Subthalamic Stimulation and Neuronal Activity in the Substantia Nigra in Parkinson’s Disease

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¹Centre d’Investigation Clinique, Fédération des Maladies du Système Nerveux, Institut National de la Santé et de la Recherche Médicale U-679, Université Pierre et Marie Curie and ²Service de Neurochirurgie, Hôpital de la Salpêtrière, Assistance Publique–Hôpitaux de Paris, Paris; ³Service de Neurologie, Centre Hospitalier Universitaire (CHU) Hôpital Poitiers, Poitiers; and ⁴Service de Neurologie, CHU Hôpital Rouen, Rouen, France

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Maltète D, Jodoin N, Karachi C, Houeto JL, Navarro S, Cornu P, Agid Y, Welter ML. Subthalamic stimulation and neuronal activity in the substantia nigra in Parkinson’s disease. J Neurophysiol 97: 4017–4022, 2007. First published April 25, 2007; doi:10.1152/jn.01104.2006. High-frequency stimulation of the subthalamic nucleus (STN) is an effective treatment for severe forms of Parkinson’s disease (PD). To study the effects of high-frequency STN stimulation on one of the main output pathways of the basal ganglia, single-unit recordings of the neuronal activity of the substantia nigra pars reticulata (SNr) were performed before, during, and after the application of STN electrical stimulation in eight PD patients. During STN stimulation at 14 Hz, no change in either the mean firing rate or the discharge pattern of SNr neurons was observed. STN stimulation at 140 Hz decreased the mean firing rate by 64% and the mean duration of bursting mode activity of SNr neurons by 70%. The SNr residual neuronal activity during 140-Hz STN stimulation was driven by the STN stimulation. How the decrease in rate and modification of firing pattern of SNr-evoked neural activity during high-frequency STN stimulation could contribute to the improvement of parkinsonian motor disability remains to be elucidated.

INTRODUCTION

High-frequency stimulation of the subthalamic nucleus (STN) improves motor symptoms of Parkinson’s disease (PD) (Limousin et al. 1998), but the effects of high-frequency stimulation on neuronal activity in the basal ganglia remain controversial. Inhibition of STN neurons has been observed during high-frequency stimulation in normal rats and rats with 6-hydroxydopamine (6-OHDA) lesions of the nigrostriatal dopaminergic pathway (Shi et al. 2006; Tai et al. 2003), in primates rendered parkinsonian (Meissner et al. 2005), and in PD patients (Filali et al. 2004; Welter et al. 2004). Contradictory effects on the neuronal activity in the basal ganglia output nuclei, however, have been reported. Whereas neurons are mostly activated in the globus pallidus of parkinsonian primates by stimulation of the STN (Hashimoto et al. 2003), inhibition of neuronal activity has been observed in the substantia nigra pars reticulata (SNr) in rat models of parkinsonism (Maurice et al. 2003; Shi et al. 2006; Tai et al. 2003). An increase in the SNr neuronal activity has been recently reported during high-frequency STN stimulation in PD patients (Galati et al. 2006). In the present study, we describe the perievent perioperative effects of low- and high-frequency electrical stimulation of the STN on the neuronal activity of the SNr in patients with PD.

METHODS

Neurosurgical procedure

Eight patients with PD (ages: 50 ± 12 yr; disease duration: 16 ± 5 yr) underwent surgery for bilateral implantation of electrodes in the STN. The neurosurgical procedure was performed as previously described (Bejjani et al. 2000), in patients awake, at rest, and free from antiparkinsonian treatment for ≥12 h. The leads were implanted in a single operation, according to stereotactic coordinates determined by preoperative magnetic resonance imaging and perioperative electrophysiological recordings. Five coaxial leads [a central tungsten recording microelectrode and an external tube for macrostimulation (FHC Instruments, Bowdoinham, ME)] were lowered stereotactically to 5 mm above the predetermined target, in 10-μm steps along five parallel trajectories using a hydraulic microdrive (David Kopf Instruments, Tujunga, CA). Four of the leads were arranged, at a distance of 2 mm, around a central lead positioned according to the stereotactic coordinates, permitting stimulation and recording from the central, anterior, posterior, medial, and lateral parts of the STN and SNr. The microelectrode tip (diameter: 25 μm; impedance: 10 MΩ) protruded 5 mm beyond the macro electrode (exposed surface diameter: 0.7 mm; length: 1.5 mm, surface area: 6.0 mm²). Signals were amplified (NL104 Neurolog System, Digitimer, Eastleigh, UK), filtered (NL125, 500 Hz to 5 kHz), monitored acoustically, displayed on an oscilloscope, and recorded magnetically (bandwidth: 0–5 kHz, eight channels TEAC FM). During the electrophysiological procedure, control profile stereotactic X-ray films were regularly obtained, right–left projections, with the short X-ray radiological device of the Leksell stereotactic frame to check the electrode trajectories and depth. This device consists of X-ray–visible fiducial markers and a cassette holder affixed to the stereotactic frame itself. Before starting the surgical procedure, the direction of the X-ray unit and the position of the stereotactic frame were adjusted to allow superimposition of the values of the right and left Z- and Y-scales of the fiducial markers at the level of the target. Trajectory reconstruction was performed on sagittal and frontal maps of a digitized Schatelbrand and Wahren (1977) stereotactic frame.

Electrophysiological procedure

Extracellular single-unit recordings were performed in awake but immobile patients at rest, and obtained simultaneously from the five leads used to identify and localize the STN and then the SNr (Hutchison et al. 1998). Electrode descent was stopped when at least two of them recorded neuronal activity characteristic of the SNr (Benazzouz et al. 2000; Hutchison et al. 1998). Nigral recorded neurons were included if they were well isolated, stable (signal-to-

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INSERM, was approved by the local ethics committee; all patients in this study, spike trains with using a script written for the Spike2 software (Degos et al. 2005). In surprise analysis (Legendy and Salcman 1985). This was carried out using a chi-square test (significant at \( P < 0.05 \)).

\[ t \text{ value} = \frac{t \text{ value}}{\text{mean discharge rate}} \]

Discharge pattern analysis was performed during the poststimulus period (25 ms). PSTHs showed an inhibitory period (9.6 ms) and a decrease, although the difference was not significant (Table 1). Twenty SNr cells were recorded during ipsilateral STN stimulation with 14- and/or 140-Hz stimulation (Table 1). Eight SNr cells were recorded with the posterior \((n = 5)\) or medial electrode \((n = 3)\) during STN stimulation with the central electrode; 12 cells were recorded with the central electrode while stimulating with the STN electrode placed medial \((n = 5)\), posterior \((n = 5)\), or anterior \((n = 2)\).

**Effects of low-frequency electrical stimulation of the subthalamic nucleus on spontaneous substantia nigra pars reticulata neuronal activity**

Stimulation at 14 Hz in the STN did not significantly modify the mean firing rate of 16 SNr neurons (Table 1). The firing pattern was not modified in 14 cells (regular, \( n = 11 \); irregular, \( n = 3 \)), one cell switched its firing pattern from irregular to regular, and one cell from regular to irregular (Table 1). Fourteen SNr cells displayed some bursts (\( S \) value \( \geq 3 \)); the mean percentage of spikes with a bursting mode activity was unchanged before and during 14-Hz STN stimulation (Table 1). The mean duration of bursting mode activity tended to decrease, although the difference was not significant (Table 1). PSTHs showed an inhibitory period of 9.6 ± 2.2 ms after the stimulation pulse in five cells (Fig. 2). No inhibitory period during the poststimulus period was detected in seven cells and a poststimulus excitatory period of 25.0 ± 3.8 ms was detected in four cells (Fig. 2). The responses of SNr cells to 14-Hz STN stimulation was similar whatever the spatial relationship of the stimulating and recording electrodes: 1) in the five SNr cells with an inhibitory period, three were recorded with the central electrode during STN stimulation with the medial \((n = 2)\) or...
Effects of subthalamic (STN) stimulation on the ipsilateral neuronal activity of the substantia nigra pars reticulata (SNr)

<table>
<thead>
<tr>
<th>Discharge pattern</th>
<th>14-Hz STN Stimulation (n = 16)</th>
<th>140-Hz STN Stimulation (n = 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>During</td>
</tr>
<tr>
<td>Frequency, Hz</td>
<td>27.2 ± 9.8</td>
<td>25.6 ± 8.5</td>
</tr>
<tr>
<td>Mean S index*</td>
<td>4.1 ± 1.9</td>
<td>4.3 ± 1.6</td>
</tr>
<tr>
<td>%Spikes, S ≥ 3</td>
<td>14.3 ± 12.8</td>
<td>8.2 ± 6.1</td>
</tr>
<tr>
<td>%Duration, S ≥ 3</td>
<td>23.5 ± 19.6</td>
<td>18.4 ± 14.5</td>
</tr>
</tbody>
</table>

Discharge pattern
(Kaneoke and Vitek 1996)
Regular 12 12 11
Irregular 4 4 5
Bursting type 0 0 0 2 1

FIG. 2. Poststimulus time histograms (PSTHs) for 14-Hz stimulation in the STN (4-ms bins). PSTHs were reconstructed for a 15-s period after STN stimulation, horizontal dashed line represents a cell without a persistent neuronal activity 2–4 ms after the stimulation pulse (Fig. 4). Fifteen cells were inhibited after 140-Hz STN stimulation (Table 1, Fig. 3). In all SNr cells, PSTHs showed a three-phase response with an inhibition (0–2 ms), excitation (2–4 ms), and inhibition (4–7 ms) sequence after stimulation pulse (Fig. 4). Fifteen cells were inhibited with a persistent neuronal activity 2–4 ms after the stimulation pulse.

Effects of high-frequency electrical stimulation of the subthalamic nucleus on spontaneous substantia nigra pars reticulata neuronal activity

STN stimulation at 140 Hz induced a 67% decrease in the mean neuronal firing rate of 16 SNr neurons (range: −32 to −100%) and a 34% increase in the mean firing rate of one SNr cell (Table 1). Before 140-Hz STN stimulation, nine cells displayed a regular activity and eight an irregular activity. There was no change in the firing pattern in 10 cells (regular, n = 7; irregular, n = 3), five cells switched from irregular to regular firing pattern, and two cells from regular to bursting firing pattern (P = 0.39, Table 1). There was a 51% decrease in the percentage of the spikes contributing to bursts and a 70% decrease in the mean duration of bursting mode activity during 140-Hz STN stimulation (Table 1, Fig. 3). In all SNr cells, PSTHs showed a three-phase response with an inhibition (0–2 ms), excitation (2–4 ms), and inhibition (4–7 ms) sequence after stimulation pulse (Fig. 4). Fifteen cells were inhibited with a persistent neuronal activity 2–4 ms after the stimulation pulse.
pulse, decreased \((n = 10)\) or similar \((n = 5)\) to the neuronal activity obtained before stimulation (Fig. 4A). In two SNr cells, a significant increase in the neuronal activity 2–4 ms after the stimulation pulse was induced by 140-Hz STN stimulation (Fig. 4B). In four of the five SNr cells with an inhibitory period during 14-Hz STN stimulation and recorded during 140-Hz STN stimulation, an inhibition was also observed during 140-Hz STN stimulation (not shown). In the two SNr cells excited by 140-Hz STN stimulation, no excitatory or inhibitory periods were noted during 14-Hz STN stimulation (not shown). In all but two cells, the neuronal activity recorded during 140-Hz STN stimulation was time-locked to the stimulation pulse with the presence of periodic spiking at 7.14-ms intervals, corresponding to a frequency of 140 Hz (Fig. 4).

This study shows that high-frequency stimulation within the STN in PD patients reduces the frequency and changes the pattern of neuronal firing in the SNr. Several lines of evidence suggest that these results are robust. 1) The recording microelectrodes were localized within the SNr because the neuronal activity recorded during the neurosurgical procedure was similar to that previously described in animal models of parkinsonism (Benazzouz et al. 2000; Tai et al. 2003) and PD patients (Hutchison et al. 1998). 2) The electrode used for high-frequency stimulation was located within the STN as shown by stereotactic X-rays taken during the operation. 3) It is unlikely that the stimulus artifact could have masked the response of SNr neurons to STN stimulation: the artifact was short (1 ms, Fig. 1) and the time-locked excitatory response observed in animals or PD patients was maximal 2 to 4 ms after the stimulation pulse (Galati et al. 2006; Shi et al. 2006); the mean firing rate of neurons recorded in the SNr was not modified when the STN was stimulated at 14 Hz (Table 1).

These results are in line with those obtained in rats rendered parkinsonian in which the SNr neuronal activity has been shown to predominantly decrease with low STN stimulation intensity (Maurice et al. 2003; Shi et al. 2006; Tai et al. 2003). However, these results are different from those recently reported by Galati et al. (2006), where an increase in the SNr neuronal firing rate during STN high-frequency stimulation was found. Two main reasons could explain these differences. 1) The volume of stimulated tissue in our experiment was smaller than that in the Galati et al. study because both intensity and surface of stimulation were smaller (2 vs. 2–3 V and 2.4 vs. 6.0 mm²). Because the effective electric field volume was smaller, the electrical stimulation was necessarily more focal, thus modulating the activity of a more restricted neuronal population. Furthermore, changes in neuronal activity could be dependent on the position and orientation of the neuron and its axon with respect to the electrode and the stimulation parameters. In a computational model of the thalamocortical cell body and axon, it has been proposed that subthreshold high-frequency electrical stimulation for direct activation of the thalamocortical relay neurons caused suppression of intrinsic firing activity in both the soma and axon, whereas suprathreshold stimulation induced suppression of intrinsic firing in the soma but ef fferent output at the stimulus frequency in the axon (McIntyre et al. 2004). More recently, a computational model constructed to elucidate the effects of STN stimulation on the neuronal activity of the internal segment of the globus pallidus (GPi) in monkeys has shown similar results for the subthalamopallidal neuron with an inhibition of the intrinsic firing in the soma and an excitation in the axon (Miccinovíc et al. 2006). 2) The duration of stimulation was different in the two studies: short stimulating periods (20 s) were used in our study, whereas 30 min of stimulation were used in the Galati et al. study. One explanation could be that high-frequency STN stimulation first decreases SNr neuronal activity, as shown in this study, but that neuronal activity is reversed when electrical stimulation is maintained for several minutes, thus leading to neuronal activation. Such an inversion of electrophysiological effects during high-frequency STN stimulation on the SNr neuronal activity could result from neuronal plasticity, either through a direct effect implicating...
the subthalamonnigral pathway or through an indirect effect implicating the activation of indirect inputs to the SNr. These electrophysiological changes observed in the SNr over time could explain, at least in part, the time course of the clinical effects observed in parkinsonian patients during STN stimulation. Whereas rigidity or tremor is known to disappear within seconds after the onset of high-frequency STN stimulation (Krack et al. 2002), improvement of bradykinesia is delayed for several minutes, hours, or even days (Krack et al. 2002).

The reduced SNr firing rate observed in PD patients during high-frequency STN stimulation could result from a direct inhibition of STN neurons leading to a decreased activity of the excitatory subthalamonnigral glutamatergic pathway (Filali et al. 2004; Meissner et al. 2005; Shi et al. 2006; Welter et al. 2004). The observation that high-frequency STN stimulation decreases the expression of messenger RNA for subunit I of cytochrome oxidase in neurons of the rat STN is compatible with this hypothesis (Tai et al. 2003). Local synaptic inhibition in the STN might also occur by excitation of myelinated fibers projecting from the external segment of the globus pallidus (GPe) or antidromic activation of axon terminals in the GPe by release of inhibitory γ-aminobutyric acid (GABA) (Benazzouz et al. 2000; Shi et al. 2006; Tai et al. 2003). Finally, neurons in the STN that project to the GPe might be activated (Hashimoto et al. 2003), thereby inducing a release of inhibitory GABA in the SNr (Windels et al. 2005). The fact that injection of bicuculline, a GABA antagonist, in the SNr induces a disappearance of this STN stimulation-induced inhibition is in line with this hypothesis (Maurice et al. 2003).

Beside the global reduction in the neuronal activity of the SNr during STN stimulation, we observed that SNr neuronal activity during STN high-frequency stimulation constituted three components: inhibition (0–2 ms)/excitation (2–4 ms)/inhibition (4–7 ms) after the stimulation pulse (Fig. 4), with a periodic spiking corresponding to the frequency of stimulation (Fig. 4). These three components of the SNr neuronal response to STN stimulation could result from the alternate activation or inhibition of inhibitory and excitatory afferents to the SNr. The excitatory component could result from the orthodromic activation of subthalamonnigral axons and consequent release of glutamate in the SNr (Boulet et al. 2006), with an oscillatory activity driven by the stimulation, as previously reported in STN neurons in rats in vitro (Garcia et al. 2005) and in the SNr in parkinsonian patients (Galati et al. 2006). The two inhibitory components could result both from the reduction of glutamatergic excitatory afferents from the STN, by inhibition of the SNr neuronal activity (Hashimoto et al. 2003). However, when the intensity of STN stimulation is low, about a third of GPe neurons shows a decrease in neuronal firing rate (Hashimoto et al. 2003).

In parkinsonian patients, high-frequency STN stimulation induced a decrease in the spontaneous neuronal activity and a change in the firing pattern of SNr neurons, one of the main output pathways of the basal ganglia. However, the mechanisms underlying this neuronal inhibition downstream from STN, the neurosurgical target of choice in the treatment of PD, is still controversial. Irrespective of whether this initial neuronal inhibition is reversed during long-term, high-frequency STN stimulation and the increased irregular and bursting activity in the SNr that is characteristic of parkinsonism (Hutchison et al. 1998; Wichmann et al. 1999) is normalized or interrupted by STN high-frequency stimulation remain to be demonstrated. Finally, how these modifications contribute to the improvement of parkinsonian motor disability remains to be elucidated.

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