Feed-forward control of movement disorders by on-demand type stimulation of the thalamus and motor cortex

Y. Katayama¹², T. Kano¹, K. Kobayashi¹², H. Oshima¹, C. Fukaya¹², and T. Yamamoto¹²

Department of Neurological Surgery¹ and Division of Applied System Neuroscience², Nihon University School of Medicine, 30-1 Ohyaguchi Kamimachi Itabashi-Ku, Tokyo 173-8610, Japan

e-mail: ykatayam@med.nihon-u.ac.jp

Abstract
Deep brain stimulation (DBS) of the thalamus (Vo/Vim) has become popular as a means of controlling involuntary movements, including post-stroke movement disorders. We have also found that post-stroke movement disorders and motor weakness can sometimes be controlled by motor cortex stimulation (MCS). In some forms of movement disorders, motor dysfunction became evident only when patients intend to move their body. We have developed an on-demand type stimulation system which triggers stimulation by detecting intrinsic signals of intention to move. Such a system represents feed-forward control (FFC) of voluntary movements. We report our experience of DBS and MCS for controlling post-stroke movement disorders, and discuss the value of FFC. Excellent control of post-stroke movement disorders was achieved by conventional DBS and/or MCS in 21 of 28 patients with hemichoreoathetosis, hemiballism, tremor, and motor weakness. FFC was tested in 6 patients who demonstrated excellent control of post-stroke postural tremor or motor weakness by conventional DBS or MCS. The on-demand stimulation provided satisfactory FFC in 4 of 4 patients with postural tremor and 2 of 2 patients with motor weakness, when the activity of muscles involved in posturing or intention to move was fed into the system. The on-demand type stimulation system may also be useful for overcoming various post-stroke movement disorders.

1. INTRODUCTION
We have treated more than 400 patients with involuntary movements by DBS since 1989 [4-7, 10-12], including post-stroke movement disorders [6]. We have also found that involuntary movements can sometimes be attenuated in post-stroke patients undergoing motor cortex stimulation (MCS) for pain control [3, 5, 8]. This observation suggested that MCS may represent another useful option for controlling involuntary movements.

In some forms of movement disorders, involuntary movements are induced only when patients intend to move their body. We have developed an on-demand type stimulation system which triggers DBS or MCS by detecting intrinsic signals of intention to move. Such a system represents feed-forward control (FFC) of involuntary movements. In cases of postural tremor, for example, the tremor mechanism is activated by certain posturing. Signals related to posturing can therefore be used for FFC of the tremor. We report here our experience of DBS of the thalamus (Vo/Vim) and MCS for controlling post-stroke movement disorders, and discuss the value of FFC based on a preliminary study.

2. METHODS
A total of 28 patients with post-stroke movement disorders, including hemichoreaathetosis, hemiballism, tremor, and motor weakness underwent DBS and/or MCS. We employed DBS of the thalamus (Vo/Vim) for controlling the hemichoreaathetosis, hemiballism or tremor. In some patients with hemichoreaathetosis and/or tremor, the effects of MCS were tested separately before or after the subjects underwent Vo/Vim-DBS. MCS was also performed in 2 patients for the primary purpose of improving motor weakness. The stimulation intensity of the MCS was carefully restricted to below the threshold for muscle contraction. The stimulation frequency employed for the long-term use of MCS was limited to below 50 Hz.

We are currently employing the electro-myographic (EMG) activity of appropriate muscles as an intrinsic signal to trigger DBS or
MCS for the on-demand stimulation system. We first developed an on-demand type stimulation system, by connecting the system to the externalized leads during the test stimulation period before internalization. An external pulse generator is triggered by the EMG activity which is involved in tremor-inducing posture. We next developed an on-demand type stimulation system, which triggers an implanted pulse generator through a console programmer by detecting the appropriate combination of multiple EMG activities which best represents tremor-inducing posture. The implanted pulse generator is activated transcutaneously. We tested whether or not tremor is controlled satisfactorily in 4 patients with post-stroke postural tremor by using these systems. In 2 patients with post-stroke motor weakness, MCS was triggered by EMG activity for intention to move, and the effect of stimulation on motor performance was evaluated subjectively. The above 6 patients comprised those who demonstrated excellent control of post-stroke postural tremor or motor weakness by conventional DBS or MCS.

3. RESULTS
Excellent control of post-stroke involuntary movement was achieved by conventional DBS or MCS in 21 of the 28 patients. In 2 patients, dual-lead DBS for stimulation of wide areas of the Vo/Vim was required to achieve satisfactory control. Some patients with post-stroke tremor preferred MCS to Vo/Vim-DBS. They underwent internalization of electrodes for MCS as well as DBS, and have so far used MCS to control their tremor for more than 8 years. The effects on tremor occurred at an intensity below the threshold for muscle contraction and at a relatively high frequency range. The inhibition of tremor was partial when the frequency was limited to below 50 Hz. The tremor under off-stimulation conditions disappeared in one patient after continuous MCS for more than 3 years. The on-demand stimulation system provided satisfactory FFC in 4 of the 4 patients with postural tremor and 2 of the 2 patients with motor weakness, when the EMG activities involved in posturing or intention to move were fed into the system.

4. DISCUSSION AND CONCLUSIONS
The present data confirm the benefits of MCS for controlling tremor in post-stroke patients. Post-stroke involuntary movements, especially those in thalamic syndrome, are sometimes associated with central pain. Vo/Vim-DBS could elicit opposite effects in these disorders. Involuntary movements can be attenuated, but the pain of the same patients may be exacerbated. MCS might represent the therapy of choice under such circumstances [2, 5].

We have found that patients who underwent MCS for pain control sometimes report subjective improvement of their motor performance, which had been impaired in association with motor weakness. It has also been reported that stimulation of the posterior limb of the internal capsule can attenuate motor deficits caused by cortical injury [1]. Such an effect is not attributable to objectively detectable muscle strength and appears to have resulted from an inhibition of the muscle rigidity.

DBS and MCS, if used with the on-demand type stimulation system, may also be useful for controlling other motor symptoms in post-stroke patients and for improving their overall motor performance. The present findings justify further clinical studies on DBS and MCS in patients with post-stroke movement disorders. The on-demand type stimulation system could be regarded as a first step towards the development of hybrid electric neural circuits to overcome various post-stroke movement disorders. Future studies on cortical stimulation, including MCS and on-demand type stimulation systems, should clarify the clinical value of these techniques in controlling movement disorders.

References
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