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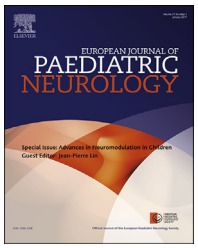

Review article

Technical challenges and safety of magnetic resonance imaging with *in situ* neuromodulation from spine to brain

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ABSTRACT

Purpose: This review summarises the need for MRI with *in situ* neuromodulation, the key safety challenges and how they may be mitigated, and surveys the current status of MRI safety for the main categories of neuro-stimulation device, including deep brain stimulation, vagus nerve stimulation, sacral neuromodulation, spinal cord stimulation systems, and cochlear implants.

Review summary: When neuro-stimulator systems are introduced into the MRI environment a number of hazards arise with potential for patient harm, in particular the risk of thermal injury due to MRI-induced heating. For many devices however, safe MRI conditions can be determined, and MRI safely performed, albeit with possible compromise in anatomical coverage, image quality or extended acquisition time.

Conclusions: The increasing availability of devices conditional for 3 T MRI, whole-body transmit imaging, and imaging in the on-stimulation condition, will be of significant benefit to the growing population of patients benefitting from neuromodulation therapy, and open up new opportunities for functional imaging research.

Contents

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1. Introduction

Neuromodulation and magnetic resonance imaging (MRI) both rely at a fundamental level on interactions between electromagnetic fields and tissue. It is not surprising therefore that there can exist significant electromagnetic interactions between implanted neuromodulation apparatus and the MRI scanner. These interactions may disrupt the imaging process, degrading image quality, or, more importantly, cause loss of therapeutic neurostimulation, damage to the neuromodulation equipment, or injury to the patient. Nevertheless, MRI and neuromodulation devices may coexist safely under specific, controlled circumstances, if the necessary device-specific conditions for safe MRI can be defined and satisfied.

This article reviews the need for MRI with *in situ* neuromodulation, summarises the key safety issues and how they may be mitigated, and surveys the current status of MRI safety for the main categories of neuro-stimulation device. Recent developments are discussed which promise to make MRI available to increasing numbers of patients previously contraindicated for MRI on account of their implants, and open new avenues for functional-imaging research.

Neuro-stimulation systems typically consist of metallic electrode contacts, either paddle-type electrodes or small arrays of cylindrical electrodes, at the end of insulated flexible leads, connected, via subcutaneous extension cables, to an implantable pulse generator (IPG) containing the pulse-generating electronics and a power cell.

Systems with this basic configuration have found clinical application in treating a range of conditions,[1] for instance deep brain stimulation (DBS) is established as a treatment for Parkinson's disease or dystonia[2]; vagus nerve stimulation (VNS) has been shown to decrease seizure frequency in patients with medically refractory epilepsy[3]; occipital nerve stimulation (ONS)[4] has shown benefit in a variety of headache disorders; spinal cord stimulation (SCS) is valuable in the management of intractable pain syndromes[5] and sacral neuromodulation (SNM) has been advocated for the treatment of bladder and bowel dysfunction.[6,7] The same general physical hazards in the MRI environment are common across the devices delivering these therapies, although the precise conditions under which MRI may be safely performed, if existing, are device-model specific. As paediatric neuro-stimulation therapy continues to increase in importance,[8] the need for devices engineered to better withstand the MRI environment, with rigorously defined conditions for safe MRI will become even more pressing. Cochlear implants (CIs), although differing in their design and function from the more generic types of neuro-stimulator listed above, are an important class of device frequently deployed in children,[9] with specific MRI safety management issues which will be discussed in a separate section.

2. The need for MRI with *in situ* neuromodulation

There are three broad motivations for undertaking MRI in patients with *in situ* neuromodulation devices: firstly, in many centres, MRI is an enabling technology in the workflow for neuro-stimulator implantation and therapy management. For instance intra- or post-operative MRI to verify anatomic electrode contact positions, and if necessary guide positional adjustment, as well as to assess for haemorrhagic complications, may be valuable in DBS implantation surgery.[10–13] Even if alternative methods to verify lead location, such as electrophysiological recordings or post-operative CT images fused to pre-operative MRI[14] are employed, MRI in subjects with pre-implanted electrode leads and IPGs may be necessary if