–100.
75 Mobin F, De Salles AAF, Behnke EJ, Frysinger R: Correlation between MRI-based stereotactic thalamic deep brain stimulation electrode placement, macroelectrode stimulation and clinical response to tremor control. Stereotact Funct Neurosurg 1999;72:225–232.
76 Zrinzo L, Foltynie T, Limousin P, Hariz MI: Reducing hemorrhagic complications in functional neurosurgery: a large case series and systematic literature review. J Neurosurg 2012;116:84–94.
77 McClelland S: A cost analysis of intraoperative microelectrode recording during subthalamic stimulation for Parkinson's disease. Mov Disord 2011;26:1422–1427.