Progressive gait ataxia following deep brain stimulation for essential tremor: adverse effect or lack of efficacy?

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Thalamic deep brain stimulation is a mainstay treatment for severe and drug-refractory essential tremor, but postoperative management may be complicated in some patients by a progressive cerebellar syndrome including gait ataxia, dysmetria, worsening of intention tremor and dysarthria. Typically, this syndrome manifests several months after an initially effective therapy and necessitates frequent adjustments in stimulation parameters. There is an ongoing debate as to whether progressive ataxia reflects a delayed therapeutic failure due to disease progression or an adverse effect related to repeated increases of stimulation intensity. In this study we used a multimodal approach comparing clinical stimulation responses, modelling of volume of tissue activated and metabolic brain maps in essential tremor patients with and without progressive ataxia to disentangle a disease-related from a stimulation-induced aetiology. Ten subjects with stable and effective bilateral thalamic stimulation were stratified according to the presence (five subjects) of severe chronic-progressive gait ataxia. We quantified stimulated brain areas and identified the stimulation-induced brain metabolic changes by multiple 18F-fluorodeoxyglucose positron emission tomography performed with and without active neurostimulation. Three days after deactivating thalamic stimulation and following an initial rebound of symptom severity, gait ataxia had dramatically improved in all affected patients, while tremor had worsened to the presurgical severity, thus indicating a stimulation rather than disease-related phenomenon. Models of the volume of tissue activated revealed a more ventrocaudal stimulation in the (sub)thalamic area of patients with progressive gait ataxia. Metabolic maps of both patient groups differed by an increased glucose uptake in the cerebellar nodule of patients with gait ataxia. Our data suggest that chronic progressive gait ataxia in essential tremor is a reversible cerebellar syndrome caused by a maladaptive response to neurostimulation of the (sub)thalamic area. The metabolic signature of progressive gait ataxia is an activation of the cerebellar nodule, which may be caused by inadvertent current spread and antidromic stimulation of a cerebellar outflow pathway originating in the vermis. An anatomical candidate could be the ascending limb of the uncinate tract in the subthalamic area. Adjustments in programming and precise placement of the electrode may prevent this adverse effect and help fine-tuning deep brain stimulation to ameliorate tremor without negative cerebellar signs.
Introduction

Motor disability in essential tremor results predominantly from the complex interaction of postural-, action- and intention-tremor with goal-directed hand movements, but ∼10–15% of patients additionally present mild cerebellar symptoms, such as saccadic abnormalities (Helmchen et al., 2003), dysmetria or impaired tandem gait (Flament and Hore, 1986; Hallett et al., 1991; Fasano et al., 2010). There is an ongoing debate on whether a cerebellar dysfunction in essential tremor is caused by disease progression and neurodegeneration (Louis et al., 2007) or a functional disruption of the cerebello-thalamo-cortical network through the interference of tremor-related neuronal oscillations with normal cerebellar timing function (Solomon et al., 1994; Elble, 1998; Deuschl et al., 2000; Blangero et al., 2009; Elble, 2009).

A strong argument in favour of a cerebellar dysfunction stems from the observed effects of deep brain stimulation (DBS) of the (sub)thalamic area. Fasano et al. (2010) described a parallel improvement of tremor and disease-related gait ataxia in essential tremor with moderate stimulation amplitudes, while a further increase of stimulation intensity (supra-therapeutic) led to recurrence of gait and balance problems, despite tremor remaining suppressed. Similar divergent effects have been observed for tremor and dysmetria during reach-to-grasp movements (Groppa et al., 2014). These findings have pointed to two segregated cerebellar networks being modulated by DBS, a circuit for the combined control of tremor and disease-related ataxia and a second circuit inducing ataxia by supra-therapeutic stimulation (Herzog et al., 2007; Groppa et al., 2014).

Thalamic DBS is now considered a mainstay treatment for disabling and drug-refractory essential tremor (Putzke et al., 2004; Pahwa et al., 2006; Fasano et al., 2010). The procedure has a high responder rate and efficacy (beyond 10 years) for severe tremors and further improved by moving the stimulation target from the ventro-intermediate thalamic nucleus to subthalamic fibre pathways (Herzog et al., 2007; Blomstedt et al., 2009; Baizabal-Carvallo et al., 2014; Coenen et al., 2014). However, there are also reports about delayed failure of DBS. A typical clinical scenario is an improvement of tremor after initial programming, but a subsequent decline in efficacy and the need for repeated stimulation adjustments. In these cases, progressive motor disability results from a worsening of intention tremor rather than action or postural tremor and the emergence of additional cerebellar symptoms, such as truncal ataxia and unsteady gait. Often these patients suffer also from tremor rebound, an acute exacerbation of tremor and ataxia beyond the presurgical baseline when turning the stimulation off. Several explanations have been proposed, including tolerance development, misdiagnosis, lead misplacement and disease progression. The exact proportion of essential tremor patients with delayed DBS failure is unknown, but a recent single centre study described a rate of 25% among 28 patients (Favilla et al., 2012). After an extensive work-up, the authors concluded that only one of seven patients with DBS failure fulfilled their criteria for tolerance, whereas the others likely suffered from disease progression (Favilla et al., 2012). Interestingly, it was not addressed in this study, whether the severe cerebellar syndrome could be an adverse effect of prolonged DBS, given the fact that supra-threshold stimulation provokes ataxia and that rescue programming attempts often lead to increasing stimulation intensity.

Following the hypothesis of a stimulation-induced (rather than disease-related) aetiology, we compared the clinical outcome of DBS, the disease severity after prolonged stimulation wash-out, the volume of tissue activated (VTA) and the DBS-related cerebral metabolic changes [18F-fluorodeoxyglucose (FDG) PET] in essential tremor patients with and without DBS failure.

Materials and methods

Subjects and clinical test battery

This study involved 10 patients with pharmacologically intractable essential tremor and bilateral DBS of the (sub)thalamic area. Entry criteria were the diagnosis of essential tremor according to the Tremor Investigation Group and the Consensus Statement of the Movement Disorder Society Group (Deuschl et al., 1998) and stable clinical response to thalamic stimulation for at least 6 months. Exclusion criteria were any neurological comorbidity (e.g. polynuropathy). Patients receiving anti-tremor medication at the time of assessment were also excluded. All patients underwent a preoperative 3 T MRI (T1, T2, T2*, FLAIR, Trio, Siemens Medical Systems) to rule out morphological anomalies.

We recruited five patients with a secondary DBS failure characterized mainly by chronic-progressive gait ataxia (ETataxia:
two males; age 75 ± 5 years; disease duration 25 ± 10 years; time from electrode implantation 23 ± 7 months; average ± standard error of the mean). After an initial benefit on tremor without any side effect (e.g., gait difficulties), these patients showed a progressive decline in DBS efficacy (starting >3 months after initial programming) and needed repeated stimulation adjustments to compensate for the reduced tremor control. Subsequently, they developed a chronic-progressive gait ataxia (in the absence of any other DBS-related adverse event) over a period of at least 4 weeks of chronic stimulation with unchanged settings.

We also recruited five patients without any gait difficulties or unsteadiness matched for age, disease duration, time from surgery (ET<sub>control</sub>: three males; age 54 ± 14 years; disease duration 31 ± 11 years; time from electrode implantation 25 ± 7 months). The Fahn-Tolosa-Marin Tremor Rating Scale (TRS) and the Scale of the Assessment and Rating of Ataxia (SARA) were performed. We recorded only SARA item 1 to 3 (SARA<sub>1-3</sub>) as referring to axial signs and not affected by upper limb tremor.

Patients were assessed in the following three conditions: (i) stimulation on (stim-ON) with the clinically optimized and chronically used stimulation parameters; (ii) immediately after deactivating the stimulation (stim-OFF<sub>direct</sub>); and (iii) stimulation off for 72 h (stim-OFF<sub>72h</sub>). Of note, 72 h was the minimum time interval after which all subjects reported an improvement of gait difficulties.

The stimulation parameters were controlled by a physician independently from this study and provided a sustained improvement of tremor without any acute side effect. Parameters remained unchanged for at least 4 weeks prior to the study.

**Standard protocol approvals, registrations and patient consents**

The study was approved by the institutional review board of the University Hospital of Wuerzburg and by the Governmental Radiation Protection Authority (Bundesamt für Strahlenschutz, Aktenzeichen: ZS-22463/2-2015-010). Written informed consent was obtained from all subjects.

**Surgical procedure**

The surgical procedure has been previously described in detail (Hamel et al., 2002; Herzog et al., 2007). In the present study, all subjects received quadripolar macroelectrodes (model 3389, Medtronic Inc.). The stereotactic coordinates of each contact of the quadripolar macroelectrode related to the midpoint of the line between anterior and posterior commissure were calculated based on fusion of the preoperative stereotactic and the postoperative CT images. The mean coordinates of the active contacts were calculated based on fusion of the preoperative stereotactic and postoperative MRI. The mean coordinates of the active contacts were x: 12.55 ± 1.63 mm, y: −5.15 ± 1.44 mm, z: −0.85 ± 1.60 mm in ET<sub>ataxia</sub> and x: 12.09 ± 1.62 mm, y: −4.55 ± 1.19 mm, z: 0.29 ± 2.10 mm in ET<sub>control</sub>.

**Volume of tissue activated modelling**

Correct lead positioning was verified with SureTune™ (Medtronic Eindhoven Design Center, MEDC) by fusing the preoperative stereotactic MRI with a postoperative CT performed more than 40 days after electrode implantation. To visually compare lead location as well as site of stimulation between ET<sub>ataxia</sub> and ET<sub>control</sub> patient images were registered to a common probabilistic anatomy model of the ventral thalamus and subthalamic area. This probabilistic anatomy model was created by registration and normalization of 50 preoperative T<sub>2</sub>-weighted MRI volumes. Registration was carried out with a rigid registration algorithm based on normalized gradient fields (Rühaak et al., 2015), together with a local bounding box of 30 × 30 × 30 mm<sup>3</sup> applied around the target area to define the volume used for registration. VTAs were simulated and displayed for each lead based on the applied stimulation parameters (Table 1) (Astrom et al., 2014). A mean VTA was created for each cohort by aggregating all VTAs of a single group, and allegorize only voxels that overlapped by ≥2 VTAs. Volume of mass and centre of mass were calculated for each mean VTA. In addition, the overlapping volume of the mean VTAs of the two patient groups was calculated.

**Imaging technique and PET data analysis**

PET scans were performed with the PET/CT scanner Biograph mCT 64 (Siemens Medical Solutions) at the University Hospital of Wuerzburg.

The patients were scanned on 2 days. On the first day scanning was performed with the stim-ON, with chronically used settings. A second scan was performed after 72 h stimulation off (stim-OFF<sub>72h</sub>). The PET study was started 30 min after the injection of 208 ± 16.5 MBq of FDG. Before each PET session, patients fasted overnight. The studies were performed with the subjects’ eyes open in a dimly lit room and with minimal auditory stimulation. The patients’ clinical condition was monitored by a neurologist (I.U.I.) from the injection of the radioligand until the end of the scan, and no patient had overt tremor or ataxia as a potential confounder of cerebral FDG uptake.

PET was performed in 3D mode for 10 min/one bed position using a 400 × 400 matrix with an axial resolution of 2 mm full-width at half-maximum and an in-plane resolution of 4.7 mm. CT scans for attenuation correction were acquired using a low-dose protocol. PET data were reconstructed iteratively (24 subsets, three iterations, Gaussian filtering) using HD reconstruction mode.

A group of 10 age- and gender-matched healthy subjects (HC; five males; age 62 ± 14 years), previously acquired with the same methods, served as control group.

FDG data preprocessing was performed with statistical parametric mapping (SPM 8, Wellcome Department of Cognitive Neurology, University College, London). Scans were spatially normalized to a FDG PET template in the standardized Montreal Neurological Institute (MNI) space (16 iterations, non-linear transformation and trilinear interpolation) and then smoothed using a Gaussian kernel at full-width at half-maximum = 8 mm. Paired t-tests were used to assess stimulation effect in voxel-wise maps. Voxel-wise comparisons between patients with essential tremor and healthy subjects were performed using the flexible factorial model. The SPM maps were obtained at a height threshold of P < 0.005, cluster extent k ≥ 30 voxels. We considered significant peak levels with Z score ≥ 3.0.
SPM findings were also confirmed by a post hoc volume of interest analysis. We calculated global and regional cerebral metabolic rates for glucose consumption within the SPM predefined brain areas. To reduce intersubject variability, the regional metabolic measurements were normalized by global values.

**Statistical analysis**

Statistical analyses were performed with the JMP statistical package, (version 12, SAS Institute, Inc., Cary, NC, USA). Gender difference between groups was analysed using Pearson’s chi-squared test. Other differences between groups were analysed by means of Mann-Whitney U-test. The threshold level of statistical significance was set at $P < 0.05$.

**Results**

**Clinical evaluation**

Evaluation of the TRS demonstrated a significant tremor reduction (>70%) during stim-ON in all patients. ET\textsubscript{control} showed greater benefit from stimulation (TRS scores for ET\textsubscript{control}: 2.0 ± 2.3 and ET\textsubscript{ataxia}: 7.8 ± 4.2, $P = 0.014$). The mean TRS score in stim-OFF$^{72h}$ was similar between the two groups of patients (ET\textsubscript{ataxia}: 17.2 ± 5.9 and ET\textsubscript{control}: 14.2 ± 2.3, $P = 0.34$). Age, disease duration and time after implantation did not influence tremor improvement.

As expected, the SARA$^{1-3}$ score in stim-ON was significantly higher for ET\textsubscript{ataxia} than ET\textsubscript{control} (6.2 ± 0.6 versus 0.2 ± 0.6, $P = 0.001$).

After 72h of deactivated stimulation (stim-OFF$^{72h}$), all ET\textsubscript{ataxia} subjects reported a significant improvement in gait difficulties and unsteadiness, which was mirrored by a lower SARA$^{1-3}$ score (Fig. 1).

**Volume of tissue activated by high-frequency stimulation**

Mean VTA volumes of the ET\textsubscript{ataxia} and ET\textsubscript{control} group were 86 mm$^3$ and 68 mm$^3$, respectively, with an overlap of the two volumes by 37.5 mm$^3$. Mean VTA of ET\textsubscript{ataxia} was located inferior and posterior in relation to mean VTA of ET\textsubscript{control} (Table 2 and Fig. 3). The most prominent effect of stimulation was a distinctive increment of FDG uptake in the cerebellar nodule of ET\textsubscript{ataxia} patients but not in ET\textsubscript{control}. DBS also had a marked impact on thalamic metabolic activity of both essential tremor cohorts, as seen by the increased FDG uptake in the left and right thalamic ventral posterior nucleus (which corresponds to the ventral intermedius nucleus) (Nazzaro et al., 2013).

**Brain metabolic changes induced by brain stimulation**

Pairwise correlations of stimulation-induced changes are presented in Table 2 and Fig. 3. The most prominent effect of stimulation was a distinctive increment of FDG uptake in the cerebellar nodule of ET\textsubscript{ataxia} patients but not in ET\textsubscript{control}. DBS also had a marked impact on thalamic metabolic activity of both essential tremor cohorts, as seen by the increased FDG uptake in the left and right thalamic ventral posterior nucleus (which corresponds to the ventral intermedius nucleus) (Nazzaro et al., 2013). Similar results were found when evaluating glucose consumption of predefined volume of interest. Of relevance, no difference was found when comparing cerebellar glucose consumption of all essential tremor (in stim-OFF$^{72h}$) to healthy controls, which was also true when considering only the volume of interest placed on the cerebellar nodule.
In this study, we forward evidence that chronic-progressive gait ataxia in subjects with essential tremor is reversible after a prolonged DBS washout and emerges from a stimulation-induced vestibulocerebellar network dysfunction.

Two main observations support this view: (i) a gradual improvement of gait ataxia after pausing stimulation for 72 h; and (ii) increased neuronal metabolic activity in the cerebellar nodule of patients with chronic-progressive gait ataxia as compared to essential tremor without. We further propose that cerebellar dysfunction in subjects with ET ataxia is a remote effect of inadvertent antidromic stimulation of vestibulocerebellar-thalamic afferents within the subthalamic target area of DBS.

Several studies have reported cerebellar ataxia as a clinical feature of advanced essential tremor (Fasano et al., 2010). However, it is worth noting that the chronic-progressive gait ataxia described here clearly differs from the disease-related ataxia, which is milder in its presentation and is typically ameliorated by thalamic-stimulation, irrespective of the affected body site and independently of co-existing tremor. Of note, a sufficiently long washout of DBS is required to overcome the initial tremor and ataxia rebound and re-establish a disease baseline, which may explain the partially conflicting observations in previous studies. A previous study reported a worsening of untreated tremor 1 year after DBS implantation, but thalamic stimulation was deactivated for 30 min only. As shown by our results (Fig. 1), clinical changes after such a small time interval possibly reflect just the pausing of stimulation per se rather than the progression of the disease.

It is worth noting that chronic-progressive gait ataxia also differs from acute upper limb ataxia induced by (supra)therapeutic stimulation (Groppa et al., 2014). The delayed onset of gait ataxia with chronic DBS suggests a maladaptive component probably involving a different cerebello-thalamo-cortical fibre system. Alternatively, intracerebellar compensatory mechanisms may be taken into account. Indeed, the lateral hemispheres of the cerebellum can greatly compensate for the loss of function of the vermis and the flocculonodular lobe, as seen for example in subjects with Joubert syndrome (Romani et al., 2013).

Several physiological studies in monkey and humans have provided evidence that the cerebello-thalamo-cortical circuit is essential for gait and balance (Diener et al., 1984; Ito, 1984; Hallett and Massaquoi, 1993; Armstrong and Marple-Horvat, 1996; Cooper et al., 2000; Ilg et al., 2007; Blangero et al., 2009). Real locomotion FDG PET studies have also confirmed a prominent activation in the vermal and paravermal cerebellum, with extensions into the superior cerebellar peduncle bilaterally (Ishii, 1995; la Fougere et al., 2010).

Three distinguished cerebello-thalamo-cortical subcircuits might be particularly relevant in the pathophysiology of thalamic stimulation-induced effects in essential tremor (Fig. 4).

First, the dentato-thalamic tract is the main output of the lateral cerebellum and projects to the motor cortex via the ventrolateral thalamus. The dentato-thalamic system is mainly involved in the control of voluntary movements of the extremities, such as single-joint and multi-joint goal-directed movements (Schwartz et al., 1987; Marple-Horvat et al., 1998; Marple-Horvat and Criado, 1999; Cooper et al., 2000). These fibres are supposed to mediate the tremor and ataxia suppressing effect of thalamic-stimulation in essential tremor (Groppa et al., 2014).

Second, the cerebello-rubrospinal system is involved in the sensory-to-motor transformation required for cerebellar control of goal-directed limbs movements. Stimulation (supratherapeutic) of these fibres was shown to induce the reappearance of ataxia, in particular the spatial variability during the deceleration phase of reach-to-grasp movements.
while maintaining near complete suppression of tremor (Groppa et al., 2014).

Third, the fastigio-bulbar tract projects from the cerebellar vermis and nodule to the motor thalamus, spinal cord and vestibular system. In particular, its ascendant uncinate tract projects to the ventrolateral/intralaminar thalamic nuclei (Paxinos and Mai, 2004). This tract is particularly important for axial coordination during movements and its failure results in severe gait ataxia (Sprague and Chambers, 1953; Imperato et al., 1984).

These cerebello-thalamic fibres run parallel with a clear functional-anatomical organization, the appendicular movements control being situated in a lateral bundle and the axial one more medially. In the (sub)-thalamic area however, these fibres run in close vicinity and effective DBS targeting the lateral fibres may inadvertently co-stimulate medial cerebello-thalamic tracts (Groppa et al., 2014).

Indeed, our study showed that the VTA of ET ataxia is located more posteromedial and caudally in the (sub)thalamic area when compared to ET control.

VTA modelling is a novel tool that computes the region in which certain stimulation settings may induce action potentials in model neurons (Butson et al., 2011). Current VTA modelling depends on stimulation parameters, tissue impedance and tissue anisotropy (McNeal, 1976; Butson et al., 2006). A possible limitation of this model is the dependency on a priori assumptions about the membrane properties of the stimulated axons. However, it was recently shown that VTA mirrored such neuronal proprieties as clinically defined (i.e. chronaxies) (Reich et al., 2015). Finally, VTA assumes that the primary effect of DBS is to activate myelinated axons, which was proved by several studies (Holsheimer et al., 2000; Paxinos and Mai, 2004; Groppa et al., 2014).

Current spreading into the ascending limb of the uncinate tract may directly influence the activity of cerebellar nodule as suggested by an increased FDG uptake in this area. Indeed, it was shown that DBS stimulation could affect functionally connected brain areas remote from the stimulation site (Hilker et al., 2008). Accordingly, we advance the hypothesis that the hypermetabolism in the cerebellar

Table 2 Brain areas (coordinates and regions in Talairach space) with significantly increased glucose consumption

<table>
<thead>
<tr>
<th>Region</th>
<th>Coordinates (mm)</th>
<th>Z-score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thalamus, VP (left)</td>
<td>14, 18, 0</td>
<td>3.84</td>
</tr>
<tr>
<td>Cerebellum, nodule</td>
<td>4, 50, 34</td>
<td>3.55</td>
</tr>
<tr>
<td>Thalamus, VP (right)</td>
<td>22, 18, 6</td>
<td>3.12</td>
</tr>
<tr>
<td>Thalamus, VP (right)</td>
<td>18, 20, 2</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Nucleus ventralis posterior (VP) corresponds to the ventral intermedius nucleus in the stereotactic atlas of Schaltenbrand and Wahren (Nazzaro et al., 2013).
nodule shown in ETataxia is due to antidromic activation of cerebello-thalamic fibres caused by the stimulation electric field. A cerebellar compensatory activity due to tremor seems unlikely as we tested the patients in resting condition, closely monitoring the complete absence of upper limb movements that could affect FDG uptake. Moreover, an antidromic activation of dentate-thalamic fibres—the presumed target of effective thalamic DBS—can also be excluded, as it would induce metabolic changes of the lateral cerebellum. Here, we also confirm a previous study reporting no abnormalities of glucose metabolism in the cerebellum of non-DBS treated essential tremor patients. These findings further support a stimulation-induced hypermetabolism rather than a disease-related cerebellar pathology (Hallett and Dubinsky, 1993; Song et al., 2015).

We also confirmed previous reports of an enhanced neuronal activity in the area surrounding the active electrodes (i.e. thalamic area) of all essential tremor subjects (Hilker et al., 2008; Martin-Blanco et al., 2015) and no other brain region. FDG is a marker of hexokinase activity that regulates the regional cerebral glucose metabolic rate. Quantification of the regional glucose accumulation can be performed by PET and correlates with regional synaptic activity (Otte and Halsband, 2006). In particular, sequential FDG PET is an established method to identify metabolic changes in subcortical structures with comparable size (Hilker et al., 2008; Le Jeune et al., 2009; Wang et al., 2010). Despite being small, the regions of interest (e.g. cerebellar nodule) more than double the resolution of our PET/CT. Partial volume effect is therefore unlikely to occur and even if present, it would underestimate the activity of small structures (Heiss et al., 2004).

A possible limitation of this study is the small sample size. However, the hypermetabolism in the cerebellar nodule was consistently detected in all ETataxia subjects and the number of included patients is comparable to previous studies addressing a similar topic (Groppa et al., 2014).

In conclusion, our study suggests that chronic-progressive gait ataxia in essential tremor is a reversible cerebellar symptom probably induced by inadvertent stimulation of the
on 31 December 2017

Conflicts of interest

M.M.R. has been a member of the advisor board of Medtronic; has received grant support from Boston Scientific, St. Jude and TEVA; and has received honoraria for speaking from Medtronic, outside the submitted work; J.R. reports other from Medtronic Eindhoven Design Center, during the conduct of the study; other from Medtronic Eindhoven Design Center, outside the submitted work; M.A. reports other from Medtronic Eindhoven Design Center, outside the submitted work; T.M. reports grants from Travel grant from AbbVie, Merz and Medtronic, outside the submitted work. M.L. has received travel grants for attending scientific congresses from Medtronic. R.L. has received payments as a consultant and lecturer for Medtronic Inc., Boston Scientific, St. Jude Medical and received honoraria as a speaker on symposia sponsored by UCB Schwarz Pharma and Bayer. J.V. reports grants and personal fees from Medtronic Inc., grants and personal fees from Boston Scientific, personal fees from St. Jude, outside the submitted work; I.U.I. reports grants and personal fees from Medtronic Inc. outside the submitted work.

Supplementary material

Supplementary material is available at Brain online.

References


Figure 5 Simulation of an ideal lead placement estimated from the VTA of patients without ataxia. The location corresponds to the posterior subthalamic area as described previously (Velasco et al., 1972; Blomstedt et al., 2009). As depicted on the T2-weighted MRI the axial targeting plane should be on the level of the maximal diameter of the red nuclei. The lead should be positioned adjacent to the medial border of the subthalamic nucleus, in its posterior third. Therefore, the T2-weighted hypointense outline of the subthalamic nucleus and of the red nucleus may be used as anatomical references for direct anatomical targeting or verification of stereotactic planning.

Ascending limb of the uncinate tract, which in turn affects the cerebellar nodule functioning (Fig. 2B). Following this hypothesis, avoiding a too caudal and ventral placement of standard DBS electrodes or directing current away from this region with novel DBS systems capable of horizontal current steering might prevent this chronic side effect. As estimated from the VTA of patients without ataxia, a relatively safe target to be further refined by intraoperative stimulation results could be the lateral part of the posterior subthalamic area, which has been proposed more than 30 years ago (Velasco et al., 1972) as the optimal target for severe tremors. For direct anatomical targeting on axial T2-weighted MRI the posterior and medial border of the subthalamic nucleus at the level of the largest diameter of the red nuclei may be used as a reference (Blomstedt et al., 2009) (Fig. 5).

As previously suggested, a shorter pulse duration of <60 μs could constitute an alternative approach of selectively stimulating dentato-thalamic fibres close to the DBS lead based on divergent chronaxies of different subthalamic fibre tracts (Reich et al., 2015).

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