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REVIEW ARTICLE/BRIEF REVIEW

Anesthesia considerations for patients with an implanted deep brain stimulator undergoing surgery: a review and update

Considérations anesthésiques pour les patients chirurgicaux chez lesquels un dispositif de stimulation cérébrale profonde est implanté: compte rendu et mise à jour

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Abstract

Purpose *Deep brain stimulation (DBS) can be an effective treatment option for patients with essential tremor and Parkinson's disease. This review provides an overview on the functioning of neurostimulators and recent advances in this technology and presents an updated guide on the anesthetic management of patients with an implanted neurostimulator undergoing surgery or medical intervention.*

Source *A search was conducted on MEDLINE®, EMBASE™, and Cochrane Database of Systematic Reviews databases to identify studies published in English from 1974 to December 2015. Our search also included relevant and available incident reports from the manufacturers, Health Canada, the United States Food and Drug Administration, and the European Medicines Agency. Thirty of 232 articles identified were found to be relevant to this review.*

Principal findings *Deep brain stimulation systems now offer a range of options, including pulse generators with dual-channel capabilities, rechargeable batteries, and current-control modes. Preoperatively, the anesthesiologist should ascertain the indications for DBS therapy, identify the type of device implanted, and consult a DBS specialist for specific precautions and device management. The major perioperative concern is the potential for interactions with the medical device resulting in patient morbidity. Neurostimulators should be turned off intraoperatively to minimize electromagnetic interference, and precautions should be taken when using electrosurgical equipment. Following surgery, the device should be turned on and checked by a DBS specialist.*

Conclusion *The anesthesiologist plays an important role to ensure a safe operating environment for patients with an implanted DBS device. Pertinent issues include identifying the type of device, involving a DBS-trained physician, turning off the device intraoperatively, implementing precautions when using electrosurgical equipment, and checking the device postoperatively.*

Résumé

Objectif *La stimulation cérébrale profonde (SCP) peut constituer une option thérapeutique efficace pour les patients atteints de tremblement essentiel ou de la maladie de Parkinson. Ce compte rendu propose un aperçu du fonctionnement des neurostimulateurs et des progrès récents de cette technologie et présente un guide mis à jour de la prise en charge anesthésique des patients ayant un neurostimulateur implanté et devant subir une chirurgie ou une intervention médicale.*

Source *Nous avons réalisé des recherches dans les bases de données MEDLINE®, EMBASE™ et la base de données Cochrane de comptes rendus méthodiques (Cochrane Database of Systematic Reviews) afin d'identifier les études publiées en anglais entre 1974 et décembre 2015. Nos recherches ont également inclus les rapports d'incident pertinents et disponibles des fabricants, de Santé Canada, de la FDA (Food and Drug Administration)*

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américaine, et de l'Agence européenne des médicaments. Au total, trente des 232 articles identifiés ont été jugés pertinents à ce compte rendu.

Constatations principales *Les dispositifs de stimulation cérébrale profonde proposent aujourd'hui une vaste gamme d'options, notamment des générateurs d'impulsions capables d'utiliser deux canaux, des piles rechargeables, et des modes de contrôle du courant. Avant l'opération, l'anesthésiologiste devrait vérifier les indications thérapeutiques d'une SCP, identifier le type de dispositif implanté, et consulter un spécialiste de la SCP pour connaître les précautions spécifiques et la prise en charge du système. La préoccupation périopératoire majeure est le potentiel d'interactions avec le dispositif médical, ce qui pourrait provoquer une morbidité pour le patient. Les neurostimulateurs devraient être éteints pendant l'opération afin de minimiser les interférences électromagnétiques, et des précautions doivent être prises lors de l'utilisation de matériel électrochirurgical. Après la chirurgie, le dispositif devrait être rallumé et vérifié par un spécialiste de la SCP.*

Conclusion *L'anesthésiologiste joue un rôle important pour garantir un environnement opératoire sécuritaire pour les patients munis d'un dispositif de SCP implanté. Les questions pertinentes sont l'identification du type de dispositif, la consultation d'un médecin formé en SCP, la mise hors tension du dispositif pendant l'opération, la mise en œuvre de précautions lors du recours à du matériel électrochirurgical, et la vérification postopératoire du dispositif.*

Deep brain stimulation (DBS) is an effective treatment option for patients with a movement disorder, and an increasing number of patients with essential tremor or Parkinson's disease are being treated with this technology.[1] Therefore, the anesthesiologist will increasingly encounter patients with an implanted DBS system in the operating room and interventional radiology suites. Most anesthesiologists are familiar with the anesthetic management of patients with a cardiac implantable electronic device, and there are established practice guidelines from various organizations.[2,3] Nevertheless, there is a paucity of information on the anesthetic management of patients with an implanted neurostimulator, and most data on patient management derive from isolated case reports and available manufacturer information sheets. The purpose of this review is to provide a brief overview on DBS systems and present an up-to-date guide on the anesthetic management of patients with an implanted DBS device.

Deep brain stimulation—a primer for anesthesiologists

Indications

The use of DBS was first reported in 1987 in patients with tremor-predominant Parkinson's disease.[4] This technology revolutionized the treatment of patients with a movement disorder such as essential tremor, dystonia, and Parkinson's disease. The advantages of DBS over ablative surgeries (e.g., thalamotomy and pallidotomy) include its reversibility, adjustability, and safety profile. To date, the use of DBS has been approved by the United States Food and Drug Administration for treatment of patients with Parkinson's disease or essential tremor as well as patients under a humanitarian device exemption for dystonia or obsessive compulsive disorder.[5,6] Ongoing research supports the potential benefit of DBS in a range of disorders, including epilepsy, chronic pain, major depression, anorexia nervosa, and Alzheimer's disease.[5-7]

Deep brain stimulation system

Current DBS systems consist of one or more cylindrical electrodes (each housing multiple contacts) implanted at pre-planned targets within the brain parenchyma, an implantable pulse generator (IPG) inserted most commonly below the clavicle, and extension wires that connect the electrodes to the IPG. This system delivers stimulation to the electrodes (unilaterally or bilaterally) at a set amplitude, pulse width, and frequency. Patients with a bilateral electrode insertion may have two implanted IPGs or a single IPG with dual-channel capabilities, allowing independent control of both electrodes from a single generator. After insertion, the treating physician can program the system wirelessly with a handheld device. The clinician and patient have separate programming devices. Depending on the manufacturer, the patient's programmer allows the patient to perform basic functions, such as checking the lifespan of the neurostimulator and programmer battery, turning the neurostimulator on or off, and adjusting therapy settings within the limits set by the physician. In addition to these functions, the physician's programmer enables the clinician to enter and check the patient's profile and system information, program stimulation parameters, perform electrode impedance measurements, and set patient control limits. Older neurostimulator models, such as Medtronic Kinetra® Model 7428 and Soletra® Model 7426 (Medtronic, Minneapolis, MN, USA), have magnetically controlled switches that can be turned on or off with an external magnet, but newer models from Medtronic Inc. and other manufacturers do not turn off with an external magnet. Medtronic Inc. was previously the sole manufacturer of

neurostimulators, but in recent years, two other companies, St Jude Medical Inc and Boston Scientific Corporation, have developed DBS systems that are approved for clinical use.

Advances in DBS system technology

The DBS system can be voltage or current controlled. Older DBS systems were voltage controlled, and it is postulated that they delivered variable amounts of current due to electrochemical-induced changes in electrode impedance at the brain-electrode interface.[8] Newer current-controlled systems provide constant current stimulation, which may be more clinically efficacious compared with the older voltage-controlled systems.[9] In addition, DBS devices can be programmed to provide unipolar or bipolar stimulation. In unipolar mode, the active electrode is set as the cathode and the IPG case is set as the anode. In contrast, bipolar stimulation is produced when at least one of the four electrodes in the DBS system functions as the cathode and at least another one of the four functions as the anode. Newer DBS systems also provide the option to implant rechargeable IPGs, which prolongs their lifespan and results in fewer surgical interventions for replacing the IPG.[10,11]

Differences between the DBS and cardiac implantable electronic devices (CIED)

Cardiac implantable electronic devices include cardiac pacemakers and implantable cardioverter-defibrillators (ICD). The cardiac pacemaker system is generally more complex and advanced compared with a neurostimulator. The basic components of cardiac pacemakers are similar to the DBS system in that the pacemaker consists of electrodes (one to three leads) implanted in the endocardium or epicardium, an energy source (lithium-iodine battery), and wires that connect the leads to the battery. The primary function of the cardiac pacemaker is to generate a threshold pacing current to evoke cardiac muscle depolarization. The pacing threshold is determined by the device's programmed amplitude and pulse width settings and lead impedance.[12] Table 1 summarizes the pertinent differences that exist between a DBS and CIED.

Anesthetic considerations for patients with a DBS device *in situ*

Literature search

MEDLINE®, EMBASE™, and Cochrane Database of Systematic Reviews databases were searched to identify human studies published in English from 1974 to December 2015. Keywords used for this search include "deep brain stimulation", "implantable neurostimulators", "anesthesiology", "anesthesia", "neurosurgery", and "neurosurgical procedures". Thirty of the 232 articles initially identified were considered as being relevant to this review. Additional articles of relevance were identified from references cited in the identified literature. The literature search also included product information and available incident reports from Medtronic Inc., St Jude Medical, Inc., Boston Scientific Corporation, Health Canada, the United States Food and Drug Administration, and the European Medicines Agency. Table 2 summarizes the available literature on patients with a DBS device *in situ* who underwent various surgical and non-surgical procedures.

Anesthetic considerations

The major considerations in the perioperative treatment of patients with an implanted DBS system include the medical condition that warranted DBS insertion, potential for electromagnetic interference with the DBS system (e.g., electrocautery use and magnetic resonance imaging [MRI]), and postoperative evaluation of the patient and device. Table 3 outlines the perioperative anesthetic management of patients with an implanted DBS device undergoing surgery.

Preoperative considerations

In the preoperative setting, patients with an implanted DBS device scheduled for elective surgery should be seen in a preanesthesia assessment clinic, particularly as their underlying medical condition may warrant special considerations. For example, patients with Parkinson's disease, dystonia, or epilepsy have their own unique perioperative anesthetic considerations.[13,14]

Intraoperative considerations

Device interactions with the DBS system Intraoperatively, there is potential for the DBS system to interact with multiple medical devices, including diathermy, electrocautery, peripheral nerve stimulator, external cardiac defibrillator, therapeutic ultrasound, and laser equipment. Some of these devices produce varying degrees of electromagnetic interference that potentially affect the functioning of the neurostimulator, which in turn may result in patient harm. For example, electromagnetic interference can cause direct damage to the IPG, resulting in suppressed or increased stimulation or complete cessation of output.[10] Alternatively, induced current can pass through the IPG along the

Table 1 Differences between neurostimulators and cardiac implantable electronic devices

Characteristics	Neurostimulators	Cardiac implantable electronic devices (CIEDs)
Technical aspects		
a) Mechanism of action	a) Provide constant stimulation to target region	a) Adjustable program parameters based on electrical feedback from the leads
b) Frequency of stimulation	b) Higher (above 100 Hz)[63]	b) Lower
c) Current consumption	c) Higher (up to 25 mA) due to higher stimulation frequency. More frequent battery changes	c) Lower (approximately 10 μA)[10,12]
d) Turn off	d) Can be turned off to conserve battery life	d) Cannot be turned off
Effect of electromagnetic interference (EMI)	EMI may potentially affect function of neurostimulators and cause harm to the patient	EMI may potentially affect function of CIEDs and cause harm to the patient
Electrocautery	Precautions for use of electrocautery are discussed in Table 3	Precautions for electrocautery similar to that for neurostimulators with the exception that pacemakers cannot be turned off[2]
		Pacemakers should be switched to asynchronous pacing mode in pacemaker-dependent patients, and special algorithms should be turned off[2]
		Antitachyarrhythmia function on implantable cardioverter-defibrillators (ICD) should be suspended[2]
Magnetic resonance imaging (MRI)		Generally contraindicated
	Safe under specified conditions. Discussed further in the section on MRI	
Effect of external magnet	Can be used to turn off older neurostimulator models with magnetically controlled switches	Response of pacemakers to magnet application is variable depending on manufacturer, programming, and remaining battery life. Some pacemakers have no magnet response[2]
	Newer neurostimulator models are controlled with remote programmers	Magnet application on ICDs often suspends the antitachyarrhythmia function. Some ICDs have no magnet response and some are permanently disabled by magnets[2]
		Generally advisable to adjust pacemaker programming and suspend antitachyarrhythmia function of ICDs with a programmer[2]
Effect of device malfunction	Not life threatening	Life threatening. May require temporary pacing (transcutaneous or transvenous) or external defibrillation/cardioversion.

conducting wires, leading to heat generation at the tip of the DBS electrodes and ensuing damage to brain tissue in proximity of the electrodes.[15,16] Even when the neurostimulator is turned off, the metallic case, leads, and DBS unit remain conductive, allowing current to pass through. Table 4 summarizes these potential device interactions and the appropriate management for each interaction.

Diathermy, electrocautery, and electrosurgery: The terms diathermy, electrocautery, and electrosurgery are often used interchangeably, but differences exist between these terms. Specifically, diathermy refers to generation of heat within body tissue from a high frequency electromagnetic current. Physiotherapists, chiropractors, and sports injury therapists often use this technique for muscle relaxation and treatment of joint conditions.[17] Electrocautery refers to generation of heat within a metal wire electrode by passing current through it; this current does not usually enter the patient's body.[17] Electrocautery is usually used for tissue hemostasis or varying degrees of tissue destruction, such as removal of benign skin lesions. Electrosurgery is commonly used during surgery, and it encompasses a range of modalities utilizing high frequency alternating current at the electrode tip to cut, coagulate, or desiccate tissue.[17] In general, electrosurgical units have two different electrode configurations, unipolar and bipolar mode. In unipolar mode, the current generated through the electrode

Table 2 Case reports or case series on procedures performed in patients with implanted DBS devices

Author/Year	Procedure	Anesthesia	Type of DBS	Management strategies and issues
Weaver 1999[20]	Basal cell carcinoma excision (face)—3 sessions in 1 patient	Local	Medtronic Activa	Battery-operated handheld cautery, unipolar and bipolar cautery used. Recurrence of tremors when DBS turned off. No complications
Martinelli 2004[21]	Squamous cell carcinoma excision (ear)	Local	Not mentioned	Battery-operated handheld electrocautery device used. No complications
Davies 2005[18]	Skin lesion excision (scalp)	GA	Medtronic Itrel II	Low power, bipolar diathermy used. No complications
Nutt 2001[15]	Diathermy treatment post dental extraction	Local	Medtronic Itrel II	Patient in persistent coma due to diencephalic and brainstem injuries
Ruggera 2003[16]	Diathermy treatment post dental extraction	Local	Not mentioned	Patient suffered significant brain tissue damage and died
Parsloe 2005[27]	Phacoemulsification for cataract removal	GA	Not mentioned	DBS off during procedure. No complications
Ozturk 2006[28]	Phacoemulsification for cataract removal	Not mentioned	Medtronic Activa	DBS not turned off. No complications
Minville 2006[23]	Shoulder surgery	RA	Medtronic Kinetra	Brachial plexus block using peripheral nerve stimulator. DBS not turned off. No complications
Gandhi 2014[24]	Arthroscopic rotator cuff repair	GA and RA	Not mentioned	Brachial plexus block using peripheral nerve stimulator. DBS turned off after GA induction and turned on before anesthesia reversal. Bipolar cautery used. No complications
Garg 2011[32]	Emergency laparotomy for obstructed paraumbilical hernia	GA	Not mentioned	No extra precautions with DBS. No complications. Type of cautery use not mentioned
Khetarpal 2014[19]	Nephrectomy for renal cell carcinoma	GA	Not mentioned	DBS turned off after GA induction and turned on before anesthesia reversal. Bipolar cautery used. No complications
Singh 2016[47]	Laparoscopic cholecystectomy	GA	Not mentioned	DBS turned off after GA induction and turned on during anesthesia reversal. Harmonic scalpel used
Moscarillo 2000[60]	ECT—8 sessions in 1 patient	GA	Medtronic Activa	DBS turned off during the sessions. No complications
Chou 2005[61]	ECT—9 sessions in 1 patient	GA	Not mentioned	DBS turned off during the sessions. No complications
Bailine 2008[62]	ECT—7 sessions in 1 patient	GA	Not mentioned	DBS turned off during the sessions. No complications
Tavernier 2000[40]	Insertion of ICD	Not mentioned	Medtronic Itrel 3	During ICD testing, shock delivery induced total reset of DBS
Obwegeser 2001[39]	Insertion of ICD	Not mentioned	Medtronic Itrel II	ICD programmed in bipolar sensing mode. No device interactions noted
Rosenow 2003[31]	Insertion of ICD	GA	Medtronic Soletra	ICD programmed in bipolar sensing mode. No device interactions noted
Ozben 2006[38]	Insertion of cardiac pacemaker	Not mentioned	Not mentioned	DBS turned off during procedure. Pacemaker in bipolar sensing mode. No device interactions noted
Tronnier 1999[51]	MRI (0.25 and 1.5 Tesla)—33 patients in 50 examinations	None	Medtronic Itrel II and III	IPG amplitude set to 0 V in some patients. DBS turned on/off in 16 patients. 21 patients had magnet activations of DBS
Spiegel 2003[56]	MRI head	None	Medtronic Kinetra	DBS electrodes not internalized. Patient developed temporary unilateral dystonic and ballistic movements immediately after MRI
Henderson 2005[57]	MRI lumbar spine	None	Medtronic Soletra	DBS status during MRI unknown. Patient developed permanent right hemiparesis from subacute hemorrhage adjacent to DBS electrode tip

DBS = Deep brain stimulation; ECT = Electroconvulsive therapy; GA = General anesthesia; ICD = Implantable cardioverter-defibrillator; IPG = Implantable pulse generator; MRI = Magnetic resonance imaging; RA = Regional anesthesia

Table 3 Outline of the anesthetic management of patients with an implanted DBS device undergoing surgery

Preoperative
1. Assess patient for indications for DBS insertion, optimize medical issues (e.g., ischemic heart disease, diabetes) and current medications
2. Obtain the following information related to the DBS device from patient, DBS information card, or DBS physician:[25]
a. DBS model, IPG location, last check and battery change by DBS physician
b. Current settings, programmability, and prior device complications
c. Severity of symptoms when device is turned off
d. Learn the use of the patient programmer, especially how to turn the device ON and OFF
3. Consult patient's neurologist or DBS physician to discuss specific precautions and postoperative assessment of both the patient and the device[25]
4. Chest *x-ray* to identify the path of DBS device wires to avoid damage during surgeries close to the device and to identify the type and make of the device.
5. Arrange with device representative/DBS physician for interrogation and adjustment of DBS settings[25]
Intraoperative
1. Turn the DBS device off to minimize electromagnetic interference:[10]
a. Older DBS models (e.g., Medtronic Kinetra® Model 7428, Medtronic Soletra® Model 7426) should be powered down (switch amplitude to 0 V) before turning off[10]
b. Turn DBS device off after induction of general anesthesia if recurrence of symptoms is severe
c. During regional anesthesia, increase sedation if symptoms are severe
d. For emergency surgery and when programmer is not available, proceed with precautions for electrocautery
e. Turn the DBS device on before reversal of anesthesia and emergence
2. Precautions with electrocautery:[10]
a. Use bipolar cautery mode with minimum power settings. Use short intermittent irregular bursts
b. If unipolar cautery mode is utilized, place the grounding pad such that the current path between the active electrode of the electrosurgical unit and the pad doesn't pass through the DBS system
Postoperative
1. Neurological examination to rule out adverse events related to device interaction
2. DBS device check by relevant device representative or DBS physician

DBS = deep brain stimulation; IPG = implantable pulse generator

enters into the patient's body and the electrical circuit is completed when the current reaches the grounding pad. In contrast, the electrical current in bipolar mode is confined to tissue between the two electrodes of the electrosurgical unit. Bipolar mode of electrosurgery has been shown to be safer for use in patients with implanted neurostimulators.[18-21]

There are two case reports of patients with an implanted neurostimulator who suffered serious brain injuries due to heat generation at the tip of the DBS electrodes after use of diathermy for dental treatment.[15,16] The manufacturer subsequently issued a product advisory to caution against the use of all forms of diathermy treatment in patients with a neurostimulator.[10,22]

Regional anesthesia: In patients with a movement disorder, inactivation of the DBS device could result in recurrence of symptoms that may be worse than the patient's baseline symptoms. This may be challenging for both the patient and surgeon during procedures performed under regional anesthesia. Providing adequate sedation may help diminish some of the symptoms and facilitate reasonable surgical conditions. Proposed sedation regimes include midazolam (0.5-1 mg *iv*), propofol infusion (25-75 $\mu g \cdot kg^{-1} \cdot min^{-1}$ *iv*), and dexmedetomidine (0.2-0.7 $\mu g \cdot kg^{-1} \cdot hr^{-1}$ *iv*), and these medications should be titrated to individual patient response. Two case reports have demonstrated the safety of using a peripheral nerve stimulator in patients with an implanted DBS device. In both cases, a brachial plexus block was performed with guidance from a peripheral nerve stimulator, and the DBS generator remained on during the procedure.[23,24] Safety precautions required in such procedures include ensuring that the path of electrical stimulation does not pass through the DBS system and that the puncture site is not in proximity to the wires of the DBS device.[23,25] Alternatively, the performance of regional blocks with ultrasound guidance obviates the potential interaction between the peripheral nerve stimulator and the DBS device.

Ultrasonic equipment, radiation therapy, laser: Ultrasound has been increasingly used as a therapeutic modality due to its capability of generating effects such as heat and

Table 4 Device interactions with the DBS system and their management

	Potential interaction(s)	Precaution(s)
Diathermy (**as defined in the text**)	Heating at DBS electrode tip	Use is contraindicated
Electrocautery/ Electrosurgery	Damage to IPG causing increased or decreased stimulation, or device inactivation	Turn DBS off. Use bipolar cautery with minimum power settings. Use short intermittent irregular bursts. If unipolar cautery used, place grounding pad such that current path between cautery electrode and pad doesn't pass through DBS system
	Heating at DBS electrode tip	
Peripheral nerve stimulator	Reportedly safe but precaution advised	Ensure path of stimulation does not pass through DBS system. Chest *x-ray* to identify path of DBS device wires to avoid damage. Ensure puncture site is not close to the wires of the DBS device
Ultrasound	Diagnostic ultrasound is safe	Do not place transducer directly over DBS
	Potential interactions with therapeutic ultrasound, e.g., lithotripsy	Turn the DBS off. Do not place ultrasound instrument head within 15 cm of DBS device
Radiation therapy	May damage the DBS system	Do not administer radiation within vicinity of the DBS device. Protect DBS device with lead shield and limit amount of exposure. Check DBS device after each treatment
External cardiac defibrillator	Damage to the DBS system	Position defibrillator paddles as far away as possible from the DBS. Position paddles perpendicular to the DBS system. Use lowest clinically appropriate output setting. Check DBS function after defibrillation
Electrocardiogram	Artifacts in ECG recordings	Turn DBS off
Cardiac pacemaker and ICD	Inappropriate sensing and response by pacemaker	Consult cardiologist and DBS physician
	Inappropriate tachyarrhythmia sensing and discharge by ICD	Program pacemaker and/or ICD to bipolar sensing mode. Place IPG of both devices as far away as possible from each other. Check DBS function if shocks delivered by ICD. Do Holter monitoring after adjusting DBS settings
	Reprogramming or inactivation of the DBS	
MRI	Damage to IPG and heating at electrode tip	Model-dependent. Refer to relevant manufacturer guidelines
	Image artifacts and distortion	
Electroconvulsive therapy	Potential damage to DBS system. Heating at electrode tip	Turn DBS off
		Place ECT electrodes as far away as possible from DBS electrodes
	Electrode displacement by induced seizures	Use lowest possible energy for seizure induction

DBS = deep brain stimulation; ECG = electrocardiogram; ECT = electroconvulsive therapy; ICD = implantable cardioverter-defibrillator; IPG = implantable pulse generator; MRI = magnetic resonance imaging

mechanical stress.[26] This technology is commonly used during phacoemulsification for cataract removal, extracorporeal lithotripsy for kidney stone removal, and harmonic scalpel for surgical cutting and cauterization. Diagnostic ultrasound can be safely performed in patients with an implanted neurostimulator, but the manufacturer recommends that the transducer should not be placed directly over the implanted device. The use of phacoemulsification for cataract removal has been shown to be safe in two case reports.[27,28] Performance of lithotripsy is not recommended by the manufacturer due to potential damage to the neurostimulator circuitry from high-output ultrasonic frequencies. Nevertheless, its use is not contraindicated, and if lithotripsy must be performed, the beam should not be directed within 15 cm of the neurostimulator.[29] Radiation therapy should not be administered within the vicinity of the DBS device. When administered, the amount of exposure should be limited, a lead shield should be used to protect the device, and the device should be checked after every treatment.[29,30] Similarly, when laser therapy is used, the neurostimulator should be turned off and the laser should be directed away from the device.[29] As there is a limited amount of safety data on the use of the above medical devices in patients with an implanted neurostimulator, the indications for their use should be carefully considered and the risks should be discussed in detail with the patient. General precautionary measures include directing the equipment away from the neurostimulator when in use, turning off the DBS device during the procedure, and checking the device following the procedure.

External cardiac defibrillators: External cardiac defibrillation and cardioversion may be lifesaving and

should not be withheld from patients with an implanted DBS device. A single case report showed that external cardioversion with 300 J did not affect the functioning of the DBS system.[31] To minimize damage to the DBS system, the manufacturer (Medtronic Inc.) recommends using the lowest clinically appropriate output setting and positioning the paddles as far away as possible from the neurostimulator and perpendicular to the DBS system.[29] Once again, the neurostimulator should be checked after shock delivery.

Effect of the DBS system on other medical devices Electrical signals from the DBS system have been shown to cause artifacts that affect the functioning of diagnostic and therapeutic cardiac equipment.

Electrocardiogram (ECG): Electrocardiogram recording can be affected by electrical signals generated from the DBS system; however, this interference resolves when the neurostimulator is turned off.[32-35] It is important to point out that, when the device is turned off, recurrence of symptoms may introduce movement-related artifacts that preclude optimal ECG recording.

Cardiac pacemakers and ICDs: The insertion of cardiac pacemakers and/or ICDs in patients with neurostimulators, and vice versa, is not contraindicated and has been performed successfully.[31,36-40] Nevertheless, precautions should be taken because of potential interactions between these devices, including inappropriate sensing and response by the cardiac pacemaker, inappropriate sensing of tachyarrhythmia by the ICD resulting in discharges, and inactivation of or adjustment to the neurostimulator settings.[29,40] A thorough preoperative assessment by a multidisciplinary team (i.e., cardiologist, DBS specialist, and anesthesiologist) is necessary to optimize the patient's clinical status and to adjust settings of the underlying medical devices as required. To minimize interactions between the cardiac pacemaker and the DBS device, the cardiac pacemaker should be programmed to bipolar sensing mode to avoid oversensing and inappropriate response.[36-38] Similarly, use of bipolar sensing electrodes for the ICD system also reduces oversensing. It is unlikely that inappropriate ICD discharges would occur at DBS outputs of up to 5 V.[31,39,40] In addition, ICD discharges up to 35 J do not seem to affect the functioning of the DBS device, although a case was reported whereby shock delivery converted the generator output to the "off" state with an amplitude of 0 V.[40] Therefore, the functioning of the neurostimulator should be checked after the ICD delivers a shock. In order to reduce electromagnetic interference, it is also recommended not to insert the IPGs of the two systems in close proximity.[37]

Magnets can interfere with the functioning and programming of both cardiac and neurostimulator IPGs, and their use should be avoided, if possible, to prevent unintentional reprogramming or suspension of these devices. Instead, the respective device-specific telemetric programmer should be utilized for programming the device.[39] If an external magnet is required intraoperatively to inactivate the defibrillator function of the ICD, precautions should be taken to avoid placing it in close proximity to the DBS device. Lastly, detailed cardiac investigations, e.g., Holter monitoring, should be performed whenever adjustments are made to the DBS device settings to ensure consistent functionality of the cardiac pacemaker device.

Perioperative risk of hardware-related infection The incidence of hardware-related infection after DBS implantation (primary insertion and/or IPG replacement) varies from 0-15%.[41-46] This wide variation is secondary to differences in the definition of hardware infection, the follow-up period after implantation, and the calculation for the incidence of infection based on the number of patients or procedures. *Staphylococcus aureus* is the commonest microorganism found in cultures.[42,43,46] Currently, there is a lack of established guidelines for the treatment of hardware-related infections after DBS insertion, but treatment options include antibiotic therapy with or without partial/complete removal of the device.[43,44,46]

There is also a paucity of available data to substantiate an increased risk of hardware infection for patients with an implanted DBS system undergoing unrelated surgery (i.e., surgeries that do not involve implantation or replacement of the IPG). Furthermore, there is a lack of evidence-based guidelines regarding specific antibiotic therapy. As such, clear recommendations cannot be made regarding specific antibiotic therapy, and protocol likely varies from centre to centre. In cases where the proposed surgery is distant from the hardware, routine antibiotic prophylaxis for the proposed surgery is likely sufficient. In those cases where the proposed surgery involves re-opening spaces with implanted DBS hardware, our recommendation is to do this in consultation with the DBS surgical team. Should a patient have a surgical site infection and/or develop sepsis, both the DBS surgical team and the infectious disease physician should be consulted so that appropriate therapy can be initiated.[46]

Postoperative considerations

At the end of the procedure, the neurostimulator should be turned on to the original settings. If general anesthesia was administered, we recommend that the device be turned on before reversal of anesthesia to avoid recurrence of symptoms when the patient is awake.[19,24,47] It has been suggested that cortical arousal may occur with subthalamic

nucleus (STN) stimulation due to possible involvement of extrathalamic arousal systems in the human sleep-wake cycle.[47-49] In a case report by Singh *et al*., a patient with bilateral STN DBS insertion for Parkinson's disease underwent a laparoscopic cholecystectomy under general anesthesia. During reversal of anesthesia, the patient did not arouse and entropy levels remained low despite an end-tidal desflurane concentration of 0.4 vol% (MAC 0.1). At this time, the DBS system was reactivated, followed by a sudden increase in entropy values and spontaneous eye opening.[47]

Non-surgical procedures

Magnetic resonance imaging The use of MRI in patients with an implanted DBS device was previously an absolute contraindication due to electromagnetic interactions that could potentially result in patient morbidity. The MRI system produces three types of electromagnetic fields: 1) static magnetic field that is constantly present, 2) gradient magnetic field that is present only during a scan, and 3) radiofrequency (RF) field that is present only during a scan and produced by a variety of transmission RF coils.

The safety concerns with MRI include excessive heating at the electrode tips of the DBS device due to compounding of the current produced by the gradient and RF magnetic fields within the DBS system, magnetic field interactions, image artifacts and distortion, and functional disruption of the DBS system.[50-54] The amount of heat generated within the DBS system is dependent on several factors, including electrical properties of the neurostimulator, field strength of the MRI system, position of the DBS components relative to the RF energy source, type of RF coil used, point of imaging, and the specific absorption rate (SAR).[55] The SAR is a measure of the rate at which energy is absorbed by the human body when exposed to an RF electromagnetic field, and this parameter is often used to identify limits for safe MRI. Transient and serious morbidities have been described in two case reports.[56,57] In the first report, a patient with bilateral STN DBS insertion experienced unilateral dystonic and ballistic leg movements that lasted several weeks after MRI of the head.[56] The second case involved a patient with bilateral STN DBS insertion who became hemiplegic after MRI of the lumbar spine. Subsequent imaging revealed subacute hemorrhage adjacent to the tip of the DBS electrode.[57]

Some neurostimulators are likely MR compatible, as suggested by studies showing the safe use of MRI under specified conditions in patients with an implanted DBS system.[50-55] With advances in DBS technology, some centres now routinely insert DBS devices under intraoperative MR guidance.[58] Specific guidelines on the use of MRI in patients with implanted DBS devices vary according to the manufacturer. For example, the use of MRI is currently contraindicated for Boston Scientific DBS systems[22] but can be performed, if necessary, in patients with Medtronic DBS systems under specified conditions. The complete MRI guideline for the Medtronic DBS system is available from http://manuals.medtronic.com/wcm/groups/mdtcom_sg/@emanuals/@era/@neuro/documents/documents/contrib_228155.pdf.[A] Pertinent points from this guideline are outlined in the following text.[10,59]

Prior to MRI, the treating physician should identify the model of the implanted neurostimulator, the presence of an implanted pocket adaptor, implant status of the lead (internalized or externalized), and the integrity of the system (breaks within the system are potential sites for production of excessive heat), as these factors determine if the DBS system permits scanning the whole body or only the head. In general, patients with a neurostimulator model using a magnetic switch or a DBS system with a pocket adaptor or externalized leads are eligible for head scans only. Once MRI eligibility has been determined, the scan must be performed under specific conditions. To date, only the 1.5 Tesla horizontal closed bore/64 MHz RF MRI system has been shown to be safe for use in patients with an implanted neurostimulator. The safety profile at specific static magnetic fields should not be extrapolated to other systems, even at lower field strengths.[55] Neurostimulators should be turned off during imaging, which, in some patients, can lead to recurring symptoms that interfere with adequate image acquisition. In neurostimulator systems with a magnetic switch, the magnetic switch must be turned off and the stimulation amplitude set to 0 V. Other safety precautions include limiting the active scan time, proper patient positioning, and constant communication with the patient to identify early complications. After imaging, the DBS specialist should check the neurostimulator and turn on the device to its original settings.

Electroconvulsive therapy (ECT) The safety concerns of performing ECT in patients with implanted neurostimulators include generation of heat at the DBS electrodes from induction of RF current by the electrical charge, functional disruption of the DBS system, and displacement of electrodes from induced seizure activity.[60-62] Three case reports showing safe administration of ECT recommend the following precautionary measures: turning the neurostimulator off, placement of the ECT electrodes as far away as possible

[A] The MRI guideline for the new St Jude Medical DBS system is not available as the device is currently not commercially available in Canada.

from the DBS electrodes, and use of the lowest possible energy for seizure induction.[50-54]

Limitations

The main limitation of our review is the lack of hypothesis-driven scientific evidence to support the safe use of certain medical devices or the performance of certain procedures in patients with implanted neurostimulators, as most data were obtained from case reports/series and manufacturer guidelines. There is also a possibility of bias as not all incident reports may be published and critical events may not be made available by the manufacturers. Nevertheless, it would be impractical or difficult to perform randomized-controlled trials to obtain information such as critical incidents and potential device interactions. As such, case reports/series, manufacturer guidelines, and critical incident reports remain the major sources of relevant information.

Conclusions

Deep brain stimulation technology has expanded and advanced considerably over the past 25 years. Current DBS systems have smaller IPGs, offer rechargeable IPG options, and are capable of providing variable frequencies and strengths of stimulation. There is now increasing interest in the development of closed-loop DBS systems,[63,64] DBS devices with directional leads,[11,65,66] and computer-guided programming of DBS systems.[63,67,68] Deep brain stimulation is now a standard of care for patients with an expanding range of neurological conditions, and the anesthesiologist will more commonly encounter patients with these devices. Thus, it is necessary for the anesthesiologist to be aware of the pertinent issues to prevent harm to the patient. The principles of anesthetic management include identification of the type of device, involvement of the DBS physician for specific precautions and device management, turning off the DBS device intraoperatively, practising precautions for safe use of electrosurgical equipment, and checking the device postoperatively.

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