Clinical Radiology 69 (2014) 993–1003

Contents lists available at ScienceDirect

Clinical Radiology

journal homepage: www.clinicalradiologyonline.net

Review

Neural stimulators: A guide to imaging and postoperative appearances

A. Adams [a,*], J. Shand-Smith [b], L. Watkins [c], A.W. McEvoy [c], S. Elneil [d], L. Zrinzo [c], I. Davagnanam [b]

[a] *Department of Neuroradiology, Barts and the Royal London Hospital, West Smithfield, London, EC1A 7BE, UK*
[b] *Department of Neuroradiology, National Hospital for Neurology and Neurosurgery, London, UK*
[c] *Department of Neurosurgery, National Hospital for Neurology and Neurosurgery, London, UK*
[d] *Department of Urogynaecology, National Hospital for Neurology and Neurosurgery, London, UK*

ARTICLE INFORMATION

Article history:
Received 12 December 2013
Received in revised form
2 March 2014
Accepted 5 March 2014

Implantable neural stimulators have been developed to aid patients with debilitating neurological conditions that are not amenable to other therapies. The aim of this article is to improve understanding of correct anatomical placement as well as the relevant imaging methods used to assess these devices. Potential complications following their insertion and an overview of the current indications and potential mechanism of action of these devices is provided.

Introduction

The aim of this article is to provide an overview of the various neural stimulator devices. These devices have been developed to aid patients with debilitating neurological conditions that are not amenable or refractory to other therapies. It is important for the interpreting physician and radiologist to be aware of these devices, their intended anatomical targets and potential complications.

Deep brain stimulators

Deep brain stimulation (DBS) is the delivery of continuous electrical stimulation to a neural structure via implanted electrodes.[1] Insulated electrodes consist of a number of metallic contacts spaced at different intervals on the implanted leads and connected, via subcutaneous cables, to a pulse generator and battery pack, typically implanted beneath the skin in a subclavicular or abdominal location. Electrical stimulation parameters can be programmed to achieve the desired clinical effects. There are an increasing number of indications and potential anatomical targets for implantation of DBS electrodes. For example, in the treatment of medically refractory Parkinson's disease (PD) there are a number of different targets including the subthalamic nucleus (STN), globus pallidus pars interna (GPi), and ventrointermediate nucleus of the thalamus (Vim).[2] The STN has also been investigated as a potential target for DBS in cases of intractable epilepsy and obsessive–compulsive disorder, whereas the Vim is also targeted in patients with essential tremor. The GPi and bilateral thalamus have also been used as potential DBS targets in patients with Tourette's syndrome.[3] This review focuses on the role of DBS in the treatment of movement disorders in order to describe the development of functional neurosurgery and improvements in imaging techniques and anatomical localization.

The aim of stereotactic functional neurosurgery is to reach a particular anatomical target, chosen for its role in producing symptomatic disease, with optimal accuracy. Principles of stereotactic technique were established by Clarke and Horsley with the triplanar co-ordinates of the

* Guarantor and correspondent: A. Adams, Department of Neuroradiology, Barts and the Royal London Hospital, West Smithfield, London, EC1A 7BE, UK. Tel.: 0203 594 0141; fax: 0203 594 3199.
E-mail address: ashokadams@hotmail.com (A. Adams).

0009-9260/$ – see front matter
http://dx.doi.org/10.1016/j.crad.2014.03.005

intended intracranial target determined in relation to fixed landmarks.[4] Subsequently, localization of intended surgical targets was achieved through a combination of stereotactic principles and ventriculography, which involved the introduction of air as a contrast medium to outline the ventricles.[4] Identification of the anterior (AC) and posterior commissures (PC) as intracerebral landmarks, combined with stereotactic atlases, provided an improvement in anatomical localization and enabled safer targeting of deep seated structures. Anatomical localization has vastly improved with advances in magnetic resonance imaging (MRI). Stereotactic MRI is increasingly used as a primary tool for anatomical targeting in functional neurosurgery due to its increased accuracy, speed, and non-invasive nature.[4]

MRI and its application to functional neurosurgery require consideration of various factors that may affect accurate surgical targeting. Inhomogeneities in the magnetic field can result in geometric distortion that affects accurate anatomical representation.[5] This is exacerbated at the periphery of the field. When performing frame-based surgery, this can affect accurate localization of the fiducial markers that guide surgical targeting. Various MRI sequences and software applications have been developed to minimize these effects. Close collaboration between the neurosurgeon and radiographer is necessary with regards to patient positioning and alignment of the head frame in relation to the scanner.[4,5] The target region should be centred within the bore of the magnet at the site of lowest MR distortion. Functional neurosurgery remains an area of ongoing research and development with the introduction of higher field MRI, improved tissue contrast and image resolution with direct visualization of new and existing anatomical targets.

A combination of direct and indirect localization techniques are available for a number of surgical targets in the treatment of movement disorders.[3,6,7] With indirect targeting, identification of the AC, PC, and mid-commissural point is combined with standard coordinates from stereotactic atlases to provide the estimated location for the surgical target.[4,6,7] Identification of these white matter commissural fibres is best performed with T1-weighted imaging. If possible, direct visualization of the target with MRI is then undertaken to tailor and refine anatomical targeting to the particular patient undergoing surgery. For example, the STN can be directly visualized on axial and coronal T2-weighted images as there is a contrast interface between the STN and surrounding white matter. The STN is a small biconvex structure in the rostral mesencephalon that returns low signal on T2-weighted sequences, which is attributed to the presence of iron.[8] On axial imaging, the STN lies anterior and lateral to the red nucleus, which also serves as an anatomical landmark (Fig 1). In addition, the GPi can be identified on proton-density and inversion-recovery sequences, and it forms the most medial part of the lentiform nucleus lying medial to the lamina interna and lateral to the internal capsule.[9,10] It is immediately superior and lateral to the optic tract and the intended target is the posteroventral portion of the GPi (Fig 2).[4] Visualization of individual thalamic nuclei is unreliable at 1.5 T and the targeting of the motor thalamus and Vim is often performed indirectly.[7] The zona incerta (ZI) has been identified as an alternative target to the motor thalamus. It lies medial to the most superior and lateral aspect of the STN, and therefore, has the advantage that it can be directly localized on T2-weighted scans. An electrode can often be placed so that it can straddle both the ZI and motor thalamic targets[4] (Fig 3). Details of the MRI sequences used for preoperative targeting are provided in Table 1 and all MRI images in this article were performed using a 1.5 T MRI system.

In most centres, intra-operative physiological recordings and/or clinical testing to determine the final DBS location follow anatomical targeting. Surgical implantation of the DBS electrodes requires the application of a head frame under local anaesthetic.[6] The surgical entry point and trajectory of insertion are chosen to avoid vascular structures, cerebral sulci, lateral ventricles, and eloquent areas of the brain parenchyma (Fig 3).[11,12] A burr hole is performed with a small dural opening on a gyrus to minimize the potential for cerebrospinal fluid (CSF) leak and brain shift during the procedure.[11]

Surgical centres differ in the technique used to guide and confirm lead placement. Neurophysiology techniques include microelectrode recording (MER). During MER, multiple fine, sharp electrodes are introduced to the target region and neural activity from single neurones is recorded. Typical firing patterns act as a neurophysiological signature of the area being traversed. Another technique is dynamic impedance monitoring as a blunt-tip radiofrequency electrode is passed to the intended target; impedance increases as the tip traverses white matter and decreases when traversing grey matter or CSF boundaries. Clinical evaluation of symptoms and side effects can also be assessed if patients undergo surgery under local anaesthesia. The quadripolar DBS electrode is then passed down the same track and subsequent stimulation is performed to assess for therapeutic benefit for the patient as well as for potential adverse effects. These neurophysiological and clinical techniques provide surrogate markers of lead location.

Postoperative computed tomography (CT) images fused to preoperative MRI to ascertain the DBS lead positions is a commonly used method by neurosurgeons and is an acceptable method of documenting the anatomical location of the electrode active contacts.[13] This method combines the advantage of the high tissue contrast afforded by MRI as well as the safety and spatial accuracy of CT images, but introduces an error factor inherent with fusion or co-registration of two imaging methods. Increasingly, immediate postoperative cross-sectional imaging with MRI is undertaken to assess for haemorrhagic complications and verify DBS lead position. The final DBS electrode position is then compared to the preoperatively defined stereotactic target and can guide relocation of suboptimally placed leads.[4] This approach allows surgery to be performed under general anaesthetic without complete withdrawal of anti-Parkinsonian medication and is considerably less traumatic for patients.