



Лекция / Lecture

Use of radiofrequency lesioning in neurosurgery

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Abstract

Radiofrequency (RF) lesioning is a precise and established destructive technique in functional neurosurgery for treating chronic pain, movement disorders, and other conditions. This paper reviews its history, technical evolution, and key applications such as trigeminal gangliolysis, cordotomy, and deep brain lesioning. Despite being irreversible and less commonly practiced today due to the rise of neuromodulation, RF lesioning offers significant advantages like predictability, minimal invasiveness, and cost-effectiveness, making it a valuable option for specific patients, particularly in oncology pain care.

Keywords: radiofrequency lesioning, functional neurosurgery, pain, epilepsy, tremor

For citation: Slavin K.V. Use of radiofrequency lesioning in neurosurgery. *Sibneuro*. 2025; 1(1): 16–25. <https://doi.org/10.64265/sibneuro-2025-1-1-16-25>

Conflict of interest. Slavin K.V. has been a member of the editorial board of the *Sibneuro journal* since 2025 but was not involved in the decision-making process regarding the acceptance of this article for publication. The article underwent the journal's standard peer-review procedure. The author declares no other conflicts of interest.

Financial disclosure. The study was carried out without any financial support.

Use of AI. No AI technologies were used in the writing of this article.

Data availability. All data used in the writing of this article are available in international scientific publication databases and are accessible for research purposes.

Received: 03.06.2025

Accepted: 12.08.2025

Published: 15.10.2025

Применение метода радиочастотной деструкции в нейрохирургии

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Резюме

Радиочастотная (РЧ) деструкция – это точная и отработанная методика в функциональной нейрохирургии для лечения хронической боли, двигательных расстройств и других заболеваний. В статье рассматриваются ее история, техническое развитие и основные показания к применению, включая ганглиолиз тройничного нерва, кордотомию и деструкцию глубоких структур мозга. Несмотря на необратимость эффекта и снижение популярности с развитием нейромодуляции, РЧ-деструкция остается ценной опцией благодаря предсказуемости, малой инвазивности и экономичности, особенно для пациентов с онкологической болью.

Ключевые слова: радиочастотная деструкция, функциональная нейрохирургия, боль, эпилепсия, тремор

Для цитирования: Славин К.В. Применение метода радиочастотной деструкции в нейрохирургии.. *Сибнейро*. 2025;1(1):16–25. <https://doi.org/10.64265/sibneuro-2025-1-1-16-25>

Конфликт интересов: Славин К.В. является членом редакционной коллегии журнала «Сибнейро» с 2025 г., но не участвовал в процессе вынесения решения о принятии статьи к публикации. Статья прошла принятую в журнале процедуру рецензирования. Об иных конфликтах интересов автор не сообщал.

Финансирование. Исследование проведено без привлечения какой-либо финансовой поддержки.

Использование ИИ. При написании статьи технологии искусственного интеллекта не использовались.

Доступность данных. Все данные, использованные при написании этой статьи, находятся в международных базах научных публикаций и доступны для изучения.

Поступила: 03.06.2025

Принята к печати: 12.08.2025

Опубликована: 15.10.2025

Introduction

In general, there are two ways to change the activity of neural tissue – destruction and modulation; the latter one changes activity of nervous system in a reversible way, as seen in cases of electrical stimulation and chemical modulation, and the former one eliminates pathological activity by irreversible damage of the neural structures, in effect removing, disconnecting or otherwise silencing abnormal neurons. Both of these general approaches are widely used in the field of functional neurosurgery, the subspecialty of neurosurgery that deals with treatment of so-called functional disorders, a broad category of neurological conditions that includes chronic pain, movement disorders, epilepsy and psychiatric disorders.

Although recently surgical neuromodulation has become a standard of care in multiple functional neurosurgical domains, destructive interventions remain widely used for many established indications. They range from mechanical disconnections (such as neurotomy/neurectomy, transections of nerve roots, spinal cord and brain) and chemical destructions (phenol, glycerol, alcohol, etc.) to thermal lesions (with extreme cold as in cryodestruction or heat as in thermocoagulation) and focused radiation (with photons as in radiosurgery and brachytherapy or with sonic waves as in focused ultrasound). Each of these approaches has its own unique advantages and disadvantages; some have long history and remain relatively popular, others were introduced relatively recently and remain experimental, whereas some others have been almost completely abandoned.

Among many destructive modalities, radiofrequency (RF) thermocoagulation stands out as a time-tested neurosurgical approach that is used whenever there is a need for precise and clearly defined area of destruction tissue within confines of the nervous system, be that a ganglion, the spinal cord or the brain. This white paper covers brief history of use of RF lesioning in neurosurgery, its main applications and technical aspects of relevant procedures.

History of radiofrequency lesioning in neurosurgery

The use of electrical lesioning in neurosurgical interventions was initially based on application of direct electrical current through metal electrodes with uninsulated tip that were

inserted into the desired part of the spinal cord or brain during open or stereotactic surgical intervention. In 1964 Sean Mullan and co-workers in Chicago suggested using unipolar anodal electrolytic lesion of the spinal cord for a purpose of pain relief instead of previously used radioactive strontium needle; the lesion was made with a 0.25 mm thick (10 mils) electrode made of iridium, iridium-platinum alloy or platinum-clad tungsten with 1 mm uninsulated tip [1]. Once this electrode is inserted into the spinothalamic tract at C₁–C₂ level through a needle under radiographic control and electrostimulation confirms proper electrode placement, a lesion is made with application of 1–2 mA anodic current for 2–10 minutes.

Although considered an improvement compared to previously used radioactive strontium needle, this approach, however, was hard to reproduce, mainly due to unpredictable tissue response to the electrical current, a significant variability in clinical effect, and wide range of recommended lesioning parameters. The direct current lesion has been associated with electrolysis, tissue polarization and gas formation, each of which phenomena are to be avoided in dealing with the nervous system. To mitigate this, Hugh Rosomoff from Pittsburgh in 1965 suggested using RF current to create thermal lesion in the spinal cord using a 0.5 mm (0.02 in) stainless steel electrode with 2 mm uninsulated tip [2]. This electrode was then connected to a commercially available RF generator allowing the surgeon to create a lesion of predictable size as the combination of the specific electrode and RF generator can be calibrated in animal tissue prior to the clinical use. In the original report, the electrode was expected to produce 5 mm ellipsoid after 30 seconds exposure. Before that, in 1960, a similar approach was suggested by Fritz Munding of Freiburg for stereotactic brain surgery, but the article describing it was published in German and did not receive proper attention [3].

The next two developments aimed at improved safety of the procedure brought neurosurgical RF lesioning to its current level. First was the introduction of impedance measurements suggested by Phil Gildenberg in early 1969 [4]; second – addition of thermocouple for the electrode tip temperature monitoring by Allan Levin and Eric Cosman in 1980 [5]. These innovations allowed surgeons to determine location of the electrode tip based on different tissue properties (impedance measurements allow one not only to differentiate cerebrospinal fluid, white matter and gray

matter, but also follow changes in the tissue conductivity during the lesioning procedure) and continuously measure the lesion temperature thereby increasing accuracy and safety.

Even more important is the ability to perform test stimulation through the lesioning electrode prior to RF thermocoagulation. Electrical stimulation at different frequencies produces different physiological effects (sensory and motor) indicating exact position of the electrode tip related to somatotopic organization of the nervous system. Evaluation of stimulation thresholds suggests proximity of important pathways that should be preserved in order to maintain patient functionality. Such physiological testing is considered standard for all RF lesioning applications, particularly those that are done with the patient awake where the feedback can be taken into consideration for electrode placement and repositioning.

Since the targets of neurosurgical lesioning happen to be of different size and in very different anatomical locations, each neurosurgical RF intervention uses dedicated electrodes that vary by diameter, shape, length of the electrode itself and its uninsulated tip, requiring diverse access tools specifically designed for each target. Many of these RF electrodes carry the names of either procedures themselves or those who introduced and/or popularized the specific procedures and technical nuances.

Common radiofrequency lesioning interventions

The most common neurosurgical RF applications are described below (Tables 1, 2). Some historical RF procedures, such as hypophysectomy and spinal ganglionectomy, have been abandoned over the years, while

Table 1. Common neurosurgical indications for RF lesioning. Source: created by the author

Таблица 1. Наиболее частые нейрохирургические показания для радиочастотной деструкции. Источник: составлено автором

Indication	Target	Procedure name
Trigeminal neuralgia	Gasserian ganglion	Trigeminal RF gangliolysis
Unilateral cancer pain	Lateral spinothalamic tract	Cordotomy
Bilateral cancer pain	Paleospinothalamic tract	Midline myelotomy
Brachial/lumbar plexus avulsion	DREZ of spinal cord	DREZ myelotomy
Trigeminal deafferentation pain	Trigeminal nucleus caudalis	Trigeminal tractotomy/caudalis DREZ
Essential tremor/parkinsonian tremor	Ventral intermedus nucleus of thalamus	VIM thalamotomy
Parkinson disease/dyskinesias/dystonia	Globus pallidus pars interna	GPI pallidotomy
Intractable epilepsy	Anterior nucleus of thalamus	Anterior thalamotomy
Obsessive compulsive disorder/medically refractory depression	Anterior limb of internal capsule	Capsulotomy
Obsessive compulsive disorder/medically refractory depression/diffuse cancer pain	Cingulum / cingulate gyrus	Cingulotomy

Note: DREZ – dorsal root entry zone; GPI – globus pallidus pars interna

Примечание: DREZ – задняя корешковая зона входа (dorsal root entry zone); GPI – внутренний сегмент бледного шара (globus pallidus pars interna)

Table 2. Common RF electrode configurations. Source: created by the author

Таблица 2. Распространенные конфигурации радиочастотных электродов. Источник: составлено автором

Procedure	Tip length (mm)	Tip diameter (mm)	Additional feature(s)
Gasserian gangliolysis	10	0.5	Straight and curved tip configurations (blunt)
Cordotomy	2	0.25	Straight and angled tips (sharp)
DREZ myelotomy	2	0.25	Insulated Teflon shoulder; sharp tip
Caudalis DREZ	1.2 and 2	0.25	Right angle bend; insulated Teflon shoulder; sharp tip
Thalamotomy/pallidotomy	1–3	1–1.8	Blunt tip
Cingulotomy	5–10	1–1.8	Blunt tip

others, such as spinal rhizotomy and sympathectomy, transitioned from neurosurgery practice to the field of interventional pain management that is manned by anesthesiologists and physiatrists. Of this list, the older generations of functional neurosurgeons are familiar with each listed procedure and indication, but recent graduates of neurosurgical residencies are likely to be well familiar only with trigeminal RF gangliolysis, whereas other RF procedures targeting structures of the spinal cord and brain would be taught during dedicated functional neurosurgery fellowships.

Radiofrequency trigeminal gangliolysis

Trigeminal ganglion is the target of neurosurgical interventions in treatment of trigeminal neuralgia. Although the preferred modality for otherwise healthy patients with typical trigeminal neuralgia is considered microvascular decompression (MVD), there are many destructive surgeries that are equally effective and widely used [6]. These include RF thermocoagulation, glycerol gangliolysis, balloon compression and stereotactic radiosurgery. In general, destructive procedures are reserved for pain recurrences after MVD, or as an initial intervention for those who are not medically fit to withstand open surgery or those who have so-called symptomatic trigeminal neuralgia (as in multiple sclerosis), when MVD is not expected to be effective.

Of all destructive trigeminal interventions, RF gangliolysis is by far most selective and allows the surgeon to focus lesioning on specific parts of the Gasserian ganglion that supply the affected part of the face. The surgery involves insertion of the cannula into the Meckel's cave through foramen ovale using Härtel technique. The anatomical landmarks are very reliable and the procedure is routinely done under fluoroscopic guidance. The patient is sedated during the cannula insertion and during the actual lesioning process but is kept awake for physiological testing prior to and after the lesioning to determine sufficiency of the intervention in terms of development of numbness and disappearance of trigger zones.

There are two RF electrodes that are used for trigeminal thermocoagulation: a straight (usually referred to as TIC electrode) [7] and a curved one (usually referred to as TEW electrode after its inventor, John Tew of Mayfield Clinic in Cincinnati) [8].

Straight (TIC) electrode is usually inserted through one of several dedicated cannu-

las that have different length of uninsulated tip (2, 5, 7 and 10 mm long). This uninsulated tip is positioned within the Gasserian ganglion and the exact position is checked with intraoperative X-ray and confirmed by electrical stimulation that elicits paresthesias in the corresponding part of the patient's face. Once the desired area of face (corresponding to first, second or third branch of the trigeminal nerve) is covered with paresthesias, the RF energy is delivered in order to heat up the ganglion. The tip temperature is raised gradually until the desired level (usually $> 70^{\circ}\text{C}$ and $< 90^{\circ}\text{C}$) is reached, and then the desired temperature is maintained for 60–120 seconds. The exact recommended settings vary based on surgeon's preference; in our practice we use 74°C for 90 seconds. The anatomical arrangement of the sensory fibers within Gasserian ganglion is such that the fibers of the third branch are reached first, the second – next, and the first – last, so the electrode may be advanced or withdrawn based on the patient's description of paresthesias. Once the lesioning is completed, the sensory testing is performed in order to determine disappearance of trigger zones and a loss of sharp/dull discrimination that tends to correlate with pain relief. Higher temperatures and longer duration of lesioning tend to result in higher incidence of permanent and complete facial numbness that is sometimes associated with severe pain, so called anesthesia dolorosa. Therefore, the conventional wisdom dictates a preference in keeping temperature and lesion duration lower.

An alternative curved electrode is the more commonly used (it is preferred electrode in our practice) – here the cannula is insulated completely and the flexible electrode tip is protruding from the cannula lumen into the ganglion itself. By aiming the curvature in different directions, it is possible to position the electrode tip in all three branches without moving the cannula. The same kit includes a straight electrode in addition to the curved one – with fully insulated cannula this straight electrode protrudes by 1 cm to create lesion in the Gasserian ganglion along the trajectory of insertion.

The proper position of the electrode is monitored with intraoperative fluoroscopy, impedance measurements and electrical stimulation; the sufficiency of the lesioning is determined by sensory examination after each lesion. Once the desired effects (pain relief and partial sensory loss) are achieved, the electrode and the cannula are withdrawn.

The clinical effect of trigeminal RF thermocoagulation is based on the difference in thermal

sensitivity of different nerve fibers – the pain transmitting fibers are smaller and more sensitive to heat with lower threshold for destruction compared to larger fibers that provide deep cutaneous sensation and supply motor innervation. This difference allows one to achieve pain relief without creating complete numbness thereby avoiding the risk of keratitis, loss of corneal reflex and *anesthesia dolorosa*. The partial sensory loss needed for lasting pain relief can be achieved without creating weakness in the muscles of mastication that are supplied by motor portion of the trigeminal nerve. In addition to this, the somatotopic organization of the fibers in the retrogasserian part of the ganglion permits selective destruction of only those pathways that correspond to the area of pain; this makes RF thermodestruction the most selective percutaneous procedure among all others (glycerol, balloon compression and radiosurgery).

Radiofrequency cordotomy

The concept of selective interruption of pain-transmitting pathways within the spinal cord was introduced more than 100 years ago after an observation of complete insensitivity to pain in an otherwise functional patient who had tuberculosis related granulomas in the spinal cord. Since the lateral spinothalamic tract that carries somatic pain signals from contralateral side of the body is located in the anterolateral quadrant of the spinal cord, the original approach to the cordotomy was to surgically transect the cord with surgical scalpel or the specially designed cutting instrument (the cordotome). Such intervention that requires surgical exposure of the spinal cord at cervical or upper thoracic level – the open cordotomy – is still rarely performed for specific indications, but the preferred option for the last 50 years has been percutaneous cordotomy, where the lesion of the spinothalamic tract is performed through a needle under radiographic guidance. The earlier techniques of cordotomy that involved radioactive needles and anodic currents have been completely abandoned in favor of RF thermocoagulation, and special cordotomy RF electrodes have been developed to create reproducible lesions the spinothalamic tract [5].

The cordotomy is indicated for treatment of medically refractory unilateral pain in patients with relatively short life expectancy. Most often, it is being considered as an option in patients with cancer pain when

the malignant process or anti-neoplastic therapy (such as radiation treatment) involve the lumbar or brachial plexus, or cause severe pain by direct invasion of the pelvis, leg, chest wall or arm. In patients with more than 6-month life expectancy surgical treatment of pain is usually focusing on intrathecal drug delivery, but for those with expected survival shorter than 3–6 months a destructive option such as cordotomy is a preferred approach due to its low invasiveness, predictable outcomes, acceptable risk of complications, low cost and no need in general anesthesia.

The procedure of percutaneous RF cordotomy is done with the patient awake and in supine position. The lesioning is usually done at the upper cervical level and the special 17 Ga needle is inserted in horizontal plane 2 cm inferior to the tip of mastoid process. It is recommended to administer intrathecal contrast dye within an hour prior to the procedure, usually through a lumbar or contralateral cervical puncture, in order to outline the contours of the spinal cord on radiographic images. Once the needle for cordotomy reaches the spinal canal, it is advanced toward the spinal cord anterior to the dentate ligament aiming at the anterolateral quadrant of the cord few millimeters anterior to the cord's equator. Before the surface of the cord is reached, the patient may experience sharp pain in the neck due to penetration of the dura and irritation of the cervical nerve roots; contact with the cord itself, just like the brain, is painless. The cordotomy electrode is very thin (0.25 mm in diameter) and has sharp uninsulated 2 mm tip; the kit usually includes electrodes with straight and slightly curved tips. The electrode is advanced through the needle and the impedance is monitored during the advancement process. Impedance increases significantly when the electrode tip penetrates the spinal cord and remains high when the electrode is advanced for another 3 mm so the part of its insulated shaft is located inside the cord and protects more superficial pathways located lateral to the spinothalamic tract.

The somatotopic organization of the spinothalamic tract allows one to pinpoint the fibers that correspond to sacral, lumbar, thoracic and cervical dermatomes. Here the electrical stimulation is used to elicit paresthesias in the body part that is affected by pain; due to early crossing of the sensory fibers in the spinal cord, the spinothalamic tract carries information from contralateral

part of the body. Once the patient describes sensation of pins and needles or a warm water flowing over the painful region, the electrode position is considered adequate for the RF cordotomy.

The RF lesion is done with tip temperature of 80 °C for 30 seconds; the lesion is usually painless as the white matter tracts do not have painful sensation receptors in them. Once the lesion is completed, the patient is asked to report the level of his/her pain – the pain improvement or disappearance indicates that the lesion is adequate. Neurological examination is performed to check for presence of sensory loss in the area of pain and the rest of contralateral body half as well as any other neurological symptoms including weakness in the ipsilateral extremities. The RF lesioning parameters vary across different centers, but the general approach remains the same.

In the past, RF cordotomy was performed under radiographic guidance using regular cervical radiographs or C-arm fluoroscopy. This was changed to primarily CT-guidance after the technique was introduced by Yucel Kanpolat in the early 1990s [9]; the specially designed “Kanpolat cordotomy” electrode was introduced in 1996 [10].

CT-guided RF cordotomy remains widely recognized pain-relieving intervention for unilateral cancer-related pain. It is not routinely used for patients with non-malignant nature of pain due to relatively high recurrence rate over time; short life expectancy of cancer pain patients makes them excellent candidates for this minimally-invasive intervention that does not require general anesthesia and results in immediate pain relief with associated improvement on quality of life. RF cordotomy is not recommended in patients with bilateral pain due to a concern about respiratory complications with bilateral procedures.

Radiofrequency dorsal root entry zone myelotomy

Dorsal root entry zone (DREZ) is the substrate for pain relieving interventions based on its role in pain generation: in patients with complete loss of the sensory input (deafferentation), nociceptive interneurons in the substantia gelatinosa and Lissauer's tract (both are located within DREZ) become hyperactive and are thought to be responsible for development of the severe and medically refractory neuropathic pain. The original description of so-called DREZotomy was published by Marc Sindou of Lyon

for treatment of spasticity and pain [11], but subsequent modification and popularization of the procedure by Blaine Nashold of Duke University [12] resulted in universal recognition of DREZ myelotomy (frequently referred to in US as Nashold procedure) as preferred approach to treatment of localized deafferentation pain.

Currently, DREZ myelotomy is used primarily for severe pain related to avulsion of the nervous plexus – in cervical region for brachial plexus avulsion and in thoraco-lumbar region for lumbar plexus avulsion. It also works for the end-zone pain related to spinal cord injury, but is considered ineffective for post-herpetic neuralgia and distal (post-ganglionic) nerve injuries. The myelotomy itself can be done with various instruments, including scalpel, bipolar coagulation, laser beam, focused ultrasound, but the most commonly used approach utilized RF thermocoagulation that is performed through an open surgery that involves laminectomy (or hemilaminectomy) and microsurgical exposure of the spinal cord.

RF lesioning in DREZ myelotomy requires a specially designed electrode that has sharpened tip (to penetrate spinal cord) with 0.25 mm diameter and 2 mm length, with an embedded thermocouple as well as shouldered insulation that prevents overpenetration of the tissue [13]. The procedure is done with a series of RF lesions with 75 °C tip temperature and 30 seconds duration performed 2 mm apart from each other along the line of DREZ as visualized under the surgical microscope.

Caudalis dorsal root entry zone radiofrequency lesioning/ radiofrequency trigeminal tractotomy-nucleotomy

A variation of DREZ myelotomy was suggested for targeting the trigeminal nucleus caudalis that is located in the uppermost segment of the spinal cord, just below the brainstem, under the vertebral levels of C₁ and C₂. The concept of selective destruction of the nucleus caudalis was introduced in 1938 by Olof Sjöqvist of Stockholm for treatment of severe facial pain [14], but deep location of the nucleus and proximity of multiple important structures prevented wide acceptance of this intervention.

RF trigeminal tractotomy, frequently referred to as nucleus caudalis DREZ, has been advocated as less invasive and overall safer

intervention compared to open tractotomy of Sjöqvist and is used for most refractory forms of facial pain, especially caused by facial deafferentation, such as anesthesia dolorosa, and cancer in the head and face region.

Since the target for trigeminal tractotomy is located under the more superficial dorsal spinocerebellar tract, the RF electrode had to be modified specifically for this application with addition of 1 mm of insulation between 2 mm electrode tip (0.25 mm diameter) and the shouldered Teflon insulation (0.6 mm diameter) [15]. This was done primarily to reduce the incidence of post-procedural ataxia. For ergonomic reason, the subsequent modification of this electrode had a right-angle bend few millimeters away from the tip to permit holding the electrode handle perpendicular to the surgical plane. The electrode itself was made in two configurations, with 2 mm uninsulated tip for RF lesion between the obex of the fourth ventricle and the C₁ level, and with 1.2 mm uninsulated tip for the narrower part of the nucleus caudalis between C₁ and C₂ vertebral levels [16]. The RF lesions with these electrodes are recommended to be performed at 1 mm intervals with 75 °C tip temperature and 15 seconds duration.

As an alternative to the caudalis DREZ procedure, Kanpolat suggested using CT-guidance to perform percutaneous trigeminal tractotomy [17]. For this, a needle is inserted into occiput-C₁ interspace from posterior direction with the patient positioned prone in the CT scanner. The electrode is inserted into the trigeminal nucleus and intraoperative electrical stimulation is used to confirm proper electrode position. Similar to percutaneous RF cordotomy, the procedure is performed with the patient awake and a myelographic contrast dye is injected into intrathecal space prior to the procedure in order to define the contours of the spinal cord below the craniocervical junction. The guiding cannula is inserted via parasagittal approach about 1 cm away from midline; the RF electrode is advanced into the spinal cord while observing continuous impedance reading. Impedance values increase from about 400 Ohm in the cerebrospinal fluid to about 1000 Ohm when the cord is entered. Following electrical stimulation with low (2–5 Hz) and high (50–100 Hz) frequencies to determine sensory and motor responses and CT confirmation of the electrode location in the posterolateral segment of the cord, an RF lesion is created with 70–80 °C for 60 seconds. A single lesion is usually sufficient to achieve desired clinical effect. In case of pain recurrence, the procedure may be repeated.

Radiofrequency thalamotomy/ pallidotomy/capsulotomy/ cingulotomy

Stereotactic lesioning of different cerebral structures has been used for treatment of chronic functional neurological disorders since 1940s. Techniques of lesioning evolved over time from mechanical excision (topectomy) to chemical destruction to focused radiation with implanted radioactive seeds and, eventually, to RF thermocoagulation. Prior to the introduction of deep brain stimulation (DBS), RF lesioning was considered standard and accepted treatment of essential tremor (RF thalamotomy), Parkinson disease and dystonia (RF pallidotomy); it was also used for treatment of severe depression and obsessive-compulsive disorder (RF capsulotomy and cingulotomy). As the matter of fact, the entire premise of DBS was born out of clinical use of electrical stimulation delivered through RF electrodes prior to the lesioning as correct location of the electrodes was usually conformed by temporary suppression of symptoms [18].

RF electrodes used for intracranial lesioning have standard length so they can be fit into a stereotactic frame that is aimed at the lesioning target. These electrodes are rigid, cylindrical in shape and have blunt tip to minimize brain injury and risk of hemorrhage. The length varies between 19 and 30 cm (25 cm is the most common length), diameter – between 1 and 1.8 mm (21 to 16 Ga), and the uninsulated tip length of 1 to 10 mm. The reason so many different sizes exist is that different neurosurgeons were trained in different places and in different decades and therefore have different preferences. Most practices would have several electrodes of the same configuration except for the length of uninsulated tip as this may be needed to create proper size lesion in selected intracranial target.

The size of the tip of RF electrode determines the size of the lesion as much as the temperature and duration of lesioning [19]. For thalamic and pallidal targets the desired lesion is 3 mm in diameter or less with the height of 5–6 mm along the chosen trajectory; therefore, a 1–3 mm electrode tip is preferred for RF thalamotomy and pallidotomy. Capsular and cingulate targets, on the other hand, are larger; for RF capsulotomy and cingulotomy one would use 5 mm or 10 mm electrode tips.

RF lesioning targets are chosen based on individual clinical presentation. The list of targets is long and includes different thalamic nuclei,

pallidum, subthalamic area, the fields of Forel, anterior limb of the internal capsule, amygdala, cingulum and cingulate gyrus, etc. In general, the targets for lesioning coincide with targets for DBS, but there are some important nuances – mainly the risk of complications – that either prevent lesioning or make DBS not feasible.

In case of essential tremor or tremor-dominant Parkinson disease, the target of choice is the ventral intermediate nucleus of the thalamus (VIM) [20]. For advanced Parkinson disease and especially for levodopa-induced dyskinesias, the ventroposterior segment of the globus pallidus pars interna (GPi) is the preferred lesioning target [21]. Same GPi location is used for treatment of dystonia [22]. Anterior limb of the internal capsule [23] and supracallosal cingulate [24, 25] targets have been used for treatment of severe depression and obsessive-compulsive disorder. The anterior nucleus of the thalamus has been a target for RF lesioning in intractable epilepsy [26].

The coordinates of the target are calculated based on widely known anatomical atlases and defined relative to standard stereotactic landmarks that were established even before three-dimensional imaging (such as computed tomography and magnetic resonance imaging) was invented. The original investigations and clinical series used cerebral ventriculography and stereotactic X-rays in orthogonal planes to evaluate the anatomy of deep cerebral structures; due to this the universal cartesian system of coordinates calculates target location in all three planes relative to the anterior and posterior commissures, the thalamic height and the width of the third ventricle. Currently, computer software is routinely used for stereotactic calculations, and the coordinates are derived not only from the atlases but also from direct visualization of target locations on frame-based or frameless imaging studies.

Once the coordinates are finalized and the stereotactic system of choice (frame-based or frameless) is locked and loaded, the physiological confirmation can be obtained through microelectrode recording and/or with intraoperative test stimulation. RF probes may be used for such stimulation; usually a low frequency stimulation is used for testing the proximity of motor and visual pathways whereas sensory testing is accomplished by a high frequency stimulation. Since the majority of surgeries for movement disorders (with the exception of generalized dystonia and pediatric patients) are done with the patient awake, the patients are asked to describe presence and location of paresthesias,

changes in the tone of extremities and fluidity of movements, as well as any visual phenomena in response to test stimulation in order to define best location for RF lesioning. Similarly, the duration of lesioning itself and the number of lesions are dictated by the degree of symptomatic improvement. This may be easily noticeable as in cases of tremor and somewhat less straightforward in cases of focal dystonia.

RF lesions are performed with 75–80 °C for 60 seconds in VIM thalamotomy and with 80–85 °C for 60–90 seconds for GPi pallidotomy. For RF anterior thalamotomy, two lesions are created on each side with 70 °C for 70 seconds. For RF cingulotomy, bilateral lesions are performed at 85–90 °C and 90 seconds with two or three lesions next to each other on each side. For RF anterior capsulotomy, lesions with 75 °C for 90 seconds are made on both sides. Usually, a control imaging is performed post-operatively to rule out hemorrhage and confirm location of RF lesions.

Radiofrequency lesioning equipment

Since RF lesioning was an integral part of functional neurosurgical practice, for many years there were many vendors of RF electrodes and generators. In the United States, the leader of the field was Radionics, Inc from Burlington, Massachusetts that was founded by Bernard Cosman in 1938 and released first commercial RF generator in 1952. For several decades it offered a comprehensive list of most electrode configurations, vast majority of which were reusable. Following acquisition of Radionics by Tyco in 2000 and subsequent transfer to Integra in 2005, the interest to RF equipment was lost and the technology was acquired by a newly formed company Cosman Medical that in essence inherited all Radionics customers and loyal followers. In 2016, Cosman Medical was acquired by Boston Scientific.

In Canada, the leader of RF equipment has been Diros Technology, Inc located in the Greater Toronto area. Diros line of RF products features OWL generators and variety of RF electrodes, both disposable and reusable ones. The first OWL RF generator came out in 1969; since that time OWL RF equipment has been used for most neurosurgical indications and was featured in many scientific publications.

In Europe, RF generators have been manufactured by Elekta (Sweden) and Leibinger-Fisher (Germany), both of which have also been making and selling stereotactic surgical equipment (Lek-

sell and Zamorano-Dujovny (ZD), respectively). It appears that Leksell Neuro Generator (Elekta) and Neuro N50 Lesion Generator (Stryker/Leibinger) are not currently sold in the US.

Neurotherm (acquired by St. Jude Medical and subsequently Abbott), Avanos Pain (former Baylis Medical, acquired by Kimberly-Clark/Halyard/Avanos Pain Management), Synergetics (acquired by Stryker) and Smith+Nephew also make RF generators, but Abbott/Neurotherm NT2000iX RF generator, Avanos/Halyard Pain Management RF generator and Stryker MultiGen 2 RF generator are designed exclusively for non-neurosurgical pain applications, and Smith+Nephew Electrothermal system has RF applications for arthroscopic use.

Conclusions

Radiofrequency thermocoagulation is an established neurosurgical modality that has many

time-tested applications in surgical treatment of chronic pain, movement disorders, epilepsy and psychiatric conditions. High selectivity, reproducible and predictable lesion size, relatively low invasiveness, as well as decades of clinical experience make RF lesioning an attractive option for a multitude of applications. Lack of implants, ability to perform majority of procedures without general anesthesia, lower procedural costs are important benefits of RF lesioning. Disadvantages of this approach include irreversibility of its effect, lack of adjustability and testability (as seen in case of electrical neuromodulation), as well as marked decline in the number of centers that are competent and comfortable offering RF lesioning to their patients. Recent renaissance of interest in targeted destructive interventions brought up a significant increase in educational offerings on this topic; all this may result in steady growth of amount of RF lesioning procedures all over the world.

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