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REVIEW ARTICLE

Role of radiology in central nervous system stimulation

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ABSTRACT

Central nervous system (CNS) stimulation is becoming increasingly prevalent. Deep brain stimulation (DBS) has been proven to be an invaluable treatment for movement disorders and is also useful in many other neurological conditions refractory to medical treatment, such as chronic pain and epilepsy. Neuroimaging plays an important role in operative planning, target localization and post-operative follow-up. The use of imaging in determining the underlying mechanisms of DBS is increasing, and the dependence on imaging is likely to expand as deep brain targeting becomes more refined. This article will address the expanding role of radiology and highlight issues, including MRI safety concerns, that radiologists may encounter when confronted with a patient with CNS stimulation equipment *in situ*.

Central nervous system (CNS) stimulation is becoming increasingly prevalent. Deep brain stimulation (DBS) has been proven to be an invaluable treatment for movement disorders and is also useful in many other neurological conditions refractory to medical treatment, such as chronic pain and epilepsy. Neuroimaging plays an important role in operative planning, target localization and post-operative follow-up.

ANATOMY OF THE DEEP BRAIN NUCLEI

The basal ganglia are a complex group of anatomically and neurochemically interconnected structures whose role is the control of complex and intentional movements and to inhibit unwanted movements.¹ They comprise the corpus striatum (caudate nucleus, nucleus accumbens and putamen), globus pallidus [external segment (GPe) and internal segment (GPi)], substantia nigra [compact part and reticular part (SNr)] and the subthalamic nucleus (STN) (Figure 1). The pedunculopontine nucleus is highly interconnected with the basal ganglia and is now considered by many to be part of this group. Disorders of the basal ganglia therefore manifest by movement, posture and muscle tone abnormalities.

There are wider connections to other parts of the brain such as the thalamus, limbic cortex and prefrontal cortex. These highlight their role in cognition and emotion and explain their implication in some psychiatric disorders and the cognitive symptoms associated with movement disorders.

It is these structures and their interconnected neighbours that are the targets for treatment by DBS. The STN is the most common target for DBS treatment because it is capable of treating the entire gamut of advanced Parkinson's disease symptoms, including tremor, rigidity, bradykinesia and drug-induced dyskinesia.² DBS reduces the need for dopaminergic medication. The benefits are a reduction of motor signs and improvement of functionality in the off-medication phase, a reduction of the required medication dose and its associated complications, and an increased quality of life.³ The benefits usually persist for at least 2 years and can last for many more.

The STN plays a key role in the basal ganglia–thalamocortical motor circuit (Figure 2). The striatum receives input from the cerebral cortex and direct pathway information passes to the GPi and the SNr. Indirect pathway information passes through the GPe and STN before reaching the GPi and SNr. The STN is excitatory and glutaminergic. The other pathways are inhibitory and GABAergic (produce gamma-aminobutyric acid). DBS is thought to interrupt abnormal and excessive neuronal activity in basal ganglia output.

The deep brain nuclei can be visualized on MRI (Figures 3–5).

DEEP BRAIN STIMULATION

The British neurosurgeon Sir Victor Horsley was the first to apply cortical electrical stimulation to the human brain

Figure 1. Basal ganglia terminology.

in the 1880s to demonstrate eloquent cortex in order to guide tumour resections.^{4,5} Horsley, along with Robert Clarke, developed a stereotactic apparatus that allowed the localization of cerebral structures and skull and brain landmarks in relation to a fixed co-ordinate system in experimental animals.⁶ The Horsley–Clarke apparatus was later adapted in 1947 by Spiegel and Wycis to enable stereotactic neurosurgery. This paved the way for irreversible ablation (“lesioning”) surgery using thermo-coagulation or chemical injections.⁷

Intraoperative DBS was then used to guide ablative surgery.^{8,9} Intraoperative stimulation along with observations from ablative surgery and animal research advanced our understanding of the STN and other deep brain structures and allowed the production of functional anatomical maps.^{10–13}

Implantable neurostimulatory devices were developed in order to produce intermittent DBS in an effort to perform reversible therapy in contrast to irreversible ablation.^{14,15} DBS was initially used successfully for cancer pain treatment in the 1950s and 1960s. Targets now include the thalamus, internal capsule, periaqueductal grey matter and cingulate gyrus for treating chronic pain syndromes.^{16–18} Over recent years, the use of DBS for chronic pain has expanded to include indications such as peripheral nerve injuries, plexopathies and amputation pain, stroke and neurological disease such as multiple sclerosis.^{16–19}

During intraoperative use of DBS to guide lesioning surgery for epilepsy and movement disorders in the 1950s–70s, it was noted that there was an improvement in dyskinesia and Parkinsonian tremor.^{9,20,21} Despite this, the success of Parkinson’s medical therapy and the already established lesioning surgery meant the introduction of therapeutic use of DBS for these conditions was delayed until the late 1980s.^{22–24}

DBS treatment has increased in recent years owing to advances in safety and efficacy of the implantable DBS devices. This has fuelled the desire to treat medically refractory Parkinson’s disease, other movement disorders such as dystonia and essential

tremor, and non-movement disorders such as chronic pain, epilepsy, obsessive compulsive disorder, Tourette’s syndrome and anorexia nervosa.

Much research on the mechanism of action of DBS is ongoing. The effects appear to be produced by stimulation-induced modulation of brain activity.^{25–27} The control of movement by the brain requires rapid and synchronized oscillations of neuronal activity between various structures, including the basal ganglia and cortex. In Parkinson’s disease, for example, the affected neurons are unable to maintain the oscillations, which then become unbalanced. One theory is that the oscillatory neurostimulation provided by DBS can restore the normal oscillatory activity between brain structures and ultimately affect the balance of the brain’s default network.

The scope of DBS is ever increasing and the number of conditions amenable to treatment is broad and includes psychiatric conditions as well as neurological disease. The common indications for DBS have been summarized in Table 1.

THE DEEP BRAIN STIMULATION PROCEDURE AND THE ROLE OF RADIOLOGY

Patient selection

Patients are usually referred from neurology or psychiatry once they are refractory to medical therapy for their condition. For example, Parkinson’s patients are referred once levodopa is reduced in efficacy, or they suffer from some of the dopamine replacement complications listed above.

A MR scan is performed to preclude those with generalized cerebral atrophy, severe small vessel disease or structural abnormalities suggestive of atypical Parkinsonism. This also aids in excluding patients with “Parkinson’s plus” syndromes such as multisystem atrophy, progressive supranuclear palsy and striatonigral degeneration.

Figure 2. The basal ganglia–thalamocortical motor circuit. GPe, globus pallidus external segment; GPi, globus pallidus internal segment; SNr, substantia nigra reticular part; STN, subthalamic nucleus.

Figure 3. Axial image from volume fluid-attenuated inversion recovery at 1.5 T. MB, mammillary bodies; PCA, poster cerebral artery; RN, red nucleus; SN, substantia nigra; VTA, ventral tegmental area.

Pre-operative imaging

Volumetric brain imaging plays a critical role in DBS. Either formulaic or atlas-based methods of stereotactically locating brain landmarks depend on accurate visualization of brain structures.²⁸

Ventriculography was initially used for stereotactic neurosurgery, but CT and MRI have superseded this owing to the ability to image the target structures in high resolution with these modalities. This non-invasive technique enables neurosurgeons to plan the surgical approach.

MRI is used to image the deep brain structures in high resolution, and stereotactic atlases can be superimposed onto the images. Imaging protocols vary between institutions. Pre-operatively, patients may undergo a MR scan under general anaesthetic in order to obtain good quality imaging. This is

specifically necessary in patients with movement disorders. High-resolution three-dimensional (3D) volume acquisitions with 1-mm isotropic voxels are acquired.

Different sequences are adept at demonstrating different nuclei. Combinations of different sequences are therefore used to calculate co-ordinates for the deep brain nuclei. T_1 weighted images demonstrate the globus pallidus well, but the STN poorly. Inversion recovery and T_2 weighted sequences demonstrate the STN, substantia nigra and the red nucleus adequately.^{29–34}

In our centre, we obtain T_1 weighted, T_2 weighted, fluid-attenuated inversion recovery and inversion recovery whole-brain volume acquisitions parallel to the anterior commissure–posterior commissure plane (AC-PC) (Table 2). Diffusion tensor imaging is also acquired.

Figure 4. (a) Coronal image from volume T_1 weighted at 7 T. (b) Coronal image from T_2 sequence at 1.5 T. Ca, caudate; GP, globus pallidus; In, insula; P, putamen; SN, substantia nigra; STN, subthalamic nucleus; Th, thalamus.

Figure 5. Axial image from volume T_1 weighted at 7 T. Ca, caudate; Cl, claustrum; EC, external capsule; GP, globus pallidus; IC, internal capsule; MD, medial dorsal nucleus; P, putamen; Pu, pulvinar; Th, thalamus; VA, ventral anterior nucleus; VI, ventral intermediate nucleus; VL, ventral lateral nucleus; VP, venal posterior.

Anatomical target localization

Targeting subcortical brain structures was traditionally performed by using a standardized brain atlas to define the co-ordinates from the mid-commissural point. This indirect method could use ventriculography to help delineate the AC and PC.

The high quality of neuroimaging now allows direct targeting because the deep brain structures are visible.

On the day of surgery, the patient has a stereotactic frame or fiducials (radio-opaque markers) affixed to the skull. In centres with MR compatible frames, the patient is then transferred to the MR scanner (often awake but sometimes under sedation or general anaesthetic) and a 3D volume is acquired.

In centres where the frame is not MR compatible, the patient is transferred to CT, and a helical volume is acquired (Figure 6a,b). CT provides excellent spatial resolution. The CT and MR data are then co-registered (computationally fused), and the neurosurgeons plan the entry point and trajectory to the target (Figure 7). CT does not suffer from the inherent inaccuracy produced by magnetic field distortion, and co-registration of the data improves the spatial resolution of the MR data to be stereotactically accurate within the millimetre range.³⁵

The trajectory to the target is planned to avoid traversing sulci, vessels, eloquent brain and the ventricles.

The operation

The patient is then taken to theatre with the frame *in situ* (Figure 8). The patient is placed supine, and the frame is fixed to the operating table. The operation is either performed under general anaesthetic or with the patient awake. If the patient is awake, then supraorbital and occipital nerve blocks are

administered to enhance the local anaesthetic with rapidly induced short-acting sedation for incision and burr holes. An awake patient can be advantageous to allow feedback during test stimulation.

Intraoperatively, physiological testing may be performed to help electrode placement. Graduated advancement of the polyurethane-insulated platinum iridium electrodes along the trajectory is achieved with mechanical assistance. Different brain structures produce typical neuronal recordings, which are measured through the electrodes and help confirm the correct direction of passage along the trajectory. Once the electrode appears to be within the correct structure according to its co-ordinate position and neuronal recordings, electrical stimulation through the electrode can help delineate its position and vicinity to other brain structures or neuronal tracts in the awake patient. Once the correct position is confirmed, then therapeutic levels of stimulation are applied to test for desired results and possible side effects. For example, in STN stimulation for Parkinson's disease, the effects on tremor, rigidity and bradykinesia are observed. Slightly misplaced leads may produce motor effects, ocular inversion or mydriasis, or paraesthesiae. If necessary, the electrode can be repositioned.

Once in a satisfactory position as assessed by post-operative CT or MR (for compatible frames), the stereotactic frame is dismantled and the lead is fixed to the skull. At a later date once the patient has recovered from the procedure, the implantable pulse generator or neurostimulator is implanted under general anaesthesia in a subcutaneous pocket and the extension leads are tunnelled to the implanted DBS lead. The first stimulation session is initiated a few weeks later to allow oedema around the DBS leads to settle and any microlesional "stun" effects to wear off.

Table 1. Deep brain stimulation targets

Indication	Deep brain target
Parkinson's disease	Subthalamic nucleus, globus pallidus interna, thalamus, pedunculopontine nucleus
Chronic pain	Ventral posterior medial and lateral thalamic nuclei, periventricular and periaqueductal grey matter, cingulate gyrus
Tremor (not including Parkinson's disease)	Ventralis intermedius thalamic nucleus, zona incerta
Dystonia	Globus pallidus interna
Cluster headache	Posterior hypothalamus
Epilepsy	Anterior thalamic nucleus
Obsessive-compulsive disorder	Anterior limb of internal capsule
Depression	Subgenual cingulate cortex, anterior limb of internal capsule
Tourette's syndrome	Ventromedial thalamic nuclei, anterior limb of internal capsule, globus pallidus interna

Table 2. Example MR scan parameters

MRI sequence	T_1 weighted volume	T_2 weighted volume	Fluid-attenuated IR volume	IR volume	DTI
Voxel (mm)	$1 \times 1 \times 1$	$1 \times 1 \times 1$	$1 \times 1 \times 1$	$1 \times 1 \times 1$	$2 \times 2 \times 2$
Echo time (ms)	3.8	250	300	14	71
Repetition time (ms)	25	2500	8000	2965	19,269
Flip angle (degree)	30	90	60	180	90
Matrix (pixels)	256×256	256×256	256×256	256×256	160×132

DTI, diffusion tensor imaging; IR, inversion recovery.

Complications can be related to the operative procedure and include infection, haemorrhage, stroke and hardware failure. Stimulation-related complications include unwanted side effects by stimulating brain outside of the target and include those listed above and cognitive or behavioural changes.

Post-operative and follow-up imaging

Post-operatively, the patient is returned to the CT or MR scanner to confirm correct placement of the stimulator electrodes and exclude any immediate complications such as haemorrhage, pneumocephalus or misplaced leads (Figure 9a,b).

Plain radiography or fluoroscopy can be used if there is a query of detached or broken leads.

Post-operative volume CT data can be used to check for correct lead position by co-registering with the pre-operative MR data to assess the positions of the leads; however, the post-operative shift in brain position can introduce some minor inaccuracies into this method.

Deep brain stimulation parameters

Several parameters can be controlled and vary depending on the brain structure that is being stimulated and the therapeutic response that the patient receives. These parameters are voltage (V), current (μ A), pulse duration (P) and rate (Hz). For the STN therapeutic ranges are 1.5–4.0 V, 60–90 P and 130 Hz. There is

a non-linear relationship between these parameters, the alteration of which allow discrimination between myelinated axons, cell bodies and dendrites, and the differential stimulation of different neural elements within the vicinity of the electrode.³⁶

Side effects

Once the neurostimulator is turned on, it can take several weeks of programming adjustments to achieve a correct balance between the therapeutic benefit of DBS and unwanted side effects. These side effects include motor symptoms, balance problems and paraesthesias along with mood changes.

Although DBS does not halt the progression of neurodegenerative diseases, it can help control symptoms for decades, reducing the need for adjunct medical therapy. In non-degenerative disease such as dystonia and chronic pain, the benefits can last a few years, but in some patients they may be life long. The batteries in the implantable pulse generator (IPG) last for up to several years and can be changed during an outpatient procedure.

MR SAFETY ISSUES

MR is increasingly used to confirm and check DBS lead position, assess for complications and evaluate disease progression. Many patients who undergo DBS may require MR follow-up for co-existent conditions. These include neurodegenerative conditions, spinal or unrelated musculoskeletal problems.

Figure 6. (a, b) Three-dimensional (3D) volume CT. Axial image and 3D reconstruction. Patient with stereotactic frame *in situ* in order to plan for a left subthalamic nucleus (STN) deep brain stimulation lead insertion. The patient already has a right STN stimulator lead *in situ*.

Figure 7. Stereotactic surgical planning. The surgical trajectory to both subthalamic nuclei is planned in order to attain accurate positioning and avoid eloquent structures. 3D, three dimensional; FLAIR, fluid-attenuated inversion recovery.

Safety is the key concern and the strong magnetic field within the MR scanner can interact with the DBS system in multiple ways.³⁷ The radiofrequency (RF) field and gradient fields can induce heating throughout the neurostimulator system by inducing voltages. This may lead to thermal damage at the lead–electrode–tissue interface or at any breaks in the lead system. Induced voltages through the system may also lead to unintended stimulation in the electrodes.

DBS systems are designed to contain materials that are not susceptible to the magnetic field, so there is minimal force or torque effects on the electrodes and IPG.

The IPG may be susceptible to being turned on or off by the magnetic field, particularly if the unit is patient operated by the application of a handheld magnet. Other functions of the IPG may be altered by the magnetic field, and the IPG may need to be reprogrammed following the MR scan.

The IPG can cause significant image distortion owing to field inhomogeneity. The implanted electrodes, however, often cause minimal distortion allowing accurate visualisation of the position within the deep brain structures.

Performing MR scans on DBS patients is therefore only recommended in centres with experience. Referral to the manufacturers' guidelines is essential and can be found on their websites. The operating parameters of the IPG must be recorded before the procedure in case reprogramming is required later.

The system should be tested for short circuits or broken leads by testing the electrode impedance. Most IPGs should be turned off before entering the magnetic field. The patient should always be scanned when awake and must be accompanied by a member of staff in the scan room who talks to the patient during the scan in order to quickly detect a problem.

Although manufacturer guidelines vary between devices, a 1.5-T MR scan is considered to be safe if specific scan protocols are followed. This includes using a transmit–receive (T/R) head coil, limiting the average head coil-specific absorption rate (SAR) to 0.1 W kg^{-1} and limiting the gradient dB/dt field to 20 T per second or less.³⁸ The T/R head coil limits the exposure of RF and gradient fields to the head only and limits exposure to the extension leads and IPG. Very few adverse events such as hardware failure, unintended stimulation or heating causing ablation at the electrode tip have been reported.^{32,33,39–42}

By following these guidelines, imaging of the brain in these patients is deemed to be very low risk. The use of any other coil or imaging another part of the body will produce larger induced voltages and may potentially increase the risk of heating. A recent literature review reported that in >4000 MR examinations in patients with implanted DBS hardware, only 1 permanent neurological deficit has been recorded. This was the result of the guidelines not being adhered to when a patient with an abdominal IPG underwent a spinal MRI.^{32,41}

Figure 8. Professor Aziz of John Radcliffe Hospital, Oxford, UK, performing stereotactic deep brain stimulation in an awake patient. Informed consent was received for the use of this image.

However, this imposed low SAR limit makes it extremely difficult to perform a full examination and some groups suggest that it is unnecessarily low.³⁴ Previously the SAR limit was 0.4 W kg^{-1} , and this allowed our centre to perform a volume T_2 weighted and diffusion tensor imaging (DTI) sequence on DBS patients with leads *in situ* via a head transmit receive coil (Figure 9b). However, since the new lower SAR limit of 0.1 W kg^{-1} have been set with the introduction of the 2014 MR safety guidelines, we are no

longer able to scan patients within this limit.³⁸ These new guidelines have imposed restrictions, meaning many other devices such as cardiac pacemakers and implanted stents are now MR conditional rather than MR safe. It is possible that in the future, with more research, regulations will be relaxed leading to more widespread MRI of DBS patients.

Recent animal and post-mortem studies have suggested that MR scanning of patients at 3 T is also safe, although more research is needed.^{33,39} One study reviewed the DBS brain tissue network's clinical and neuropathological database and found no clinical signs or symptoms of MRI-induced adverse effects.³³ The same authors also studied four post-mortem brains exposed to prolonged 3-T magnetic field exposure with DBS leads left in place and found no pathological changes consistent with thermal damage.

The use of 3 T is becoming increasingly important as the application of functional MRI (fMRI) and diffusion tensor imaging is useful for investigating the neurobiological effects of DBS on inducing alterations in neuronal activity and the "resting state network".^{27,39} This research in the future will help develop new targets and refine treatments with DBS.

As the availability of ultrahigh magnetic field (7 T) MRI becomes more prevalent, the improved visualization of the deep brain structures and improved structural and functional information acquired will promote more accurate target delineation and advance DBS research.^{43–45} Studies have shown that although 7 T is prone to increased susceptibility and geometric distortion artefacts, the central parts of the brain within the middle of the field of view have comparable distortions when compared with those of 1.5 T.⁴⁶

THE FUTURE

Ongoing translational animal research and advances in functional neuroimaging using fMRI, positron emission tomography and magnetoencephalography are helping us to understand the

Figure 9. (a) Post-operative CT to assess for the position of the electrode and to exclude surgical complications. The right deep brain stimulation (DBS) electrode lead is demonstrated to terminate in the region of the right subthalamic nucleus (STN). (b) Post-operative T_2 weighted MRI to assess for the position of the DBS electrodes. There are two DBS electrode leads *in situ*. One terminates in the region of the left STN and the other in the region of the left pedunculopontine nucleus.

Figure 10. (a, b) Anteroposterior (AP) and lateral radiography demonstrate correct placement of the spinal cord stimulator electrode pad. It should be central (equidistant between the pedicles on the AP view) and dorsal within the vertebral canal.

mechanism of action of DBS, map the complex neurological pathways and find new targets for the treatment of neurological and psychiatric disorders.

Cardiac pacemakers have become more customizable and adaptive. Similar improvements in DBS hardware will provide intelligent technology that can alter stimulation

Figure 11. (a-c) Two anteroposterior views and a lateral radiography demonstrated misplaced spinal cord stimulator electrode pad. The electrode pad has moved towards the left side of the vertebral canal.

Figure 12. (a, b) Lateral and anteroposterior maximum intensity projection of a CT demonstrating the sacral nerve stimulator electrode passing through the right S3 neural foramen. (c) Abdominal radiograph demonstrating the sacral nerve stimulator electrode passing through the right S3 neural foramen with the implantable pulse generator sited in the right lumbar soft tissues.

parameters to adapt to the patient's behaviour state and avoid side effects.

SPINAL CORD AND OTHER NEURO STIMULATORS

The spinal cord is also amenable to neuromodulation. The dorsal horn of the spinal cord receives nociception, light touch and proprioception. Melzack and Wall⁴⁷ proposed the "gate control theory" in 1965 where they hypothesized that by activating tactile and non-noxious fibres, this would lead to interneuron inhibition within the dorsal horn to "close the gate" to pain reception. This soon led to the development of spinal cord stimulators (SCSs) for chronic pain.^{48,49} Epidural dorsal column stimulation by implanted electrodes or paddles activates these interneuron inhibitory pathways.

Currently, SCS is effective in many conditions, including patients with leg or arm neuropathic pain following spinal surgery (failed back surgery syndrome), complex regional pain syndrome, amputation pain, chronic limb pain, plexopathies, peripheral vascular disease pain and refractory angina pectoris.⁵⁰ These devices are becoming more prevalent and therefore pose similar imaging challenges to the DBS systems for radiologists.

The epidurally placed electrode "pad" or "plate" is usually placed in the lower thoracic level percutaneously via a Tuohy needle or surgically with a laminectomy. The leads are connected to an IPG that is implanted in a similar fashion to the DBS IPGs.

The assistance of a radiologist may be sought in order to ensure correct position of the electrode pad and to investigate for complications. Commonly, one electrode pad is inserted and should be positioned in the midline over the posterior epidural surface, as demonstrated in Figure 10a,b. One complication that may arise is migration or misplacement of the electrode pad (Figure 11a,b). Two electrodes may sometimes be placed on either side of the

midline. Another complication that the radiologist may be asked to look for is lead integrity. With repeated patient movement the leads can occasionally break.

Other complications include pain at the IPG site, cerebrospinal fluid leakage, infection and epidural haematoma.⁵¹

As with DBS, there are complex issues surrounding MRI safety. Although newer SCS devices are MR compatible, the IPG and electrodes may be displaced by the magnetic field and induced voltages through the system can cause heating at the electrode tip. MRI is therefore best avoided and, if necessary, should be considered on a case-by-case basis and with adherence to manufacturer guidelines. In our trust, patients undergo CT myelography rather than MRI when investigation of the spine is required.

The systems are becoming more slimline, and the implantation procedures are becoming increasingly minimally invasive. This coupled with advances in stimulation parameters (such as high frequency or burst stimulation⁵²) and new stimulation targets (such as angina, peripheral occlusive vascular disease and high cervical cord stimulation for cluster headaches), SCS is likely to become more prevalent.

SACRAL NERVE STIMULATORS

Implantable programmable stimulators that deliver stimulation to the sacral nerve via a lead through the S3 neural foramen (Figure 12a,b) are indicated in the treatment of urinary retention, frequency, urge incontinence and faecal incontinence.^{53,54} All patients go through a test period of percutaneous nerve evaluation where a temporary electrode is inserted and connected to an external pulse generator. If this provides symptom improvement, an implantable pulse generator is inserted.

Temporary pulse generators are not MRI compatible. The implantable pulse generators vary from being MR incompatible to

MR conditional and correlation with the manufacturer's guidelines is essential.

CONCLUSION

Central neural stimulators for neuromodulation are becoming more prevalent. Radiologists are now more likely to encounter

patients who attend for follow-up or other imaging. Whilst patient safety is the ultimate concern, if imaging protocols are adhered to, these patients are able to undergo limited MRI. The use of imaging in determining the underlying mechanisms of DBS is increasing, and the dependence on imaging is likely to expand as deep brain targeting becomes more refined.

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