

REVIEW ARTICLE



Anaesthesia for deep brain stimulation and in patients with implanted neurostimulator devices

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Deep brain stimulation has become an increasingly common treatment for Parkinson's disease and other movement disorders. Consequently, it is important to understand the concepts of appropriate patient selection, the implantation process, and the various drugs and techniques that can be used to facilitate this treatment. Currently, none of the anaesthetic techniques for neurostimulator implantation has proven to be superior to others, although awake or sedation techniques are popular as they facilitate intraoperative neurological testing. However, even with meticulous anaesthetic care, perioperative complications such as hypertension and seizures do occasionally occur and close monitoring is required. Anaesthesia in patients with an implanted neurostimulator requires special considerations because of possible interference between neurostimulators and other devices. We have reviewed the current knowledge of anaesthetic techniques and perioperative complications of neurostimulator insertion. Anaesthetic considerations in patients with an implanted neurostimulator are also discussed.

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Functional stereotactic neurosurgery has become an increasing common treatment over the past 10 yr. In particular, deep brain stimulation (DBS)^{8 48} is now an effective treatment for Parkinson's disease. Thalamic DBS was first developed for tremor control. Subsequently, subthalamic nucleus (STN) and internal globus pallidus (GPi) stimulation were also investigated. In particular, STN stimulation can improve a wide range of parkinsonian symptoms and is currently the preferred target for most patients with this disease. The exact mechanism of action of this neurostimulation, however, remains unclear.³⁷ Nonetheless, after this initial success in patients with Parkinson's disease, the indications and applications for DBS have expanded to other disorders such as essential tremor, dystonia, chronic pain, and psychiatric disorders.^{51 52} When STN DBS is contraindicated, thalamic DBS remains an option for patients with severe tremor, and GPi stimulation can be used for those with severe dyskinesia.

The most common DBS hardware used (Medtronic, USA) has four main components: (i) the multicontact intracranial quadripolar electrodes, which are surgically inserted into the deep brain unilaterally or bilaterally, (ii) a plastic ring and cap seated onto a burr hole to fix the electrodes to the skull, (iii) a single- or dual-channel internal

pulse generator (IPG), and (iv) an extension cable that is tunnelled s.c. from the cranial area to the chest or abdomen, connecting the DBS electrode(s) to the IPG. The battery lasts between 2 and 5 yr and has to be replaced together with the pulse generator.

This article reviews the current knowledge regarding anaesthetic techniques for neurostimulator insertion. After a description of the surgical procedure, anaesthetic issues and possible perioperative complications will be discussed. Finally, anaesthesia for patients with a neurostimulator implant will be considered.

Deep brain stimulation electrode insertion

Preoperative evaluation

The preoperative preparation starts with careful patient selection as this is a major determinant of successful post-operative outcome. As in any other procedure, the decision whether to operate on a patient is based on the risk-to-benefit assessment, balancing the risk of the procedure against the perceived improvement in quality of life. This is best accomplished using a multidisciplinary approach in which anaesthetic, medical, neurological,

psychiatric, and social issues are assessed and addressed by a team consisting of anaesthetists, neurologists, neurosurgeons, neuropsychologists, and nurses.

Surgery can be considered for Parkinson's disease when the patient develops moderate to severe motor fluctuation, medication-induced dyskinesia, medication refractory tremor, or intolerance to medication. The most disabling symptoms should be identified and assessed as to whether they are dopa-sensitive or dopa-induced. Dopa-sensitive symptoms may be more likely to respond to surgery.⁹⁴ The best timing for surgery is, however, still unclear. A multicentre study is in progress to evaluate the effect of STN DBS earlier in the course of disease.⁸¹

Evaluation of suitability for surgery necessitates assessment of the patient's general physical condition (in particular, cardiopulmonary co-morbidities), psychiatric history, and cognitive function.⁸⁷ The decision to operate on any particular patient should be individualized, taking into account the level of disability, risk factors for complications, general life expectancy, and patient motivation. Contraindications include factors that increase either the operative risk or risk of device malfunction and those that may limit the effectiveness of DBS (Table 1). Although there is no specific age limit for DBS, older patients may have only modest motor improvement⁹⁴ and an increased incidence of cognitive dysfunction after STN stimulation. Dementia is a common problem in patients with Parkinson's disease, posing practical obstacles to achieving optimal outcome. During DBS insertion, they may be unable to tolerate and cooperate during the awake procedures typically used and, after surgery, they may have trouble accurately observing and communicating their symptoms, complicating the adjustment of DBS and medication. Additionally, patients with pre-existing dementia may experience worsening of their cognitive status after surgery.⁷⁹ A Mini Mental Status Exam (MMSE) score of <24 or a Mattis Dementia Rating Scale (MDRS) total score of <120 have been suggested as indicative of poor surgical candidacy.⁵

Various medical conditions can substantially increase the surgical risk. The risk of intracranial haemorrhage is increased by poorly controlled hypertension, coagulopathy, magnetic resonance imaging (MRI) evidence of small

vessel ischaemic disease, or extensive cerebral atrophy. Some clinicians require that a screening MRI of the brain be obtained before making a final decision on surgical candidacy.

If an 'awake' technique is contemplated for the electrode insertion procedure, the patient's ability to cooperate during the surgery should be evaluated. A history of claustrophobia or previous sedation failure warrants special attention. If MRI stereotactic planning will be carried out, it is imperative that a check is made for any previous ferromagnetic implant such as pacemaker, internal cardioverter-defibrillator (ICD), aneurysm clips, or cochlear implant. The feasibility of the planned surgical positioning should also be ascertained. Preoperative neurological status should be documented as there is a risk of deterioration after surgery. The medication regime needs to be carefully reviewed. Antiplatelet agents should be withheld if possible before and immediately after surgery. The need for chronic anticoagulation does not necessarily contraindicate surgery, but requires careful perioperative management of the coagulation status. As good hypertensive control is mandatory, antihypertensive medication should be continued. Patients and families should be given detailed verbal and written information about the procedure, the risks, and the potential benefits and also the limitations for any surgery. A clear description of what will happen and what patients will experience helps to clarify expectations. Questions must be fully addressed, and patients should be committed and motivated to work closely with the medical team.

Patients are usually admitted the evening before surgery. A standard preoperative fasting regimen is implemented. Anti-parkinsonism medication is withheld to render the patients in an 'off' drug state for intraoperative neurological testing. Premedication should be used judiciously. Benzodiazepines and other GABA agonists can interfere with patients' cooperation and tremor interpretation, and thus may be better avoided.

Surgical and anaesthetic techniques

Successful outcome with DBS relies on accurate insertion of electrodes. Target nuclei are localized using a combination of methods. Stereotactic MRI is useful as both STN and GPi are visible on MRI. Thalamic nuclei are not visible on standard MRI and thus require indirect targeting using atlas coordinates for pinpointing. On the day of surgery, a headframe is fitted on the patient's head either under regional nerve blockade or local anaesthetic infiltration to the pin sites. A combined supraorbital and greater occipital nerve block may be better than local s.c. infiltration for this.⁹² The procedure is usually well tolerated without sedation or general anaesthesia except for uncooperative patients or those with severe dystonia. With the stereotactic frame in place, MRI is performed to identify target nuclei and allow surgical planning. In patients with

Table 1 Contraindications to DBS

<i>Patients with increased operative risk or risk of device malfunction</i>
Patients with increased bleeding risk with brain penetration (e.g. coagulopathy, uncontrolled hypertension)
Patients who will be exposed to MRI using a full body RF coil, a receive-only head coil, or a head transmit coil that extends over the chest area
Patients who require the use of shortwave, microwave, or therapeutic ultrasound diathermy since diathermy energy can be transferred through the implanted system (or any of the separate implanted components)
<i>Patients with limited expected benefits from DBS</i>
Dementia and cognitive deficits
Patients who are unable to properly operate the neurostimulator
Patients with unsuccessful test stimulation

a contraindication to MRI assessment, computer tomography has been used.

After surgical planning is completed, the patient is brought to the operating theatre for electrode insertion, either unilaterally or bilaterally, as required. A burr hole procedure is performed, and a DBS electrode is passed down to the target area. To further fine tune the location of the electrode, a method known as microelectrode recording (MER) is frequently used. A microelectrode is passed along its trajectory towards the target nuclei (STN or GPi) as neuronal activities are simultaneously recorded. Specific brain structures can be identified based on their unique patterns of spontaneous neuronal firing. These neuronal discharges are viewed on an oscilloscope and played on an audio monitor since they are often best appreciated aurally. As the surgeon lowers the microelectrode in 50–100 μm increments, neurologists or neurophysiologists can make a scaled drawing of the cells encountered at each depth. This information then is superimposed on the brain atlas to assist in determining the electrode's exact location. Finally, intraoperative macrostimulation through the inserted deep brain electrode allows observation and confirmation of clinical improvement and side-effects in a conscious patient.

The anaesthetist's aim in deep brain electrode insertion is to: (i) provide optimal surgical conditions and patient comfort, (ii) facilitate intraoperative monitoring, including neuromonitoring for target localization, and (iii) rapidly diagnose and treat any complications. As MER and macrostimulation have become important means of target localization, questions have arisen regarding the effect of anaesthetic agents on them. Anaesthetics can alter neuronal firing frequency⁷⁸ and impair patient assessment. The use of gabaminergic sedative medication, even in small doses, has been shown to affect the quality of MERs.³⁵ Temporary modification and suppression of parkinsonian tremor has been reported with the use of propofol and remifentanyl.^{11 12 45} It is unclear which general anaesthetic agents allow the most effective MER. To date, only class IV data exist and there are no studies in the literature that have looked at their effects on MER data gathered specially in the context of DBS surgery for Parkinson's disease. Consequently, an 'awake' technique has obvious advantages and most centres avoid anaesthesia at least during the mapping phase in order to best detect cellular activity and movement-related responses to neurostimulation. Options include monitored anaesthetic care with or without sedation, analgesia, or both.⁹¹ In the operating theatre, the patient with the headframe attached is carefully positioned in the semi-sitting position with special attention to patient comfort. I.V. access is established, and the degree of intraoperative monitoring is largely dictated by the patient's co-morbidities. If the patient is conscious and cooperative, intraoperative electrical stimulation and assessment of clinical improvement is possible. Side-effects such as dysarthria, induction of dyskinesia,

sensory deficits, eye movement, muscle cramps, and cerebellar signs can also be readily observed.

In an 'awake' technique, the anaesthetist provides patient comfort and helps facilitate clinical testing. Withholding the anti-parkinson medications before surgery to optimize assessment can be unpleasant, with possible dystonia or even pain. During electrode placement, the patient's head is usually fixed to the stereotactic apparatus, and the inability to move for a prolonged period of time after the procedure has commenced can be distressing. Furthermore, macrostimulation and performance of various tasks during neurophysiological testing is also exhausting. Good pain control, meticulous patient positioning and padding, attention to thermal control, and avoidance of excessive fluid administration to prevent bladder distension are thus very important. Patients should be encouraged to void before surgery and urinary catheterization is undesirable, particularly in males where a sheath catheter is a good alternative. Attention to detail, good patient communication, reassurance, and motivation are all necessary.

Owing to the extreme sensitivity of subcortical areas of the brain to GABA receptor-mediated medications which may completely abolish MER and tremor, many physicians are reluctant to use sedative drugs, but many patients need sedation during the initial phase of surgery before neurophysiological testing. Ideally, the sedative effect should be readily reversible to allow patient cooperation. Benzodiazepines should be avoided. Propofol is popular and has been used extensively in neurosurgery, but its use in this setting is not straightforward. There is evidence that the pharmacokinetic behaviour of propofol in patients with Parkinson's disease may differ from that of the population from which the target-controlled infusion models were developed.²⁴ Attempts to use the bispectral index to titrate the level of sedation in propofol anaesthesia during DBS also did not seem to offer any advantage regarding times to arousal, total propofol consumption, and cardiopulmonary stability.⁸⁰ It is not yet clear whether propofol interferes with MER, but it is known to cause dyskinetic effects^{22 45} and abolish tremor,² which can hinder surgery and intraoperative testing. Another interesting, although unusual, problem is a tendency to occasionally cause sneezing. Although sneezing may seem harmless and readily resolves after propofol is stopped, it leads to patient discomfort, interferes with physiological mapping, and causes sudden increase in intracranial pressure (ICP) that could result in intracranial haemorrhage. An opioid (fentanyl or alfentanil), given minutes before propofol, eliminated the sneeze reflex in patients with periocular injections.⁸⁶

Dexmedetomidine reliably produces conscious sedation where the patient remains responsive and cooperative to verbal commands. This is mediated through activation of α_2 -adrenoreceptors in the locus coeruleus which is a major site of noradrenergic innervation in the central nervous system. It has been implicated as a key modulator for

a variety of critical brain functions, including arousal, sleep, and anxiety.⁹ This, together with minimal respiratory depression, makes it an attractive agent to use in 'awake' functional craniotomy. Low-dose infusion of this drug provides sedation from which patients are easily arousable and cooperative with verbal stimulation. Consequently, there are a number of reports on the successful use of the drug in this situation both alone^{1 7 53} and in combination with intermittent propofol.⁸⁴ More importantly, since patient cooperation is maintained, this allows cognitive tests to be successfully carried out.⁷⁵ Dexmedetomidine has also been shown to attenuate the haemodynamic and neuroendocrine responses to headpin insertion in patients undergoing craniotomy and significantly reduce the concomitant use of antihypertensive medication.^{76 90} It can theoretically decrease cerebral blood flow via direct α_2 -mediated vascular smooth muscle constriction and, indirectly, via effects on the intrinsic neural pathways modulating vascular effects. α_2 -Agonists have a more potent vasoconstrictor effect on the venous than on the arteriolar side of the cerebral vasculature and can, therefore, decrease ICP. There is, so far, no evidence of adverse effects on cerebral haemodynamics associated with its use, even in the setting of a compromised cerebral circulation. Dexmedetomidine does not ameliorate clinical signs of Parkinson's disease, such as tremor, rigidity, bradykinesia, or all. The pharmacologic profile of dexmedetomidine suggests that it may be an ideal sedative drug for deep brain stimulator (DBS) implantation.⁷⁵

Although dexmedetomidine has been successfully used in paediatric patients,³ general anaesthesia may be necessary in some and also in adults who cannot tolerate the awake technique, either due to concurrent psychiatric problems, discomfort due to off-period dystonia, or severe anxiety with associated hypertension. The decision to use general anaesthesia is best made before surgery, as the presence of a stereotactic headframe can complicate airway management. It is unclear, if the lack of intraoperative assessment of motor disability and dyskinesia in patients who receive general anaesthesia actually results in a difference in surgical outcome. A retrospective study⁵⁴ on the effect of general anaesthesia with i.v. propofol on the postoperative outcome of patients with Parkinson's disease who underwent bilateral placement of electrodes within the STN concluded that both techniques were feasible. However, the residual motor disability and intensity of stimulation appeared to be slightly higher in patients under general anaesthesia, implying that STN stimulation was less precise in the absence of intraoperative clinical assessment. This result was not reproduced in another small study comparing awake stereotactic STN stimulation with general anaesthesia,⁹⁵ which found no significant difference in the degree of postoperative improvement rate, postoperative S-E ADL scores, or the amplitude of STN stimulation. Both total i.v. anaesthesia and inhalation techniques have been used in patients unsuitable for a conscious technique.

Once the electrodes are inserted, the burr holes can be closed off. In some centres, the insertion of electrodes is routinely followed by radiological confirmation. Implantation of the pulse generator and internalization of electrodes can be performed either immediately or as second-stage surgery under general anaesthesia. Postoperative monitoring is necessary even in patients recovering from sedation. Patients should receive their usual anti-parkinsonian medication as soon as possible to avoid motor fluctuation that could cause profound deterioration in neurological function and respiratory muscle impairment.

Intraoperative anaesthetic-related complications

There is limited information on the incidence of intraoperative anaesthetic complications. A review of intraoperative anaesthetic-related complications in small series of 158 cases of deep brain ablation or stimulation under sedation with propofol or dexmedetomidine⁴¹ found that intraoperative events occurred in 6.96% of cases. These events included coughing, sneezing, aspiration, pulmonary oedema, combative behaviour and agitation/confusion, bronchospasm, angina, and intracranial haemorrhage. In a subsequent paper,⁴² the same group reviewed 258 electrode insertion procedures under a variety of techniques, including monitored anaesthetic care and general anaesthesia (Table 2). The most common neurological complications were intracranial haemorrhage and seizure. Age ≥ 64 yr was found to be an independent risk factor for complications during DBS. In another report of 172 DBS and six ablative procedures, intraoperative adverse events occurred in 16%.⁹¹ The most frequent were seizure (4.5%) and hypertension (3.9%). Rarer complications included decreased level of consciousness (2.2%), neurological deficit (0.6%), airway obstruction (1.1%), respiratory distress (1.1%), excessive pain (1.1%), nausea and vomiting (1.7%), and blood loss (0.6%).

Cardiovascular complications

Hypertension is a common intraoperative problem and can be related to poor preoperative control, patient distress, or anxiety during the procedure, or can be secondary to other events. Uncontrolled intraoperative hypertension is associated with intracranial bleeding. Arterial pressure control should be optimized before surgery with appropriate antihypertensive medication. During surgery, comfortable positioning and reassurance may ease distress. Dexmedetomidine sedation is advantageous⁷⁵ and, if necessary, beta, alpha, or calcium channel antagonists may be used judiciously after excluding other causes.

Venous air embolism (VAE) can occur at any time during the burr hole procedure both in the supine²¹ and in the semi-sitting positions.⁶¹ Partial airway obstruction from sedation and hypovolaemia from preoperative fasting may contribute to the development of this complication.

Table 2 Reported intraoperative complications of DBS insertion and their incidences

	Khatib and colleagues ⁴²	Venkatraghavan and colleagues ⁹¹	Kenney and colleagues ⁴⁰
Overall rate	11.6%	16%	
Neurological	3.60%		
Seizures	0.80%	4.5%	1.2%
Decreased level of consciousness/confusion	2.8%	2.2%	0.3%
Intracranial haemorrhage	2.8%		1.2%
Neurological deficit		0.6%	0.3%
Severe anxiety	0.40%		0.3%
Respiratory	1.60%, including respiratory arrest, airway obstruction, prolonged intubation, postoperative ARDS, nosocomial pneumonia, aspiration	1.1%	
Airway obstruction		1.1%	
Respiratory distress			
Cardiovascular	0.40%, including intraoperative/postoperative myocardial infarction, new onset angina, new onset congestive heart failure, and systemic arterial hypertension	3.9%	0.6%
Hypertension			0.3%
Chest pain			2.5%
Vasovagal response			1.2%
Syncope			0.3%
Arrhythmia			
Others			
Coughing/moaning/sneezing	1.20%		0.9%
Excessive pain		1.1%	
Nausea/vomiting		1.7%	
Blood loss		0.6%	

Cough is the most common initial symptom in awake patients.³³ Tachypnoea, hypoxaemia, chest discomfort, tachycardia, and hypotension may follow. Coughing and the associated deep inspiration can aggravate VAE and lead to dangerous increases in ICP. Preventive measures include limiting head elevation, adequate hydration, and careful surgical technique. Unfortunately, the usual recommended monitoring for air embolism such as transoesophageal echocardiography, end-tidal carbon dioxide, and precordial Doppler is either impractical, poorly tolerated, or inaccurate in an awake patient. Thus, clinical observation is very important. If VAE is suspected, patients should be placed immediately in the Trendelenburg position and surgeons asked to irrigate the surgical field, reapply bone wax to the exposed edges, seal the headpins, and cauterize any open vessels. If a central line is present, air aspiration can be attempted. Rapid i.v. fluid administration and inotrope support may be needed to maintain perfusion.⁶⁹

Neurological complications

Most seizures during intraoperative stimulation testing are self-limiting and focal in nature. A minority of patients with generalized tonic clonic seizures may require a benzodiazepine or propofol for termination. Anticonvulsants should always be readily available. A change in neurological status may present as confusion or speech deficit. The aetiology of this can be difficult to determine but includes patient fatigue, medication withdrawal, seizures, intracerebral bleeding, or pneumocephalus. Tension pneumocephalus³⁶ can arise from prolonged continuous leak of cerebrospinal fluid from cranial burr holes. Akinetic crisis is possible in severe Parkinson's disease, in which the patient is alert and aware but unable to

communicate. A high bispectral index value in an unresponsive patient may be a valuable clue in this case.⁸⁰

Haemorrhage¹⁰ can be a devastating complication resulting in permanent neurological deficit. Patient age, underlying pathology, and the number of MER penetrations were not related to the occurrence of haematoma. Interestingly, the brain target may have an effect on risk of haemorrhage: GPi was associated with the highest risk, STN was intermediate, and VL thalamus had the lowest risk. To prevent intracranial haemorrhage, patients need to be screened before operation for uncontrolled hypertension, coagulopathy, and recent use of antiplatelet medication. Intraoperative arterial pressure control, meticulous surgical haemostasis, and avoidance of coughing or sneezing are all important measures.

Regardless of the underlying cause, sudden onset neurological injury during or after surgery, if severe, may require immediate airway intervention and haemodynamic control. Urgent CT or MRI scanning may be warranted and, in some cases, the patient may need a craniotomy.

Stimulation-related side-effects

DBS itself may also have side-effects, including the induction of paraesthesia, involuntary movements, or cognitive and mood changes. Many of these can be prevented by accurate electrode insertion and terminated by adjusting the stimulation parameters.

Respiratory complications

Potential airway compromise is an important consideration with the conscious technique, especially with concomitant sedation. A stereotactic headframe will make airway access difficult. A gradual shift of the body with neck

flexion often occurs during surgery and may make talking difficult and even obstruct the airway. Sedation can further aggravate this situation. It is important to note that although dexmedetomidine is known to cause minimal respiratory depression in healthy volunteers and patients without respiratory disease, it can still produce upper airway obstruction. High-risk patients (for example, those with, or with features suggestive of, obstructive sleep apnoea) should be identified before operation. Anaesthetists should have a clear plan of how to tackle any airway difficulties during surgery. Prompt laryngeal mask airway insertion or repositioning can be life-saving.

Intraoperative stress, discomfort, and movement

The 'awake' technique may initially seem simple, but it is important to realize that the procedure can impose significant stress to patients. Patients have to tolerate the 'off-periods', stay immobile for a prolonged period in a strange environment, and perform various mental tasks. In a retrospective questionnaire interview of patients who underwent DBS electrode insertion, almost all recalled physical pain and psychological suffering during the procedure.¹⁴ A report of coronary vasospasm during DBS electrode insertion²⁹ could be a manifestation of this.

Besides sedation, other techniques have been implemented to improve patient tolerance. Intraoperative physiotherapy with mobilization, local massage, and respiratory exercises were found to alleviate pain and psychological stress.¹⁴ Intrathecal hydromorphone has been used to provide relief of intraoperative lower back pain.⁵⁰

Long-term complications

Surgical trials have now demonstrated the ability of DBS to improve the cardinal motor features of Parkinson's disease, including rigidity, tremor, bradykinesia, gait disturbances, and motor fluctuations. Bilateral STN stimulation in advanced Parkinson's disease has been shown to improve 'off' medication motor function, reduce time spent in the medication-off stage and medication requirements.⁴⁷ Long-term DBS, however, is not without complications. Hardware-related complications have been reported, including infection, migration or misplacement of the leads, lead fractures, and skin erosion.³⁰ Sudden inadvertent failure of the DBS system can lead to acute reappearance of akinetic parkinsonian symptoms and even parkinsonian crisis.³¹

Cognitive side-effects of DBS include mood changes,²⁸ depression,⁶ decreased working memory performance,⁵⁸ impulsivity,²⁶ and hallucinations,⁵⁷ especially those with a history of major depressive episodes before the procedure, should be evaluated and followed up closely for depression and referred for early treatment if necessary.

The battery life of the pulse generator is 2–5 yr and it is important to replace the unit before depletion to avoid emergency surgical replacement. Battery change typically

requires general anaesthesia. In this case, anti-parkinsonian medication should be continued before operation. Despite continuing these medications, patients can often be neurostimulator-dependent, since chronic stimulation of STN can decrease the short-duration response to levodopa.^{16 62} Therefore, pulse generators should be activated immediately after battery replacement to prevent akinesia that may complicate emergence.¹⁹

Anaesthetic considerations for patients with a DBS implant

As DBS is a treatment for refractory Parkinson's disease, candidates are usually elderly patients with a long history of the disease and its complications. The anaesthetic management of patients with Parkinson's disease has been discussed,⁶⁴ but it is important to add that one should specifically look for the history of DBS in patients with severe Parkinson's disease as they may not be able to volunteer the history due to communication difficulties. A preoperative X-ray examination to trace the position of the leads usually reveals the true nature of any implantable device palpated over the chest or abdomen.

There is little information on the management of patients with a DBS who present for surgery. From experience with other implantable devices such as cardiac pacemakers, electrical devices may mutually interfere, and device–device or device–programmer interactions may occur. DBS can interfere with domestic³⁸ and medical equipment such as electrocardiography (ECG), slow wave diathermy, electrocautery, peripheral nerve stimulators, pacemakers, external and implantable cardioverters and defibrillators. Furthermore, the safety of the DBS device in patients undergoing MRI investigation and electroconvulsive therapy (ECT) is a concern. Some of these interactions are summarized in Table 3.

Electrocardiography

DBS is known to produce ECG artifacts and may make interpretation difficult.⁵⁵ Deactivating the DBS system before ECG acquisition can remove such interference, but can sometimes lead to recurrence of severe tremor with electromyographic activity sufficient to affect ECG recording, significant patient discomfort, and inconvenience. Patients may take up to 1 h to regain the ability to walk safely after even brief inactivation of DBS.

The degree of interference is affected by the polarity of DBS. There are two types. In unipolar stimulation, one, two, three, or four electrodes of the quadripolar lead act as the cathode and the neurostimulator case behaves as the anode. The electrode(s) activated provides a radial current diffusion covering a spherical space around the stimulating electrode. In bipolar stimulation, one, two, or three electrodes of the quadripolar lead act as the anode and the remaining electrode(s) act as the cathode. The

Table 3 Summary of devices that may potentially interfere with a neurostimulator

Device	Potential interactions	Precaution(s)
Electrocardiography	DBS may directly produce ECG artifacts	Bipolar stimulation of neurostimulator may minimize ECG artifacts
Short wave diathermy	Severe tremor after DBS deactivation can lead to ECG artifacts Induces heating of DBS electrodes leading to brain damage	Use of short wave diathermy is contraindicated
Phaecoemulsification	No interference reported	Switching off pulse generator may decrease damage to neurostimulator
Electrocautery	Potential thermal injury to brain Reprogramming and damage of DBS	Use of battery-operated heat-generating pulse generator Use the lowest diathermy energy in short irregular pulses Re-interrogate DBS system after surgery
Pacemakers	Cross-interference between the two devices	Bipolar DBS and bipolar pacemaker stimulation can decrease interference Interrogation of the two devices before and after surgery
External defibrillator and ICD	Tissue heating around the brain target Reprogramming and damaging of DBS	Position external defibrillator paddle as far away from neurostimulator as possible, perpendicular to the lead system Bipolar DBS+ICD electrodes can minimize interference Interrogation of DBS+ICD device after defibrillation
Peripheral nerve stimulator	No interference reported	Place ECT electrodes away from DBS hardware
Electroconvulsive therapy (ECT)	No interference reported	Follow safety MRI guidelines
Magnetic resonance imaging	Electrode heating leading to brain damage DBS reprogramming and damage MRI image artifacts	Limit MRI exposure

neurostimulator case is not active. Bipolar stimulation creates a narrower and more focused current field with less diffusion into adjacent structures, thus producing far less electrical artifact than monopolar DBS. In the event that ECG diagnosis is required in someone whose DBS cannot be turned off, one can consider either increasing their medication to support them while the DBS is turned off electively or switching the DBS setting to bipolar with appropriate selection of parameters.^{17 27}

Short wave diathermy

Short wave (microwave and ultrasound) diathermy is commonly used to provide tissue heating for muscle or joint conditions. There have been two case reports of diathermy causing significant brain damage in patients with DBS, with one death.^{65 77} In one case, pulse-modulated radiofrequency diathermy was applied to the maxilla and this resulted in permanent brain damage. The mechanism of interaction is believed to be a result of induction of a radio-frequency current and heating of the electrodes. An *in vitro* study has suggested that, with typical diathermy power levels, heating may occur at a rate exceeding $2.54^{\circ}\text{C s}^{-1}$ at the tip of the electrode.⁷⁷ The manufacturer advises against the use of any short wave diathermy in patients with DBS.

Phaecoemulsification

Phaecoemulsification for cataract surgery has been successfully performed in patients with DBS without interference.^{68 70}

Electrocautery

Potential problems include thermal injury to brain tissue, reprogramming, and damage of the device and its leads. Manufacturer recommendation and literature review^{56 59 93} encourages preoperative pulse generator adjustment and postoperative interrogation. If the patient can tolerate the tremor and it does not interfere with surgery, the pulse generator can be safely turned off before the operation. Bipolar electrocautery may reduce the potential for electromagnetic interference. If a monopolar device is necessary, haemostasis can be obtained with the aid of a battery-operated heat-generating handheld electrocautery device or with the use of a dispersive plate to direct the current away from the pulse generator and lead system. Surgeons should be reminded to use the lowest diathermy energy possible in short irregular bursts.

Pacemakers

Previously DBS was considered a contraindication in patients with cardiac pacemakers. Although the two devices use a different range of frequencies, cardiac pacemakers and the pulse generators used for DBS are both susceptible to external electromagnetic interference. The worry is that DBS systems might impair pacemakers' ability to sense and pace the heart or, conversely, cardiac pacemakers could affect the operation of neurostimulators. The presence of a cardiac pacemaker also precludes the use of MRI for surgical planning and postoperative

electrode localization in potential candidates for DBS. Finally, both pacemakers and neurostimulators share common implantation sites, and the presence of one device would necessitate a modification of the implantation site for the other.

There have been a few reports on the simultaneous use of cardiac pacemakers and DBS systems.⁶⁷ It was found that a bipolar configuration of DBS and pacemaker is less susceptible to interaction, a result consistent with experience with spinal cord stimulators in patients with pacemakers.⁷³ Patients must be prepared and motivated to tolerate thorough neurological and cardiac testing. Careful preoperative simulation may be useful to identify significant interference between the two systems.

If a patient requiring DBS has a pacemaker *in situ* before neurostimulator implantation, the usual anaesthetic considerations pertaining to the perioperative management of patients with cardiac rhythm devices apply.⁷¹ Before operation, cardiac pacemaker configuration should be optimized and bipolar mode for sensing and stimulation is preferable to minimize interference. MRI is contraindicated, but stereotactic CT, intraoperative MER, and test stimulation are still possible.⁸² As the quadripolar lead is inserted, the ECG should be observed for interference during test stimulation. Pulse generators should be implanted away from cardiac pacemakers to minimize interference between devices during telemetry reprogramming. The initial programming sessions should be done cautiously under cardiac monitoring to detect any cross-talk. Although bipolar DBS and bipolar pacemaker mode offers the least chance of interference, bipolar sensing pacemaker with unipolar DBS mode has also been reported as feasible.¹³ With the current evidence, it seems that, with appropriate planning, it can be safe for patients to receive both cardiac pacemakers and DBS devices for treatment of concomitant disorders.

External defibrillator and internal cardioverter-defibrillator

Safe use of external defibrillators on patients with neurostimulation systems has not been established. Obviously, if a patient with a neurostimulator requires external defibrillation, the primary consideration should be patient survival and the presence of a neurostimulator should not delay treatment. Cardioversion has been reported as causing lesions around the target area in a patient with DBS, whose IPG was implanted s.c. in the anterior chest wall.¹³ A study in pigs, however, did not find any histological evidence of cerebral thermal injury after repeated external cardiac defibrillation.⁴⁴ Defibrillation can also impair subsequent DBS function. The manufacturer recommends positioning the paddles as far from the neurostimulator as possible, perpendicular to the implanted neurostimulator-lead system, and using the lowest clinically appropriate energy output. The

neurostimulator should be checked carefully after any defibrillation.

There have been some concerns over the use of DBS with ICD. A high frequency of neurostimulation can result in the ICD undersensing or inappropriately discharging. Conversely, ICD discharges can interfere with DBS function and lead to inadvertent reprogramming. There are several case reports of successful ICD insertion in patients with a DBS system *in situ*.^{66 74 88} It is necessary to test both devices repeatedly over a wide range of settings to ensure the absence of any device-device interference. Bipolar ICD and DBS systems appear to be safer. Single-coil ICD leads have a true bipolar electrode at the tip and facilitate better sensing at the endocardial interface, but dual-coil leads increase the surface area of detection and can increase the likelihood of inappropriate sensing. Since both DBS and ICD generators can be affected by placement of a magnet over them, patients should not use a magnet to adjust the DBS device. The telemetric programmers of ICD and DBS pulse generators should be kept as far away as possible. Telemetric ICD programmers are able to deactivate the pulse generator of DBS, and the resulting patient tremor ('pseudoventricular tachycardia') has the potential to set off the defibrillator.^{43 49} Should defibrillation occur, interrogation of the DBS device would be necessary to ensure its proper function.

Peripheral nerve stimulators

Successful use of nerve stimulator-guided supraclavicular block has been reported in a patient with DBS who had a dislocated shoulder.⁶⁰ The DBS was interrogated to ensure proper function before and after the procedure. Stimulation wires were palpated to make sure they were far away from the needle insertion site. No interference between the two devices was noted.

Electroconvulsive therapy

The prevalence of depression in patients with Parkinson's disease has been estimated to be as high as 31% and may be more frequent after STN DBS.⁶⁰ In many cases, symptoms occur within 1 month of starting DBS and resolve either without specific therapy or with minor stimulator adjustments. However, occasionally, it can be refractory and can result in morbidity and even mortality.^{23 34} ECT is a recognized treatment for severe, debilitating depression. Although the energy used in ECT is much less than cardioversion, its safety in patients with a neurostimulator is not clear. Electrical discharges can induce radiofrequency currents in the DBS electrodes, leading to electrode heating and permanent damage to the surrounding brain tissue. The motor activity induced by seizures could also potentially shift the position of electrodes.

Recent case reports of successful ECT in patients with a neurostimulator suggest that ECT can be safe in these patients.^{4 15 63} In these cases, the neurostimulator was

switched off before administration of ECT and the ECT electrodes were positioned away from the edge of the s.c. tunnelled cable. Seizure activity did not seem to be modified by DBS, and comparison of pre- and post-ECT images revealed no shift in electrodes' position.

It seems, therefore, that if the depression is severe or refractory to anti-depressant pharmacotherapy, ECT may be a safe and effective option. Care in placing the ECT electrodes, switching the DBS off before ECT, and limiting the number of ECT sessions should be considered.

Magnetic resonance imaging

The use of MRI can be essential for patients with DBS, aiding in the diagnosis of intracranial haemorrhage and assessing disease progression. MRI produces three types of electromagnetic fields that may interact with implanted neurostimulation systems: a static magnetic field which is always on, a low-frequency pulsed magnetic (gradient) field that is present only during a scan, and a radiofrequency field produced by a variety of transmission radiofrequency coils. The hazards are the result of one or a combination of these three components and include force and torque effects on metallic components, heating effect at the electrode, magnetic field-induced stimulation in leads, reprogramming of neurostimulators, and image distortions of MRI images. Of these, the heating effect at the electrode is the most important and problematic safety issue because of its potentially serious consequences. The amount of heat generated in a DBS system depends on multiple factors, including the specific electrical characteristics of the implanted device, the field strength of the magnetic resonance system, the orientation of the implantable device relative to the source of radiofrequency energy, the type of radiofrequency coil used, the location of the target MRI image, and the total amount of radiofrequency energy delivered. The amount of radiofrequency absorbed by the body is related to the subject's body weight and can be approximated by calculating the specific absorption rate (SAR). *In vitro* studies have indicated that the degree of heating is linearly related to SAR,²⁵ and the lead tip is the most critical part in terms of heat generation.^{39–72} Similar to spinal neurostimulator systems,²⁰ the DBS appears to be compatible with MRI procedures under certain controlled situations. The manufacturer has published a MRI guideline for their neurostimulator system⁸⁹ (Appendix). Deviation from these safety recommendations can have serious consequences. A 73-yr-old patient with bilateral implanted DBS electrodes who underwent an MRI procedure of the head developed dystonic and ballistic movement of the left leg immediately afterwards.⁸⁵ This scan was performed with a transmit/receive head coil on a 1.0 T MRI system with the leads externalized and disconnected from the pulse generators. The authors speculated that this adverse side-effect was a result of induced current in the implanted leads that

caused heating and subsequent thermal tissue damage. The second incident occurred where a patient with an abdominally implanted DBS developed serious, permanent neurological injury after MRI of the lumbar spine to evaluate back pain.³² The MRI scan sequences were performed with a 1.0 T system. Immediate CT scan revealed haemorrhage surrounding the left electrode. Retrospectively, the imaging parameters and patient weight were re-examined, and SAR head values of up to 3.92 W kg^{-1} had been given.

These two incidents prompted the FDA to issue a public health notification and the manufacturer to revise the recommendation to limit the applied head SAR to 0.1 W kg^{-1} , a substantial reduction from the previously recommended 0.4 W kg^{-1} .⁸⁹ This cut-off value of SAR and the reliability of SAR as an index of heating were recently questioned by Larson and colleagues in their large series.⁴⁶ Previously, it was mistakenly assumed that if an implant is safe for a patient undergoing an MRI examination at 1.5 T, the use of an MRI system operating at lower field strength will also be safe. It is clear now that extrapolating safety information defined for a particular static magnetic field to a lower-field-strength scanner is inappropriate, since MRI-related heating is not dependent on the field strength of the MRI system alone. There is a need for caution and safety guidelines when considering imaging that is necessary for the patient. More comprehensive studies will be needed to ensure the MR safety of neurostimulation systems.⁸³

Effect of anticoagulation in patients with DBS

Although there are numerous studies on the incidence of intracerebral haemorrhage immediately after insertion of DBS electrodes, the risk of subsequent anticoagulation is unknown. It is not known whether long-term anticoagulation is a relative contraindication in patients with DBS. Anticoagulation has been temporarily administered to patients with DBS for cardiac conditions.⁶⁷ There is a report of a patient with DBS who underwent successful aortic valve replacement for tight aortic stenosis.¹⁸ In this case, a biological prosthetic aortic valve was implanted to avoid the need for anticoagulation. To reduce the risk for coagulopathy and excessive bleeding after cardiopulmonary bypass, a high-dose aprotinin protocol was also implemented. No intracranial bleeding was reported in this case.

Conclusion

DBS is an attractive treatment option for severe and refractory Parkinson's disease and other illnesses such as essential tremor, intractable epilepsy, and chronic pain. In view of the ageing population, it is likely we will encounter more patients for DBS implantation or who already have a system implanted. DBS implantation surgery using an

awake or sedative technique is currently most popular as it facilitates intraoperative MER and neurological testing, but the technique is far from simple and perioperative complications do occur. Dexmedetomidine appears to be the most suitable drug for sedation.

Care is required in the management of patients who already have a DBS implanted, as it can interfere with other monitoring and therapeutic devices, sometimes with severe consequences. However, with good preparation, it seems that serious complications are uncommon and avoidable.

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Appendix

MRI/neurostimulator exposure guidelines

(apply to Activa Systems comprising combinations of the following components:

Neurostimulator Models: Itrel II 7424, Soletra 7426, Kinetra 7428; Lead Extension Models: 7495, 7482; Lead Models: DBS 3387, 3389)

Supervision

A responsible individual such as an MRI radiologist or MRI physicist must assure these procedures are followed. If the MRI is operated by an MRI technician, it is strongly recommended the responsible individual verifies that the MRI recommendations are followed.

Preparation

Do the following before performing an MRI examination on an Activa patient:

- (1) inform the patient of the risks of undergoing an MRI;
- (2) check if the patient has any other implants or conditions that would prohibit or contraindicate an MRI examination. Do not conduct an MRI examination if any are found.
- (3) verify that all proposed MRI examination parameters comply with the 'MRI Operation Settings'. If not, the parameters must be modified to meet these requirements. If this cannot be done, do not perform an MRI.
- (4) If the patient has implanted leads but does not have an implanted neurostimulator, perform the following steps:
 - (a) wrap the external portion of the leads/percutaneous extensions with insulating material;
 - (b) keep the external portion of the leads/percutaneous extensions out of contact with the patient;

- (c) keep the external leads/percutaneous extensions straight, with no loops, and running down the centre of the head coil.
- (5) If the patient has an implanted neurostimulator, perform the following steps:
- (a) review the neurostimulator with a clinician programmer and print out a copy of the programmed parameters for reference;
 - (b) test for possible open circuits by measuring impedance and battery current on all electrodes in unipolar mode (Table A1a). If an open circuit is suspected, obtain an X-ray to identify whether the open circuit is caused by a broken lead wire. If a broken lead wire is found, do not perform an MRI.
 - (c) If the Activa System is functioning properly and no broken lead wires are found, program the neurostimulator to the settings provided in Table A1b.

Table A1a Measurement values indicating possible open circuits. Warning: An MRI procedure should not be performed in a patient with an Activa System that has a broken lead wire because higher than normal heating may occur at the break or the lead electrodes which can cause thermal lesions. These lesions may result in coma, paralysis, or death

Neurostimulator	Impedance (Ω)	Battery current (μ A)
Itrel II Model 7424	>2000	<10
Soletra Model 7426	>2000	<10
Kinetra Model 7428	>4000	<15

Table A1b Recommended neurostimulator settings for MRI

Parameter	Setting
Stimulation output	OFF (all programs)
Stimulation mode	Bipolar (all programs)
Amplitude	0 V (all programs)
Magnetic (reed) switch	Disabled (Kinetra Model 7428 only)
Other parameters	Do not change

MRI operation settings

Before the MRI examination, a responsible individual such as an MRI radiologist or MRI physicist must assure the examination will be conducted according to the following MRI requirements. If standard MRI pulse sequences will be used, they must meet these requirements. If they do not, the pulse parameters must be adjusted so that they comply with these requirements.

Warning

In vitro testing has shown that exposure of the Activa System to MRI under conditions other than described in this guideline can induce excessive heating at the lead electrodes or at breaks in the lead to cause lesions. These lesions may result in coma, paralysis, or death.

- Use only a 1.5 T horizontal bore MRI (do not use open sided or other field strength MRI systems).
- Use only a transmit/receive head coil.

Contraindication

Implantation of an Activa Brain Stimulation System is contraindicated for patients who will be exposed to MRI using a full body transmit radio-frequency (RF) coil, a receive-only head coil, or a head transmit coil that extends over the chest area. Performing MRI with this equipment can cause tissue lesions from component heating, especially at the lead electrodes, resulting in serious and permanent injury including coma, paralysis, or death.

- Enter the correct patient weight into the MRI console to assure the head SAR is estimated correctly.
- Use MRI examination parameters that limit the displayed average head SAR to 1/10 (0.1) W kg⁻¹ or less for all RF pulse sequences unless the applied SAR is known. If known, an applied SAR up to 1/10 (0.1) W kg⁻¹ may be used.

Warnings

- Ensure the SAR value is the value for head SAR. Some MRI systems may only display SAR, whole body SAR, or local body SAR. Make sure the value being limited is for head SAR. Excessive heating may occur if the wrong SAR value is used.
- If MRI parameters must be manually adjusted after the initial automatic MRI prescan, do not make any adjustments that will increase the SAR value. Some MRI machines may not automatically update the displayed SAR value, if manual adjustments are made. This may lead to higher than expected temperature increases in the Activa System, particularly at the lead electrodes.
- Limit the gradient dB/dt field to 20 T s⁻¹ or less.

Note: The recommendations provided are based on *in vitro* testing and should result in a safe MRI examination of a patient with an implanted Medtronic Activa System. However, due to the many variables that affect safety, Medtronic cannot absolutely ensure safety or that the neurostimulator will not be damaged. The user of this information assumes full responsibility for the consequences of conducting an MRI examination on a patient with an implanted Activa System.

Before the MRI examination

Before the scan examination, the responsible individual must verify the MRI examination parameters comply with these guidelines.

- Patients with implanted Activa Systems should be informed of the risks of undergoing an MRI.
- If possible, do not use sedation, so the patient can inform the MRI operator of any heating, discomfort, or other problems.

- Instruct the patient to immediately inform the MRI operator if any discomfort, stimulation, shocking, or heating occurs during the examination.

During the MRI examination

- Monitor the patient both visually and audibly. Check the patient between each imaging sequence. Discontinue the MRI examination immediately if the patient is unable to respond to questions or reports any problems.
- Conduct the examination using only the MRI pulse sequence that the MRI radiologist or physicist has confirmed meets the MRI requirements above.

Post-MRI examination review

- Verify that the patient is feeling normal.
- Verify that the neurostimulator is functional.
- Reprogram the neurostimulator to pre-MRI settings.

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