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Interventional neurophysiology: A new frontier in investigation, treatment and research

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TABLE OF CONTENTS

1. ABSTRACT

In this short review, we highlight and reference the new developments in the newly emerged field of Interventional Neurophysiology in relation to neurosurgery, particularly the functional neurosurgery. The review covers clinical aspects of neurophysiological interventions into investigation, treatment and research on the pathophysiological mechanisms of neurological disorders.

2. INTRODUCTION

The concept of Interventional Neurophysiology reflects the changes in clinical practice as many surgical procedures require more use of neurophysiological methods. Neurophysiologists integrate themselves as a part of team, particularly in functional neurosurgery, where intracranial recordings of neural activity are increasingly needed, and electrical modulation of brain activity becomes an alternative to ablative and pharmacological treatments. New frontiers are created as the emergence of Interventional Neurophysiology aids clinical research on the pathophysiological mechanisms of neurological disorders, their investigation and treatment.

Interventional Neurophysiology emerges from the clinical need in an increasingly large number of neurosurgical procedures (involving brain, cranial nerves, spinal cord and the peripheral nervous system) to achieve maximal efficacy and safety by applying neurophysiological methods. Traditional 'Clinical Neurophysiology' has consequently extended its participation not only in the pre-operative stage, playing a diagnostic role to help select the patients, but also in the operating room during the surgical procedure itself. This is largely reflected by the increase in use of the various procedures generally termed as 'Neurophysiological monitoring' or 'Surgical neurophysiology' in the literature. The term "neurophysiological monitoring", as defined by the American Society of Neurophysiological Monitoring (ASNM, http://www.asnm.org/), refers to any measure that is used to assess the functional integrity of the peripheral or central nervous system in the operating room, the intensive care unit or other acute care setting. The participation of neurophysiology in operating room has been highlighted by Aage R. Møller's book "Intraoperative Neurophysiological Monitoring" of the 1st edition in 1995 (1) and the 2nd

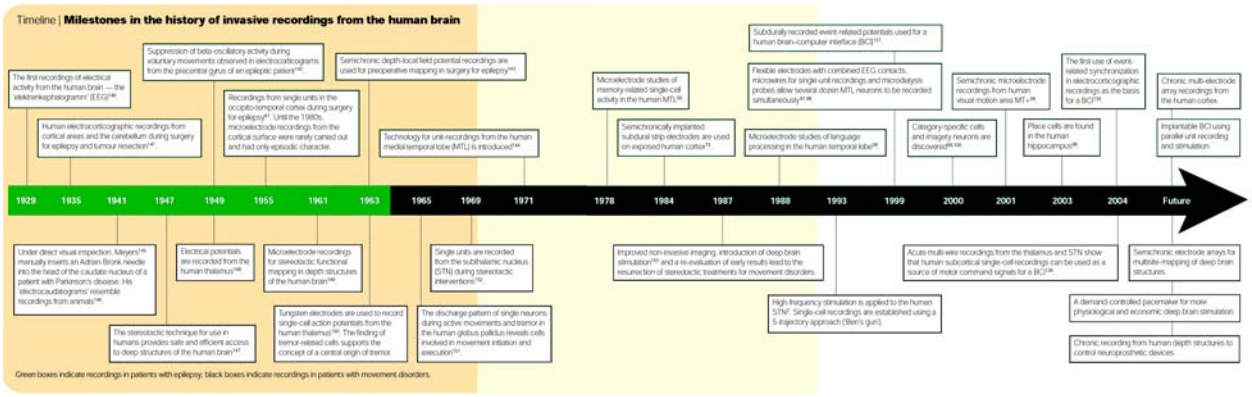

Figure 1. Timeline. Milestones in the history of invasive recordings from the human brain. Reproduced with permission from (67).

edition 10 years later (2). A clear emphasis on the motor system is seen in a book from Deletis and Shils, (3). The new international association 'International Society for Intraoperative Neurophysiology' has been established recently in Rome, (http://www.ptsroma.it/isin/) reflecting the expanding of the field.

With the resurgence of functional and stereotactic neurosurgery, some neurophysiological procedures are practically integrated as an essential part of surgical procedures, not only to achieve efficacy and attain safety, but by detecting the spontaneous or evoked potential signals to provide functional markers for target localisation, and more profoundly, to deliver the final therapeutic outcome by electrically modulating neuronal activity via the implanted electrodes. This makes the neurophysiology become therapeutic in itself, as represented by the terms of 'Neurostimulation' and 'Neuromodulation'. The latter has been used to name the official journal of the International Neuromodulation Society (INS, http://www.neuromodulation.com/).

In this short review on the frontiers of neurosurgery research, we will provide an over view with highlights and references on developments in the newly emerged field of Interventional Neurophysiology in relation to functional neurosurgery, covering clinical aspects of investigation, treatment and research into the pathophysiological mechanisms of neurological disorders.

3. NEW ROLES IN CLINICAL INVESTIGATION PLAYED BY INTERVENTIONAL NEUROPHYSIOLOGY

Interventional neurophysiology plays new roles in diagnostic investigations beyond the boundary of conventional procedures, largely based on the advances of technology. Clinically, the new roles have been very much led by the needs and opportunities associated with functional neurosurgery (Figure 1). Firstly, various types of neurophysiological investigations involving transitional surgical procedures have been developed in order to get a close access to the pathological sources for more accurate identification and quantification so that the selectivity on the extent of a permanent ablation and accuracy of the target localisation can be enhanced. For examples, "stereotactic electroencephalography, SEEG" (4-6), cortical mapping (7), and depth microelectrode (8-12) and macroelectrode recordings (13-17) have been integrated with the procedure of ablation or stimulation. Secondly, in order to predict the long-term outcome of surgery, transient alleviation of symptoms may be induced by neurophysiological means, such as magnetic stimulation to the cerebral cortex at pre-operative stage (18-22) or electrical stimulation to the deep brain structures during operation (23-25).

4. NEW ROLES IN THERAPEUTIC INTERVENTIONS PLAYED BY INTERVENTIONAL NEUROPHYSIOLOGY

The new roles of neurophysiological techniques in therapeutic interventions are mainly reflected by achieving therapeutic effects using electrical or magnetic modulation of the neural activity. Since 1970s, (26) spinal cord stimulation has been widely used for control of intractable pain and spasticity. High-frequency electrical deep brain stimulation has been widely used to treat epilepsy, with progressively greater success, (27-30) and 'closed loop' systems, where a discharge is detected, and high frequency stimuli applied to abort a seizure, are being developed. Movement disorders also respond to high frequency stimuli, (31-40) as may neuropathic pain, (41-50) and psychiatric disorders. (51-53) Transcranial magnetic stimulation as a treatment has been attempted in movement disorders (22, 54-58) and various psychiatric disorders. (59-66)

5. RESEARCH INTO THE PATHOPHYSIOLOGICAL MECHANISMS

Interventional Neurophysiology provides new approaches in clinical research on the pathophysiological mechanisms of brain disorders by directly investigating the function of deep brain structures in conscious patients, as highlighted by a recent review on invasive neurophysiological recording in human brain (67). The obvious advantages of this approach are the greatly

enhanced spatial resolution and signal to noise ratio, and the ability to correlate the neural signals with either the symptoms (13, 15, 68-76) or the performance of specifically designed behavioural or cognitive tasks (77-84). Recently, the neural control of the systemic blood pressure has been investigated in the patients with electrode implanted in the periventricular/periaqueductal region (85-87). New area of research has also been created in association of the treatment of deep brain stimulation. One distinctive example is the studies on the effects of neuromodulation to increase our understanding of its actions, and to refine the indications for this therapy. This may extend the range of relevant applications and lead to increased availability, as the objectives set by the International Neuromodulation Society (http://www.neuromodulation.com/). Studies have been carried out to investigate the mechanisms of deep brain stimulation at neuronal (88) and system levels (89), and have ranged from clinical studies (31, 90-94) to experimental studies focusing on the depth electrode-brain interface (95-100). Some recent studies have focused on optimising stimulation parameters, including frequency, pulse width, intensity, and the pattern settings of either electrical or magnetic stimulation to ensure therapeutic effects become more selective, effective and with fewer complications (35, 37, 101-105). Last but not least, given the nature of the neurophysiological procedures mentioned above as of many other interventional procedures, safety is an important issue. A clear therapeutic need assessed against other treatment options, with favourable benefit/risk ratio, will be mandatory for deploying any interventional neurophysiology procedure. This has provoked much discussion concerning the safety and efficacy. For example, using microelectrode recordings in movement disorder surgery has been strongly challenged (106). Efficacy and safety issues on various procedures during deep brain stimulation (107-113) or surface brain stimulation (107, 114, 115) have been vigorously investigated and assessed.

6. THE MULTI-DISCIPLINARY NATURE OF INTERVENTIONAL NEUROPHYSIOLOGY

The development of interventional neurophysiology have been largely based on the interactions from a wide range of clinical specialities, including neurosurgery, neurology, anaesthesia, and intensive care. Due to the rapid expanding of interventional neurophysiological procedures in response to the needs of developments in functional neurosurgery, there has been a vacuum of trained specialists playing the newly developed interventional roles. It was surveyed that, before the 90's, a large proportion of the simple procedures for intraoperative monitoring were carried out without involvement of specialised neurophysiologists (see the Report of the Therapeutics and Technology Assessment Subcommittee of the American Academy of Neurology (116). This vacuum has been initially (and, to a large extent, is still) filled by one individual from a team of neurosurgeons and neurologists with an interest in neurophysiology. Helps also come from experimental neurophysiologists or medical engineers with an interest in the clinical application of their skills. For instance, electrical/magnetic neurostimulation procedures have been adapted from an experimental tool to an alternative therapeutic intervention for psychiatric disorders (117, 118). In addition, neurophysiologists have been interacting with other clinical disciplines such as anaesthesia and intensive care for monitoring neuronal activity in a clinical setting (119, 120). The speciality has also been assisted by the expertise of laboratory-based neurophysiologists and by the advances in basic scientific fields of medical physics and neural engineering. All of these interactions with other clinical and scientific disciplines have become the fundamental guiding force for developing and defining the multi-disciplinary nature of Interventional Neurophysiology. Encouragingly, the involvement of clinically trained neurophysiologists with an interest in playing a more interventional role has been steadily on the increase.

7. CONCLUDING REMARKS

Neurophysiology has gone beyond the traditional boundary of playing diagnostic roles in assessing brain functions. It now becomes more interventional and creates a new frontier in investigation, treatment and research related to functional neurosurgery and neurosurgery as a whole.

8. REFERENCES

1. Moller, A.R. Intraoperative Neurophysiologic Monitoring, Taylor & Francis, Lucxembourg, (1995)
2. Moller, A.R. Intraoperative neurophysiological monitoring, Humana Press, Totowa, (2005)
3. Deletis, V & J.L. Shils Neurophysiology in *Neurosurgery*: A modern intraoperative approach, Academic Press, London, New York, (2002)
4. Lamarche, M., J. Louvel, P. Buser & I. Rektor: Intracerebral recordings of slow potentials in a contingent negative variation paradigm: an exploration in epileptic patients. *Electroencephalogr Clin Neurophysiol* 95, 268-276 (1995)
5. Bancaud, J., R. Angelergues, C. Bernouilli, A. Bonis, M. Bordas-Ferrer, M. Bresson, P. Buser, L. Covello, P. Morel, G. Szikla, A. Takeda & J. Talairach: Functional stereotaxic exploration (SEEG) of epilepsy. *Electroencephalogr Clin Neurophysiol* 28, 85-86 (1970)
6. Guenot, M., J. Isnard, P. Ryvlin, C. Fischer, K. Ostrowsky, F. Mauguiere & M. Sindou: Neurophysiological monitoring for epilepsy surgery: the Talairach SEEG method. StereoElectroEncephaloGraphy. Indications, results, complications and therapeutic applications in a series of 100 consecutive cases. *Stereotact Funct Neurosurg* 77, 29-32 (2001)
7. Miller, K.J., E.C. Leuthardt, G. Schalk, R.P.N. Rao, N.R. Anderson, D.W. Moran, J.W. Miller & J.G. Ojemann: Spectral Changes in Cortical Surface Potentials during Motor Movement. *J Neurosci* 27, 2424-2432 (2007)
8. Alterman, R.L., D. Sterio, A. Beric & P.J. Kelly: Microelectrode recording during posteroventral pallidotomy: impact on target selection and complications. *Neurosurgery* 44, 315-321 (1999)
9. Lozano, A.M., A.E. Lang, W.D. Hutchison & J.O. Dostrovsky: Microelectrode recording-guided

posteroventral pallidotomy in patients with Parkinson's disease. *Adv Neurol* 74, 167-174 (1997)
10. Mandir, A.S., L.H. Rowland, P.M. Dougherty & F.A. Lenz: Microelectrode recording and stimulation techniques during stereotactic procedures in the thalamus and pallidum. *Adv Neurol* 74, 159-165 (1997)
11. Lenz, F.A., H.C. Kwan, R. Martin, R. Tasker, R.T. Richardson & J.O. Dostrovsky: Characteristics of somatotopic organization and spontaneous neuronal activity in the region of the thalamic principal sensory nucleus in patients with spinal cord transection. *J Neurophysiol* 72, 1570-87 (1994)
12. Lenz, F.A., H.C. Kwan, R.L. Martin, R.R. Tasker, J.O. Dostrovsky & Y.E. Lenz: Single unit analysis of the human ventral thalamic nuclear group. Tremor related activity in functionally identified cells. *Brain* 117, 531-543 (1994)
13. Liu, X., I.C. Griffin, S.G. Parkin, R.C. Miall, J.G. Rowe, R.P. Gregory, R.B. Scott, T.Z. Aziz & J.F. Stein: Involvement of the medial pallidum in focal myoclonic dystonia: A clinical and neurophysiological case study. *Mov Disord* 17, 346-353 (2002)
14. Liu, X., J. Rowe, D. Nandi, G. Hayward, S. Parkin, J. Stein & T. Aziz: Localisation of the subthalamic nucleus using Radionics Image Fusion (TM) and Stereoplan (TM) combined with field potential recording. A technical note. Stereotact Funct Neurosurg 76, 63-73 (2001)
15. Liu, X., H.L. Ford-Dunn, G.N. Hayward, D. Nandi, R.C. Miall, T.Z. Aziz & J.F. Stein: The oscillatory activity in the Parkinsonian subthalamic nucleus investigated using the macro-electrodes for deep brain stimulation. Clin Neurophysiol 113, 1667-1672 (2002)
16. Chen, C.C., A. Pogosyan, L.U. Zrinzo, S. Tisch, P. Limousin, K. Ashkan, T. Yousry, M.I. Hariz & P. Brown: Intra-operative recordings of local field potentials can help localize the subthalamic nucleus in Parkinson's disease surgery. Exp Neurol 198, 214-221 (2006)
17. Kuhn, A.A., T. Trottenberg, A. Kivi, A. Kupsch, G.H. Schneider & P. Brown: The relationship between local field potential and neuronal discharge in the subthalamic nucleus of patients with Parkinson's disease. Exp Neurol 194, 212-220 (2005)
18. Lefaucheur, J.P., X. Drouot, I. Menard-Lefaucheur, F. Zerah, B. Bendib, P. Cesaro, Y. Keravel & J.P. Nguyen: Neurogenic pain relief by repetitive transcranial magnetic cortical stimulation depends on the origin and the site of pain. J Neurol Neurosurg Psychiatry 75, 612-616 (2004)
19. Huang, Y.-Z., M.J. Edwards, K.P. Bhatia & J.C. Rothwell: One-Hz Repetitive Transcranial Magnetic Stimulation of the Premotor Cortex Alters Reciprocal Inhibition in DYT1 Dystonia. Mov Disord 19, 54-59 (2004)
20. Velasco, F., M. Velasco, F. Jimenez, A.L. Velasco, F. Brito, M. Rise & J.D. Carrillo-Ruiz: Predictors in the treatment of difficult-to-control seizures by electrical stimulation of the centromedian thalamic nucleus. Neurosurgery 47, 295-304 (2000)
21. Brambilla, P., J. Perez, S. Monchieri, P.M. Rossini & C. Bonato: Transient improvement of tardive dyskinesia induced with rTMS. Neurology 61, 1155 (2003)
22. Cantello, R.: Applications of transcranial magnetic stimulation in movement disorders. J Clin Neurophysiol 19, 272-293 (2002)
23. Kraus, J.K., T. Pohle: Intraoperative test stimulation with a modified implantable pulse generator in deep brain stimulation. *Acta Neurochir (Wien)* 142, 587-589 (2000)
24. Carrol, C., L. Munro Davies, R. Scott & T.Z. Aziz: Pallidotomy: The Debate. *Brit J Neurosurg* 12, 146-150 (1998)
25. Lenz, F.A., R.H. Gracely, A.J. Romanoski, E.J. Hope, L.H. Rowland & P.M. Dougherty: Stimulation in the human somatosensory thalamus can reproduce both the affective and sensory dimensions of previously experienced pain. *Nat Med* 1, 910-913 (1995)
26. Waltz, J.M.: Spinal cord stimulation: a quarter century of development and investigation. A review of its development and effectiveness in 1,336 cases. *Stereotact Funct Neurosurg* 69, 288-299 (1997)
27. Bernier, G.P., F. Richer, N. Giard, G. Bouvier, M. Mercier, A. Turmel & J.M. Saint-Hilaire: Electrical stimulation of the human brain in epilepsy. *Epilepsia* 31, 513-520 (1990)
28. Loddenkemper, T., A. Pan, S. Neme, K.B. Baker, A.R. Rezai, D.S. Dinner, E.B.J. Montgomery & H.O. Luders: Deep brain stimulation in epilepsy. *J Clin Neurophysiol* 18, 514-532 (2001)
29. Feindel, W.: Brain stimulation combined with electrocorticography in the surgery of epilepsy: historical highlights. *Electroencephalogr Clin Neurophysiol* 48, 1-8 (1998)
30. Alarcon, G.: Electrical stimulation in epilepsy. *Clin Neurophysiol* 116, 716-717 (2005)
31. Yianni, J., D. Nandi, M. Ch, J. Hyam, V. Elliott, P. Bain, R. Gregory & T. Aziz: Failure of Chronic Pallidal Stimulation in Dystonic Patients Is a Medical Emergency. Neuromodulation 7, 9-12 (2004)
32. Parkin, S., T. Aziz, R. Gregory & P. Bain: Bilateral internal globus pallidus stimulation for the treatment of spasmodic torticollis. Mov Disord 16, 489-493 (2001)
33. Krack, P., P. Limousin, A.L. Benabid & P. Pollak: Chronic stimulation of subthalamic nucleus improves levodopa-induced dyskinesias in Parkinson's disease. Lancet 350, 1676 (1997)
34. Rizzone, M., M. Lanotte, B. Bergamasco, A. Tavella, E. Torre, G. Faccani, A. Melcarne & L. Lopiano: Deep brain stimulation of the subthalamic nucleus in Parkinson's disease: effects of variation in stimulation parameters. J Neurol Neurosurg Psychiatry 71, 215-219 (2001)
35. Moro, E., R.J. Esselink, J. Xie, M. Hommel, A.L. Benabid & P. Pollak: The impact on Parkinson's disease of electrical parameter settings in STN stimulation. Neurology 59, 706-713 (2002)
36. Vitek, J.L.: Mechanisms of deep brain stimulation: excitation or inhibition. Mov Disord 17, S69-S72 (2002)
37. Dowsey-Limousin, P.: Postoperative management of Vim DBS for tremor. Mov Disord 17, S208-S211 (2002)
38. Benabid, A.L., P. Pollak, C. Gross, D. Hoffmann, A. Benazzouz, D.M. Gao, A. Laurent, M. Gentil & J. Perret: Acute and long-term effects of subthalamic nucleus stimulation in Parkinson's disease. Stereotact Funct Neurosurg 62, 76-84 (1994)

39. Ashby, P., A. Strafella, J.O. Dostrovsky, A. Lozano & A.E. Lang: Immediate motor effects of stimulation through electrodes implanted in the human globus pallidus. *Stereotact Funct Neurosurg* 70, 1-18 (1998)
40. Foffani, G., G. Ardolino, M. Egidi, E. Caputo, B. Bossi & A. Priori: Subthalamic oscillatory activities at beta or higher frequency do not change after high-frequency DBS in Parkinson's disease. *Brain Res Bull* 69, 123-130 (2006)
41. Carroll, D., C. Joint, N. Maartens, D. Shlugman, J. Stein & T.Z. Aziz: Motor cortex stimulation for chronic neuropathic pain: a preliminary study of 10 cases. *Pain* 84, 431-437 (2000)
42. Nandi, D., H. Smith, S. Owen, C. Joint, J.F. Stein & T.Z. Aziz: Peri-ventricular grey stimulation versus motor cortex stimulation for post stroke neuropathic pain. *J Clin Neurosci* 9, 557-561 (2002)
43. Smith, H., C. Joint, D. Schlugman, D. Nandi, J.F. Stein & T.Z. Aziz: Motor cortex stimulation for neuropathic pain. *Neurosurgical Focus* 11, Article 3 (2001)
44. Dieckmann, G., A. Witzmann: Initial and long-term results of deep brain stimulation for chronic intractable pain. *Appl Neurophysiol* 45, 167-172 (1982)
45. Gybels, J., R. Kupers: Deep brain stimulation in the treatment of chronic pain in man: where and why? *Neurophysiol Clin* 20, 389-398 (1990)
46. Kumar, K., G.M. Wyant & R. Nath: Deep brain stimulation for control of intractable pain in humans, present and future: a ten-year follow-up. *Neurosurgery* 26, 774-781 (1990)
47. Mundinger, F., J.F. Salomao: Deep brain stimulation in mesencephalic lemniscus medialis for chronic pain. *Acta Neurochir (Wien)* 30, 245-258 (1980)
48. Tasker, R.R., F.O. Vilela: Deep brain stimulation for neuropathic pain. *Stereotact Funct Neurosurg* 65, 122-124 (1995)
49. Young, R.F., F.W. Bach, A.S. Van Norman & T.L. Yaksh: Release of beta-endorphin and methionine-enkephalin into cerebrospinal fluid during deep brain stimulation for chronic pain. Effects of stimulation locus and site of sampling. *J Neurosurg* 79, 816-25 (1993)
50. Nguyen, J.P., J.P. Lefaucheur, P. Decq, T. Uchiyama, A. Carpentier, D. Fontaine, P. Brugieres, B. Pollin, A. Feve, S. Rostaing, P. Cesaro & Y. Keravel: Chronic motor cortex stimulation in the treatment of central and neuropathic pain. Correlations between clinical, electrophysiological and anatomical data. *Pain* 82, 245-51 (1999)
51. Nuttin, B.J., L.A. Gabriels, P.R. Cosyns, B.A. Meyerson, S. Andreewitch, S.G. Sunaert, A.F. Maes, P.J. Dupont, J.M. Gybels, F. Gielen & H.G. Demeulemeester: Long-term electrical capsular stimulation in patients with obsessive-compulsive disorder. *Neurosurgery* 52, 1263-1272 (2003)
52. Kopell, B.H., B. Greenberg & A.R. Rezai: Deep Brain Stimulation for Psychiatric Disorders. *J Clin Neurophysiol* 21, 51-67 (2004)
53. Roth, R.M., L.A. Flashman, A.J. Saykin & D.W. Roberts: Deep brain stimulation in neuropsychiatric disorders. *Curr Psychiatry Rep* 3, 366-372 (2001)
54. Tsuji, S., N. Akamatsu: Does transcranial magnetic stimulation improve the motor symptoms of Parkinson disease? *J Neurol* 250, III47-III50 (2003)
55. Chen, J.T., H.Y. Yu, Z.A. Wu, K.P. Kao, M. Hallett & K.K. Liao: Modulation of symptomatic palatal tremor by magnetic stimulation of the motor cortex. *Clin Neurophysiol* 111, 1191-1197 (2000)
56. Pascual-Leone, A., J. Valls-Sole, J.P. Brasil-Neto, L.G. Cohen & M. Hallett: Akinesia in Parkinson's disease. I. Shortening of simple reaction time with focal, single-pulse transcranial magnetic stimulation. *Neurology* 44, 884-891 (1994)
57. Siebner, H.R., C. Mentschel, C. Auer & B. Conrad: Repetitive transcranial magnetic stimulation has a beneficial effect on bradykinesia in Parkinson's disease. *Neuroreport* 10, 589-594 (1999)
58. Mills, K.R., K.A. Nithi: Motor cortex stimulation does not reset primary orthostatic tremor. *J Neurol Neurosurg Psychiatry* 63, 553 (1997)
59. Acosta, M.T., F.E. Leon-Sarmiento: Repetitive transcranial magnetic stimulation (rTMS): new tool, new therapy and new hope for ADHD. *Curr Med Res Opin* 19, 125-130 (2003)
60. Zyss, T.: Deep magnetic brain stimulation--the end of psychiatric electroshock therapy? *Med Hypotheses* 43, 69-74 (1994)
61. Cohen, H., Z. Kaplan, M. Kotler, I. Kouperman, R. Moisa & N. Grisaru: Repetitive transcranial magnetic stimulation of the right dorsolateral prefrontal cortex in posttraumatic stress disorder: a double-blind, placebo-controlled study. *Am J Psychiatry* 161, 515-524 (2004)
62. Hausmann, A., G. Kemmler, M. Walpoth, S. Mechtcheriakov, K. Kramer-Reinstadler, T. Lechner, T. Walch, E.A. Deisenhammer, M. Kofler, C.I. Rupp, H. Hinterhuber & A. Conca: No benefit derived from repetitive transcranial magnetic stimulation in depression: a prospective, single centre, randomised, double blind, sham controlled "add on" trial. *J Neurol Neurosurg Psychiatry* 75, 320-322 (2004)
63. Kirkcaldie, M., S. Pridmore & P. Reid: Bridging the skull: electroconvulsive therapy (ECT) and repetitive transcranial magnetic stimulation (rTMS) in psychiatry. *Convuls Ther* 13, 83-91 (1997)
64. Pridmore, S., R. Bruno, Y. Turnier-Shea, P. Reid & M. Rybak: Comparison of unlimited numbers of rapid transcranial magnetic stimulation (rTMS) and ECT treatment sessions in major depressive episode. *Int J Neuropsychopharmacol* 3, 129-134 (2000)
65. Saba, G., R.J. Francois, K. Kalalou, R. Benadhira, M. Plaze, H. Lipski & D. Januel: Repetitive transcranial magnetic stimulation as an add-on therapy in the treatment of mania: a case series of eight patients. *Psychiatry Res* 128, 199-202 (2004)
66. Schlaepfer, T.E., M. Kosel & C.B. Nemeroff: Efficacy of repetitive transcranial magnetic stimulation (rTMS) in the treatment of affective disorders. *Neuropsychopharmacology* 28, 201-205 (2003)
67. Engel, A.K., C.K. Moll, I. Fried & G.A. Ojemann: Invasive recordings from the human brain: clinical insights and beyond. *Nat Rev Neurosci* 6, 35-47 (2005)
68. Brown, P.: Oscillatory nature of human basal ganglia activity: relationship to the pathophysiology of Parkinson's disease. *Mov Disord* 18, 357-363 (2003)
69. Hutchison, W.D., J.O. Dostrovsky, J.R. Walters, R. Courtemanche, T. Boraud, J. Goldberg & P. Brown:

Neuronal oscillations in the basal ganglia and movement disorders: evidence from whole animal and human recordings. *J Neurosci* 24, 9240-9243 (2004)
70. Liu, X.: What can be learned from recording local field potentials from the brain via implanted electrodes used to treat patients with movement disorders? *Cur Med Lit: Neurology* 19, 1-6 (2003)
71. Lozano, A.M., A.E. Lang, R. Levy, W. Hutchison & J. Dostrovsky: Neuronal recordings in Parkinson's disease patients with dyskinesias induced by apomorphine. *Ann Neurol* 47, S141-S146 (2000)
72. Marsden, J.F., P. Limousin-Dowsey, P. Ashby, P. Pollak & P. Brown: Subthalamice nucleus, sensorimotor cortex and muscle interrelationships in Parkinson's disease. *Brain* 124, 378-388 (2001)
73. Rodriguez, M.C., O.J. Guridi, L. Alvarez, K. Mewes, R. Macias, J. Vitek, M.R. DeLong & J.A. Obeso: The subthalamic nucleus and tremor in Parkinson's disease. *Mov Disord* 13, 111-118 (1998)
74. Silberstein, P., A.A. Kuhn, A. Kupsch, T. Trottenberg, J.K. Krauss, J.C. Wohrle, P. Mazzone, A. Insola, L. Di, V, A. Oliviero, T. Aziz & P. Brown: Patterning of globus pallidus local field potentials differs between Parkinson's disease and dystonia. *Brain* 126, 2597-2608 (2003)
75. Marceglia, S., G. Foffani, A.M. Bianchi, G. Baselli, F. Tamma, M. Egidi & A. Priori: Dopamine-dependent non-linear correlation between subthalamic rhythms in Parkinson's disease. J Physiol 571, 579-591 (2006)
76. Liu, X., J. Yianni, S. Wang, P.G. Bain, J.F. Stein & T.Z. Aziz: Different mechanisms may generate sustained hypertonic and rhythmic bursting muscle activity in idiopathic dystonia. Exp Neurol 198, 204-213 (2006)
77. Brown, P., D. Williams, T. Aziz, P. Mazzone, A. Oliviero, A. Insola, P. Tonali & V.D. Lazzaro: Pallidal activity recorded in patients with implanted electrodes predictively correlates with eventual performance in a timing task . Neurosci Lett 330, 188-192 (2002)
78. Cassidy, M., P. Mazzone, A. Oliviero, A. Insola, P. Tonali, V.D. Lazzaro & P. Brown: Movement-related changes in synchronization in the human basal ganglia. Brain 125, 1235-1246 (2002)
79. Kuhn, A.A., D. Williams, A. Kupsch, P. Limousin, M. Hariz, G.H. Schneider, K. Yarrow & P. Brown: Event-related beta desynchronization in human subthalamic nucleus correlates with motor performance. Brain 127, 735-746 (2004)
80. Marsden, J.F., P. Ashby, P. Limousin Dowsey, J.C. Rothwell & P. Brown: Coherence between cerebellar thalamus, cortex and muscle in man: cerebellar thalamus interactions. Brain 123, 1459-70 (2000)
81. Williams, D., A. Kuhn, A. Kupsch, M. Tijssen, G. van Bruggen, H. Speelman, G. Hotton, K. Yarrow & P. Brown: Behavioural cues are associated with modulations of synchronous oscillations in the human subthalamic nucleus. Brain 126, 1975-1985 (2003)
82. Williams, D., M. Tijssen, G. van Bruggen, A. Bosch, A. Insola, V.D. Lazzaro, P. Mazzone, A. Oliviero, A. Quartarone, H. Speelman & P. Brown: Dopamine-dependent changes in the functional connectivity between basal ganglia and cerebral cortex in humans. Brain 125, 1558-1569 (2002)
83. Chen, C.C., C. Brucke, F. Kempf, A. Kupsch, C.S. Lu, S.T. Lee, S. Tisch, P. Limousin, M. Hariz & P. Brown: Deep brain stimulation of the subthalamic nucleus: a two-edged sword. *Curr Biol* 16, R952-R953 (2006)
84. Kuhn, A.A., A. Kupsch, G.H. Schneider & P. Brown: Reduction in subthalamic 8-35 Hz oscillatory activity correlates with clinical improvement in Parkinson's disease. *Eur J Neurosci* 23, 1956-1960 (2006)
85. Green, A.L., S. Wang, S.L. Owen, K. Xie, X. Liu, D.J. Paterson, J.F. Stein, P.G. Bain & T.Z. Aziz: Deep brain stimulation can regulate arterial blood pressure in awake humans . *Neuroreport* 16, 1741-1745 (2005)
86. Green, A.L., S. Wang, R.G. Bittar, S.L.F. Owen, D.J. Paterson, J.F. Stein, P.G. Bain, D. Shlugman & T.Z. Aziz: Deep brain stimulation: A new treatment for hypertension? *J Clin Neurosci* 14, 592-595 (2007)
87. Green, A.L., S. Wang, S.L. Owen, D.J. Paterson, K. Xie, X. Liu, P.G. Bain, J.F. Stein & T.Z. Aziz: Functional *Neurosurgery* Resident Award: controlling the cardiovascular system with deep brain stimulation. *Clin Neurosurg* 53, 316-323 (2006)
88. Kiss, Z.H., D.M. Mooney, L. Renaud & B. Hu: Neuronal response to local electrical stimulation in rat thalamus: physiological implications for mechanisms of deep brain stimulation. *Neuroscience* 113, 137-143 (2002)
89. Benazzouz, A., D. Gao, Z. Ni & A.L. Benabid: High frequency stimulation of the STN influences the activity of dopamine neurons in the rat. *Neuroreport* 11, 1593-1596 (2000)
90. Back, C., F. Alesch & H. Lanmuller: Postoperative Monitoring of the Electrical Properties of Tissue and Electrodes in Deep Brain Stimulation. *Neuromodulation* 6, 248-253 (2003)
91. Hemm, S., N. Vayssiere, G. Mennessier, L. Cif, M. Zanca, P. Ravel, P. Frerebeau & P. Coubes: Evolution of Brain Impedance in Dystonic Patients Treated by GPi Electrical Stimulation. *Neuromodulation* 7, 67-75 (2004)
92. Rattay, F., S. Resatz, P. Lutter, K. Minassian, B. Jilge & M.R. Dimitrijevic: Mechanisms of Electrical Stimulation with Neural Prostheses. *Neuromodulation* 6, 42-56 (2003)
93. Vitek, J.L.: Deep brain stimulation for Parkinson's disease. A critical re-evaluation of STN versus GPi DBS. *Stereotact Funct Neurosurg* 78, 119-131 (2002)
94. Hashimoto, T., C.M. Elder, M.S. Okun, S.K. Patrick & J.L. Vitek: Stimulation of the subthalamic nucleus changes the firing pattern of pallidal neurons. *J Neurosci* 23, 1916-1923 (2003)
95. Xie, K., S. Wang, T.Z. Aziz, J.F. Stein & X. Liu: The physiologically modulated electrical potential at the electrode-brain interface of deep brain stimulation in humans. *Neurosci Lett* 402, 238-243 (2006)
96. McIntyre, C.C., S. Mori, D.L. Sherman, N.V. Thakor & J.L. Vitek: Electric field and stimulating influence generated by deep brain stimulation of the subthalamic nucleus. *Clin Neurophysiol* 115, 589-595 (2004)
97. Holsheimer, J., H. Demeulemeester, B. Nuttin & P. de Sutter: Identification of the target neuronal elements in electrical deep brain stimulation. *Eur J Neurosci* 12, 4573-4577 (2000)
98. Arle, J.E., L. Mei: DBS electrode electric field potentials: Calculated solutions and implications. *Mov Disord* 19, P944 (2004)

99. Moss, J., T. Ryder, T.Z. Aziz, M.B. Graeber & P.G. Bain: Electron microscopy of tissue adherent to explanted electrodes in dystonia and Parkinson's disease. *Brain* (2004)
100. Yousif, N., R. Bayford, P. Bain & X. Liu: The peri-electrode space is a significant element of the electrode-brain interface in deep brain stimulation: A computational study. *Brain Res Bull* in press, (2007)
101. Diener, H.C., F.B. Horak & L.M. Nashner: Influences of stimulus parameters on human postural responses. *J Neurophysiol* 59, 1888-1905 (1988)
102. Gennaro, L.D., M. Bertini, F. Pauri, R. Cristiani, G. Curcio, M. Ferrara & P.M. Rossini: Callosal effects of transcranial magnetic stimulation (TMS): the influence of gender and stimulus parameters. *Neurosci Res* 48, 129-137 (2004)
103. Kuncel, A.M., W.M. Grill: Selection of stimulus parameters for deep brain stimulation. *Clin Neurophysiol* 115, 2431-2441 (2004)
104. Yamamoto, T., Y. Katayama, C. Fukaya, H. Oshima, M. Kasai & K. Kobayashi: New method of deep brain stimulation therapy with two electrodes implanted in parallel and side by side. *J Neurosurg* 95, 1075-1078 (2001)
105. Huang, Y.Z., M.J. Edwards, K.P. Bhatia & J.C. Rothwell: One-Hz repetitive transcranial magnetic stimulation of the premotor cortex alters reciprocal inhibition in DYT1 dystonia. *Mov Disord* 19, 54-59 (2004)
106. Hariz, M.I., H. Fodstad: Do microelectrode techniques increase accuracy or decrease risks in pallidotomy and deep brain stimulation? A critical review of the literature. *Stereotact Funct Neurosurg* 72, 157-169 (1999)
107. Bezard, E., T. Boraud, J.P. Nguyen, F. Velasco, Y. Keravel & C. Gross: Cortical stimulation and epileptic seizure: a study of the potential risk in primates. *Neurosurgery* 45, 346-50 (1999)
108. Ghika, J., J.G. Villemure, H. Fankhauser, J. Favre, G. Assal & F. Ghika-Schmid: Efficiency and safety of bilateral contemporaneous pallidal stimulation (deep brain stimulation) in levodopa-responsive patients with Parkinson's disease with severe motor fluctuations: a 2-year follow-up review. *J Neurosurg* 89, 713-718 (1998)
109. Koller, W.C., K.E. Lyons, S.B. Wilkinson, A.I. Troster & R. Pahwa: Long-term safety and efficacy of unilateral deep brain stimulation of the thalamus in essential tremor. *Mov Disord* 16, 464-468 (2001)
110. Vilela Filho, O.: Risk factors for unpleasant paresthesiae induced by paresthesiae-producing deep brain stimulation. *Arq Neuropsiquiatr* 54, 57-63 (1996)
111. Baskin, D.S., W.R. Mehler, Y. Hosobuchi, D.E. Richardson, J.E. Adams & M.A. Flitter: Autopsy analysis of the safety, efficacy and cartography of electrical stimulation of the central gray in humans. *Brain Res* 371, 231-236 (1986)
112. Harnack, D., C. Winter, W. Meissner, T. Reum, A. Kupsch & R. Morgenstern: The effects of electrode material, charge density and stimulation duration on the safety of high-frequency stimulation of the subthalamic nucleus in rats. *J Neurosci Methods* 138, 207-216 (2004)
113. Lopiano, L., M. Rizzone, B. Bergamasco, A. Tavella, E. Torre, P. Perozzo, M.C. Valentini & M. Lanotte: Deep brain stimulation of the subthalamic nucleus: clinical effectiveness and safety. *Neurology* 56, 552-554 (2001)
114. Wassermann, E.M.: Risk and safety of repetitive transcranial magnetic stimulation: report and suggested guidelines from the International Workshop on the Safety of Repetitive Transcranial Magnetic Stimulation, June 5-7, 1996. *Electroencephalogr Clin Neurophysiol* 108, 1-16 (1998)
115. Nitsche, M.A., D. Liebetanz, N. Lang, A. Antal, F. Tergau & W. Paulus: Safety criteria for transcranial direct current stimulation (tDCS) in humans. *Clin Neurophysiol* 114, 2220-2222 (2003)
116. : Assessment: intraoperative neurophysiology. Report of the Therapeutics and Technology Assessment Subcommittee of the American Academy of *Neurology*. *Neurology* 40, 1644-1646 (1990)
117. Kopell, B.H., B. Greenberg & A.R. Rezai: Deep Brain Stimulation for Psychiatric Disorders. *J Clin Neurophysiol* 21, 51-67 (2004)
118. Keck, M.E.: rTMS as treatment strategy in psychiatric disorders--neurobiological concepts. *Clin Neurophysiol* 56, 100-116 (2003)
119. Wiedemayer, H., B. Fauser, W. Armbruster, T. Gasser & D. Stolke: Visual evoked potentials for intraoperative neurophysiologic monitoring using total intravenous anesthesia. *J Neurosurg Anesthesiol* 15, 19-24 (2003)
120. Sala, F., M.J. Krzan & V. Deletis: Intraoperative neurophysiological monitoring in pediatric Neurosurgery: why, when, how? *Childs Nerv Syst* 18, 264-287 (2002)

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