Technical Aspects of Radiofrequency

M. Sluijter, MD, PhD*; G. Racz, MD†
*Pain Unit, Swiss Paraplegic Center, Nottwil, Switzerland;
†Dept. of Anesthesiology, Texas Tech University Health Sciences Center,
Lubbock, Texas, USA

Abstract: Radiofrequency (RF) is an alternating electric field with an oscillating frequency of 500,000 Hz. If the resulting current flows through a percutaneously introduced electrode, heat will be produced around the electrode because the body tissue acts as a resistor. RF can, therefore, be used to ablate nervous tissue in the treatment of chronic pain. This method has gained acceptance for percutaneous cordotomy and for the treatment of trigeminal neuralgia. For spinal pain, the method had little success initially, but since the introduction of small diameter instrumentation, the results have markedly improved.

The mechanism of action of RF has not been challenged until recently even though there was awareness that some observations were not consistent with the heat concept. The formation of heat is not the only occurrence during RF treatment, however. The tissue surrounding the electrode is also exposed to the RF electric field. This exposure has a biological effect as has been demonstrated both in cells in a cell culture and in the exposure to RF of dorsal root ganglia, resulting in transynaptic induction of early gene expression in the dorsal horn. The mode of action of RF is, therefore, uncertain at the moment.

The method of pulsed RF is based on the concept that the production of heat has been a by-product of RF treatment and that the clinical effect is due to exposure to the electric field. In pulsed RF, the generator output is interrupted to allow for the elimination of heat in the silent period. The early results have been encouraging, but the results of controlled, prospective studies are not yet available.

Since there are now 2 almost diametrically opposed views on the mode of action of RF, it is difficult to give recommendations for treatment. The decision is easy for indications for which heat RF has traditionally been contraindicated such as the treatment of peripheral nerves and trigger points. When the application of heat carries a potential risk, for instance if the dorsal root ganglion is the target structure, the use of pulsed RF is also recommended. As for the medial branch the situation is controversial. Since there are controlled studies available showing the effect of heat lesions, it is recommended that the technique should not be changed until further studies have been completed.

Finally, the equipment for RF treatment is described and safety issues are discussed.

I. WHAT IS RADIOFREQUENCY TREATMENT?

When causative treatment is not feasible and when conservative modalities have been exhausted in the treatment of chronic pain, invasive treatment may be considered. RF is one of those invasive forms of treatment. During RF treatment and electrode is introduced through the skin to be positioned in or near to a neural target structure. The electrode is connected to a RF lesion generator and the electric circuit is completed by connecting the patient to a dispersive groundplate.

RF is an alternating current with an oscillating frequency of 500,000 Hz. When the lesion generator pro-
duces an output current starts flowing in the circuit. This current flows through body tissue, which acts as a resistor. Current flowing through a resistor produces heat. The production of heat will be highest where the current density is highest at the electrode tip. In this region, the tissue heats up and the tissue in turn heats the electrode tip, it is not the other way around.

RF may, therefore, be used for destruction of tissue. For example, RF is used to ablate tumour metastases. This article deals exclusively with the application of RF for the treatment of chronic pain by modifying the behaviour of nervous tissue.

The use of RF for the treatment of pain originates from the percutaneous lateral cordotomy for unilateral malignant pain. Initially, Mullan described a technique using a direct current but Rosomoff modified the technique to use RF current because this was found to produce more predictable, circumscribed lesions. A few years later Sweet described a technique for using RF lesions in the Gasserian ganglion in the treatment of trigeminal neuralgia. The use of RF for the treatment of pain of spinal origin was first described by Shealy.4

Initially the use of RF for spinal pain did not acquire general acceptance. The electrode that was used by Shealy was large in diameter, confining its use to the medial branch of the posterior ramus of the segmental nerve, innervating the facets joints. Approaching more anterior structures with such a large instrument carries the risk of causing mechanical damage. Since only a minority of back pain patients have a facet problem, indications were limited. The use of this large electrode to make RF lesions in the dorsal root ganglion had too many side effects and was soon discarded. By the end of the 1970s, RF for spinal pain was only practised by a handful of neurosurgeons. The main indications for RF remained the percutaneous cordotomy and the treatment of trigeminal neuralgia.

In 1980, there was a turning point. Small diameter equipment became available. This predictably diminished the discomfort during the procedure, but it also became possible to apply RF to targets in the anterior compartment such as the dorsal root ganglion, the communicating ramus, and the sympathetic chain. Since spinal pain is often of complex origin, this greatly contributed to the applicability and the effectiveness of RF treatment.

A final development was the advent of intradiscal RF for the treatment of discogenic back pain. Since its first introduction, more sophisticated equipment has been developed for this application. Although the mechanism of action is not entirely clear yet the initial results are encouraging.

The present position of RF can be described as follows. The original application of percutaneous cordotomy is no longer used any longer. This is because the development of newer analgesics and the administration of analgesics through the epidural and intraspinal route has limited the number of indications. This in turn has a cycle effect. A percutaneous cordotomy requires routine and technical adroitness. If the number of procedures is limited, this also limits the possibilities of teaching the procedure. The treatment of trigeminal neuralgia with RF remains a widely accepted form of treatment with a large and stable popularity. RF treatment of spinal pain enjoys a fast growing popularity and acceptance. Indications include acute and chronic radicular pain, mechanical back pain and sympathetically mediated pain.

II. ASSUMED MODE OF ACTION OF RADIOFREQUENCY

The mode of action of RF is presently a subject of discussion. Since its introduction, the role of heat in producing the clinical effect has never been questioned. A number of observations however are difficult to explain from that hypothesis. Since RF electric fields do have a biological effect that is temperature independent, there is a possibility that the views on the mode of action of RF need further examination. This matter has not been decided yet. These subjects will now be dealt with in more detail.

Heat Production and the Effects of Heat

As soon as RF current starts flowing in the electric circuit, heat will be generated. Since the current mainly spreads sideways from the tip of the electrode, this is where most of the heat is produced. This fits with experimental work. A heat lesion is pear-shaped with the base where the insulation of the electrode ends and with very little heat spreading ahead of the electrode tip.

The relationship between the generator output and the resulting temperature around the electrode tip is not a direct one. It is controlled by variables governing both the production of heat and the rate at which heat is eliminated. On the production side the important variable is the impedance (resistance to alternating current). The impedance varies widely from tissue to tissue and the production of heat is inversely proportional to the impedance for a given current density. The elimination of heat depends on 2 factors: the conductivity of the tissue and the vascularisation, because blood flow carries heat.
away from the heated area. Both factors vary widely and, therefore, the temperature at the electrode tip must be measured to know what the net result of generator output and heat washout really is.

An RF lesion has 2 phases. During the first phase, a large generator output is needed to build up heat in the lesioning region. The lower the impedance, the higher the generator output that is needed. The voltage in this phase may vary from 25-60 V. Once the desired tip temperature has been reached, the second phase sets in and the output of the generator is gradually lowered until a level is reached that compensates for the heat washout. This level will be higher in vascular tissue and the other way around.

The effects of heat on neural tissue are of course destructive. Changes are thought to be reversible up to 45°C. Coagulation of protein occurs at temperatures > 60°C. Since there is a temperature gradient within the RF lesion from the central area to the periphery, the more peripheral areas in the lesion are only exposed to moderate temperatures. Some RF techniques specifically aim to expose the target structure to these moderate zones. This is because this may prevent deafferentation sequelae and because moderate temperatures are thought to have a selective effect on small unmyelinated nerve fibers. This view is based on one single publication describing an experiment on a cat's nerve. An anatomical correlate of this assumption has repeatedly been sought but it has not been found.

The concept of the mode of action of a heat lesion in the treatment of chronic pain is in fact quite simple. If there is continuous nociceptive input from a focus this input can be stopped by destroying the fibers conducting it. If heat at moderate temperatures indeed destroys small nerve fibers selectively, this enhances the effect of heat lesions on chronic nociception and it may even give us a tool to destroy small fibers while large fibers are left relatively intact. Postoperative discomfort is caused by reactive swelling of tissue and recurrence of pain eventually occurs because the nervous tissue regenerates.

Observations That Are Not Consistent with the Heat Concept

Throughout the period that heat lesions have been used universally there have been a number of observations that were not adequately explained. Little attention was paid to these discrepancies, because the role of heat was an undisputed cornerstone of RF treatment. The most important discordant observations are the following:

The duration and the time sequence of the phase of postoperative discomfort. This discomfort typically starts 4 to 5 days following treatment and it may last up to 6 weeks. If the discomfort is really due to swelling it is hard to see why it takes so long before it starts and why it lasts so long once it has started. Additionally “preventive” injection of steroids at the end of the procedure do not have the slightest effect.

The effectiveness of so-called “perpendicular procedures.” Certain RF procedures are by general consensus successful. In a number of these procedures the position of the electrode is perpendicular to the target structure. For example, the most widely-used technique for treating the medial branch in the cervical region has been the approach from the side, the electrode ending up in a perpendicular position. Since heat hardly spreads ahead of the electrode tip, it is hard to explain that this approach has been so successful. Other examples include the dorsal root ganglion procedures in the lumbosacral and thoracic regions.

The duration of the clinical effect. Once treatment with a RF lesion has relieved pain, the effect may last up to 2 years or even longer. This is difficult to explain from the heat concept. If damage is done to a nerve there are 2 options: the neuron may survive or the neuron may die. There is nothing in between. If it survives, any lasting clinical effect is unlikely. If it dies, regeneration may occur, but it is hard to see why this should take so long.

An apparently unique position of RF. Throughout medical history neuroablative procedures have almost invariably had disappointing if not dismal results. Relief of pain has at best been temporary and in many instances neuropathic pain has been substituted for nociceptive pain. There is no explanation why RF should be so different. Again, there are 2 options here. Either RF really denervates a nociceptive focus. Then why is it not followed by clear signs of sensory loss and by neuropathic pain? Or RF, in fact, does not denervate at all. Then the heat concept is wrong.

Biological Effects of RF Fields

The formation of heat is not the only occurrence during RF lesions. The tissue that surrounds the electrode is also exposed to the RF electric field. The question then arises if these fields do have a biological effect that is temperature independent. This is indeed the case. RF elec-
tric fields are used by cell biologists to separate various types of cells in a cell culture. Archer investigated if this exposure had any biological effect on such cells during the exposure period. It turned out that there was no effect on morphology, division rate and respiration but that there was expression of c-fos and other as yet unidentified early and intermediate genes. These experiments were done while the temperature was held constant.

Another indication of a biological effect of RF fields is the result of experimental work with pulsed RF. Pulsed RF is a new method of applying RF without raising the temperature and it will be discussed below. When pulsed RF is applied to the dorsal root ganglion of a rat c-fos is expressed in lamina I and II of the corresponding part of the dorsal horn. Since during pulsed RF the delivered output has its normal oscillating frequency of 500.000 Hz, which is far higher than the physiological threshold, this cannot be an effect of cell depolarisation. Additionally, a transient modulation of excitatory synaptic transmission in hippocampal organotypic nervous tissue has recently been reported.

These findings result in a totally different working hypothesis for the mode of action of RF. This hypothesis can be summarised as follows:

RF acts by exposure of the first neuron to a RF electric field. This exposure causes expression of various early and possibly intermediate genes in the dorsal horn — and possibly in more central parts of the afferent chain — through transsynaptical induction. Conceivably each gene has its own time cycle, both in its primary effect and in its secondary effect. For example, the fos protein combines with other nuclear proteins to form the AP1 transcription factor, regulating the expression of other genes. This whole train of events might explain the cyclic course of the clinical effect of RF.

The effect occurs selectively in small fibre neurones, presumably because large neurones are shielded from the electric field by their myelin sheath.

Postoperative discomfort is due to facilitation at the dorsal horn level as a sequence of gene changes.

Recurrence of pain is due to a return of the dorsal horn neuron to its original state by default of further exposure to the electric field.

It is of interest to note that since the electric field spreads forward ahead of the electrode tip — and not sideways like heat — the position of the electrode should preferably be perpendicular to the target structure if this concept is valid, but this needs clinical and experimental evaluation.

Pulsed RF

These lines of thinking have led to a search for methods to apply RF at nondestructive tip temperatures. This could be achieved by cooling the electrode tip, but this may lead to very high temperatures away from the electrode tip. This is in fact the principle of tissue ablation for metastatic tumours. Alternatively the generator output could simply be reduced but this would only permit the use of very weak electric fields.

In pulsed RF, the output of the generator is interrupted. The usual pattern is 2 cycles of 20 msec each of active cycle. This offers the advantage that a generator output of normal intensity can be used during the active phase of the duty cycle. The passive phase is inserted to enable the heat washout to take away the heat that has been formed during the active cycle. The pulsing characteristic of the duty cycle supposedly does not have any biological effect by itself.

Clinical results have been encouraging so far, but controlled studies are still lacking since the method is still young. The method seems to work irrespective of the site of exposure of the neuron. Peripheral nerves have been treated successfully, procedures involving the sympathetic system have been effective as well in cases of sympathetic mediated pain. Even peripheral painful trigger points have been treated with good results.

Recommendations

In conclusion there are now 2 almost diametrically opposing views on the mode of action of RF. This is confusing, but hopefully this period of uncertainty will be of limited duration. In the meantime, clinical work goes on and recommendations have to be made. The authors recommend the following guidelines:

When RF is applied for indications for which heat RF has traditionally been contraindicated the decision is easy: Pulsed RF should be used exclusively. These indications include the application of RF to peripheral nerves and to painful trigger points.

Since the advent of small diameter electrodes, RF has been a relatively safe method. Nevertheless, complications have occurred and heat is potentially dangerous when applied to certain targets. When there is such a potential hazard, the use of pulsed RF is recommended. These indications include dorsal root ganglia, the superior cervical ganglion,
III. EQUIPMENT FOR RADIOFREQUENCY TREATMENT

Traditionally a RF lesion generator has the following modules:

Impedance Measurement. This measurement is indispensable for detecting breaks or short circuits in the electrical circuit. In certain procedures impedance measurement is also used to detect entry into a different medium. For example, when doing a percutaneous cordotomy a steep rise in impedance indicates that the electrode has entered into the spinal cord from its position in the cerebrospinal fluid. Also, inside an intervertebral disc a very low impedance indicates that the tip is in the nucleus instead of in the annulus fibrosus, where the impedance is much higher.

Electrical Stimulation. Usually one can at least choose between a 2 Hz current for motor stimulation and a 50 Hz current for sensory stimulation. Stimulation is important for physiological confirmation of the position of the electrode in relation to the target structure. Sensory stimulation confirms proximity to the target, motor stimulation confirms a safe distance to motor fibers in case a heat lesion is made.

The Lesioning Module. This mode should provide the facility for generating both continuous and pulsed RF.

Temperature Measurement. The necessity to measure temperature has been explained above. For heat lesions the role of temperature measurement needs no further comment. During pulsed RF temperature measurement is needed to avoid neurodestructive temperature levels. Occasionally the heat washout is so low that a slight adjustment downwards of the generator output has to be made during the final part of the procedure.

IV. SAFETY ISSUES

Safety issues include manufacturing aspects and basic knowledge of the operator. A lesion generator should be properly grounded to prevent electric shocks during treatment. Also it is mandatory that changes from one functional module to the next should be impossible while the output is not in zero position. Inadvertent stimulation for example while an electrode is close to a major nerve is very unpleasant to the patient.

Safety issues that the operator should be aware of are virtually non-existent when pulsed RF is used, since this is a non-destructive method of applying RF. When continuous RF is used safety issues include the following:

Sensory Stimulation. Some procedures require a minimum value for the sensory stimulation threshold. This is to prevent the occurrence of denervation sequelae (neuropathic pain) following the procedure.

Motor Stimulation. Motor stimulation should always precede heat lesioning. If there is a break in the insulation of the shaft of the needle or the hub, current can leak and cause coagulation of tissues.

Electrode Configuration. Electrodes should be used that have been manufactured for the type of lesion generator that is being used. Also, many electrodes consist of a RF probe fitting into a disposable cannula. These cannulae may slightly vary in length. If the tip of the probe does not reach all the way down in the cannula, this leads to temperature readings that are too low. This is especially dangerous when automatic temperature control is used since the generator then gets the wrong signal that it needs a larger output. Electrical parameters should always be closely watched during a procedure and if there is any discrepancy the procedure should be terminated.

Lesions in Inhomogeneous Tissue. Heat lesions are not always nicely demarcated. In regions in close proximity to bone or in scar tissue a heat lesion may potentially have a very irregular outline due to local differences in impedance and in conductivity. This has led to complications in the past. It
is suggested that pulsed RF be used when the possibility of such an occurrence is suspected.

**Lesions in Patients with Pacemakers.** Patients that have sensing pacemakers need consultation with a cardiologist to convert the pacemaker to a fixed rate device for the duration of the procedure.

**Lesions in Patients with Spinal Cord Stimulators.** If the patient has 1 or more implanted spinal cord stimulators in the monopolar mode setting, the setting needs to be changed to bipolar and OFF for the duration of the procedure.

**REFERENCES**


