RADIOFREQUENCY ELECTROSURGERY

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Although most otolaryngologists use electrosurgical instruments routinely, many are not familiar with the basic principles as to how these instruments produce their effect. This problem is compounded not only by numerous recent advances in otolaryngology applications of electrosurgery, but also by improper terminology propagated in the literature. This article presents a review of the history, physics, techniques, and histological effects of electrosurgery specifically relating to the radiofrequency needle ablation technique.

Heating of tissues has been used for thousands of years to treat a variety of conditions or to help stop bleeding from a wound.[1] Hippocrates suggested that heat often was a predominant manifestation of disease and could be used to treat joint problems and hemorrhoids. Medieval warriors used heated stakes to treat bleeding injuries. It was not until the late nineteenth century, however, that a French physicist named d'Arsonval introduced electrical current flowing through the body as a way of producing heat in tissue.[2] The first electrosurgical generator to be widely accepted by physicians was produced through the collaboration of a physicist and a surgeon.[1,3,4] In the 1920s, a Harvard physicist named William T. Bovie developed an electrosurgical device to aid in the removal of tumors. Harvey Cushing attended a staff meeting where the progress of this research device was discussed and Cushing became interested. He asked Bovie "if [Bovie] thought we could prevent some loss of blood in a brain operation," and with that, Bovie developed the prototype of the modern electrosurgical unit. Little has changed in the basic principles applied in Bovie's invention.

Recent advances in otolaryngology applications of electrosurgery, such as radiofrequency tissue volume reduction for upper airway obstruction, have raised questions about the fundamental principles of operation of electrosurgical units.[5,6,7,8]

Electrosurgery often is confused with electrocautery. The latter, however, does not use high-frequency current and does not perform cauterization by passing current through tissue. Electrocautery operates like a toaster oven or soldering iron: ordinary current passes through a heating element that raises its temperature to the desired level. In electrocautery, the heating element conducts heat to an active blade, and this "hot blade" is used to cauterize. Electrosurgery is fundamentally different because it uses electromagnetic energy passing through tissue to produce heat within the tissue.

ELECTROMAGNETIC SPECTRUM

Electromagnetic energy is used in electrosurgery to heat tissue. The portion of the spectrum in which radiowaves are broadcast is between 300 kHz and 3 MHz and includes AM and ham radio as well as air and marine navigation (Fig 1). Because the frequency range used by electrosurgery lies within the radiofrequency broadcasting band, the electrosurgical unit often is referred to as a "radiofrequency" or RF generator.

Passing current through tissues is not without risk. Ventricular fibrillation occurs at current levels in the range of 50 to 500 mA passing through the body at extremely low frequencies (50 to 60 Hz) of commercially delivered power.[9] Current levels of about 1 A and above produce asystole at these frequencies. In the radiofrequency range, however, the nervous and muscular systems are significantly less sensitive to the current flow, although muscle or nerve stimulation can occur.[10,11] The radiofrequency portion of the electromagnetic spectrum is therefore particularly useful to the surgeon as a way of using electromagnetic energy passing through the body to selectively create lesions in tissue without creating electrical shock.

BASIC PHYSICS

The basic principle of electrosurgery is that of rapid and selective tissue heating using high frequency current passing through tissue for cutting, coagulation, or ablation. Electrosurgery exploits localized heating in tissue by a high frequency alternating current in the range of 300 kHz (300,000 Hz) to 3 MHz (3 million Hz). This high-frequency current flows between a probe or electrode manipulated by the surgeon and a grounding or dispersive pad placed in contact with the patient, often with the thigh for head and neck procedures (Fig 2). The power is dissipated in the form of heat not in the probe, however, but rather in tissue near the probe, typically within millimeters from its tip.

Radiofrequency current in the body arises from the flow through extra and intracellular fluid ions that include the common electrolytes Na^+, Cl^-, Ca^{++}, and Mg^{++}. These ions move under the force of the electric field, which is present in the radiofrequency wave propagating through the body. The ions encounter resistance in their path by way of collisions with other molecules generating heat. The greater the resistance to flow, the more heat is generated. If we assume homogeneous tissue, the general equation which expresses the local rise in temperature ΔT (°C) is,

$$\Delta T = \frac{J^2 \rho t}{CD}$$

where t is the duration of the current flow (sec), D is the

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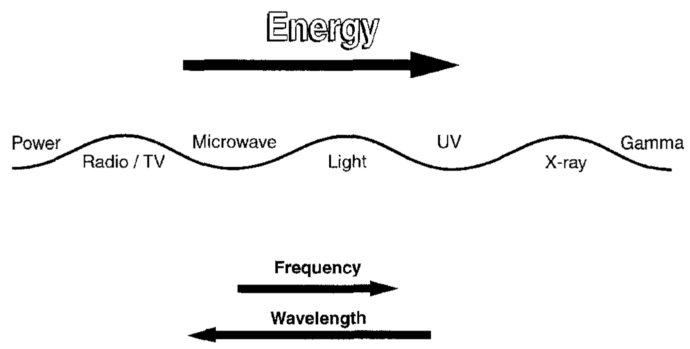

FIGURE 1. The electromagnetic spectrum.

tissue density (kg/m^3), and C is the tissue's specific heat capacity (kcal/kg/°C). Note that resistivity varies from tissue to tissue, depending upon its microstructure, water content, and electrolytic ion concentration.

The equation referred to before is particularly instructive in the practical application of electrosurgery. First, the temperature rise ΔT is directly proportional to the time t that the probe is activated and held in place. Doubling that time doubles the temperature rise in the tissue. Second, the rise in temperature is proportional to J^2; thus, the current density is especially important in determining local tissue heating and the desired effect. For example, if the current and thus the current density, is doubled, the local temperature rise is increased by a factor of 4.

The equation also explains why the tissue heating is so localized in the vicinity of the active probe, generally in the range of about 1 mm to 1 cm. When we examine what happens within the tissue as we move away from the probe, we would observe that the current fans out, the current density J decreasing approximately as the inverse square of the distance (Fig 3). From the equation we see that the local temperature rise ΔT depends on J^2. Therefore, ΔT must fall off inversely as the 4th power of the distance from the probe tip. This means that if the temperature rise is ΔT near the probe, at twice that distance away, ΔT would be a factor of 16 lower. Of course, these considerations can only be regarded as first approximations to the dynamic processes occurring in practice. For example, we are treating direct action of the electric field and induced current density on the tissue; one must also consider that heat will flow from the high T into lower T regions by normal thermal conduction.

EQUIPMENT

The basic components of an electrosurgical system include the electrosurgical unit (radiofrequency generator), the active electrode, the dispersive pad, and the patient (Fig 2).[12] The RF current leaves the electrosurgical unit via the active output, along a cable to the active electrode. The active electrode is the pencil or needle, which is insulated except for the tip or point. The current flows from this area of high current density through the patient's tissues, incorporating the patient as part of the electrosurgical circuit. The dispersive (grounding) pad refers to the larger area electrode through which the current is returned to the electrosurgical unit to complete the circuit. Notice that the current density is much lower at the dispersive electrode and therefore no tissue effect or "burn."

NEEDLE ABLATION (RADIOFREQUENCY NEEDLE ABLATION, THERMAL ABLATION, RADIOFREQUENCY TISSUE REDUCTION)

Needle ablation technology is used in cardiology for the ablation of aberrant pathways, in neurosurgery for selective destruction of central nervous system lesions, and in urology for transurethral needle ablation for prostate hypertrophy. These techniques have proven safe, precise, and well tolerated methods of lesion making in areas containing nearby critical anatomy. More recently, needle ablation has been applied to otolaryngology as a way to ablate excess upper airway tissue to treat obstruction and sleep disordered breathing.[5-8]

In needle ablation, the high current density in tissue within a few mm of the needle electrode causes a rapid local temperature rise, to a range of 50° to 90°C, within seconds to minutes, resulting in thermal injury and irreversible tissue destruction (Fig 4). When the 100°C threshold is reached, boiling at the electrode-tissue interface results in tissue coagulum adhering to and insulating the electrode and there is an abrupt drop in current density; tissue heating ceases, as do lesion formation and tissue damage.[13]

In recent years, electrosurgical devices developed for needle ablation, ie, thermal ablation, have incorporated thermistors or other sensors in the electrode to monitor local tissue temperature to prevent tissue near the electrode from attaining 100°C. The sensor automatically shuts off the current and this determines maximum lesion size.

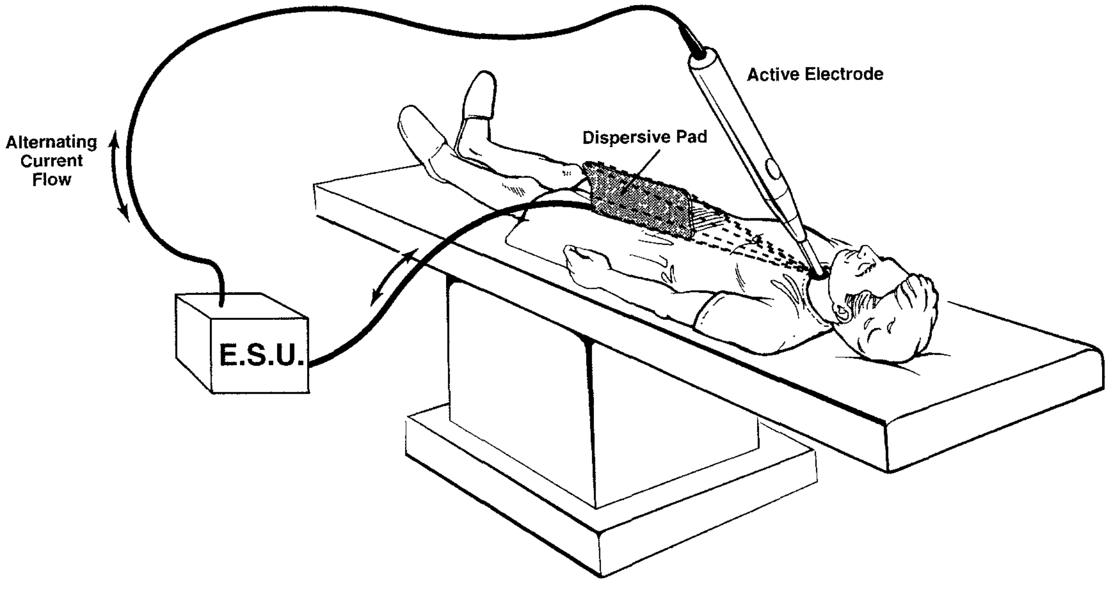

FIGURE 2. The electrosurgical circuit. Current flows through tissues from the active electrode to the dispersive pad.

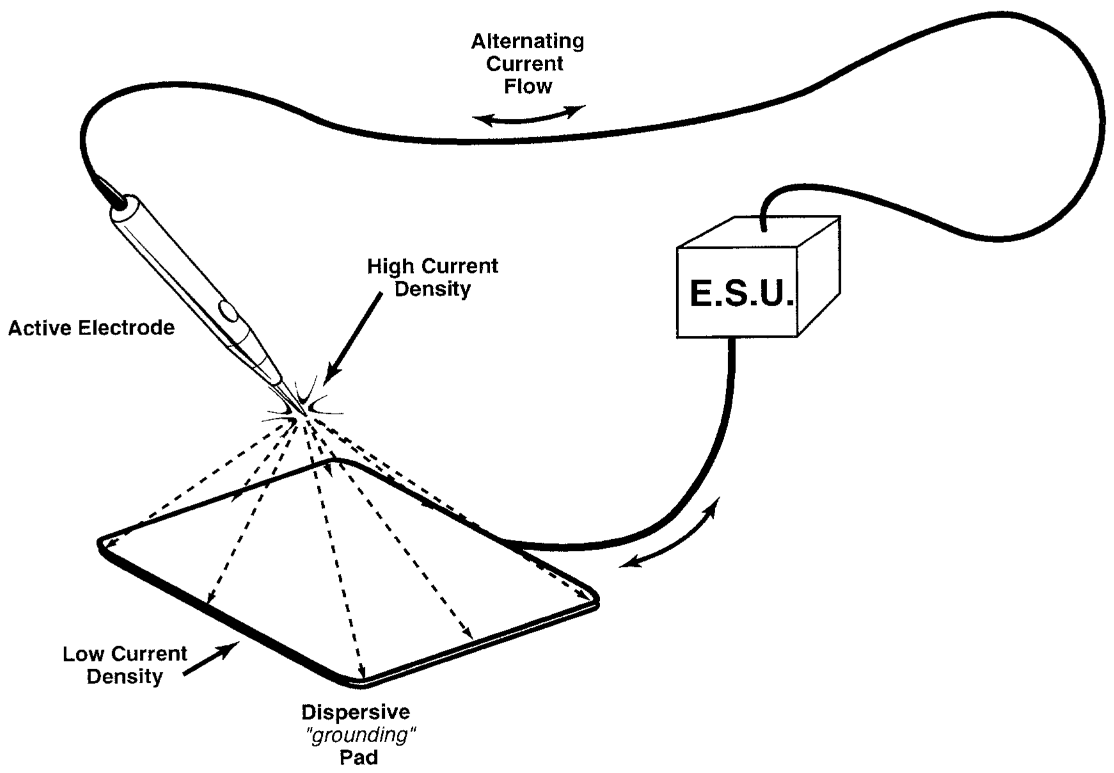

FIGURE 3. The high current density at the active electrode disperses to the grounding pad.

Several authors have described the advantages of temperature monitoring during ablation procedures.[5-8,14,15]

Lesion size depends on current intensity and duration, and on electrode size. Lesions produced by needle ablation techniques have a "football shape" known as a prolate spheroid (Fig 5).[15] Controlling for current intensity and duration, maximum lesion size can be predicted by examining the axes of a prolate spheroid: the major axis is 2 times the length of the uninsulated electrode, and the minor axis two thirds the length of the major axis. For example, a 10 mm uninsulated 22-gauge electrode would produce a maximum lesion of 20 mm × 13 mm (approximately). For larger electrodes, the current must be increased so as to generate sufficient current density and heat to obtain the larger lesion.

During formation, lesions of varying sizes and shapes result from heat loss by convection and conduction as well as from nonuniformity in heat generation by the radiofrequency current. Tissue surrounding areas of high current density and temperature will act as a heat sink conducting heat away from the site of lesion formation. Blood will carry heat even more rapidly away from well vascularized areas such as nasal turbinate tissue.

TISSUE EFFECTS

We have discussed how the (1) frequency of the alternating current, (2) the power used in the application of the current, (3) the waveform produced by the electrosurgical unit, and (4) the time of application can dramatically change the effect on tissue. Another important factor that influences tissue effect is (5) the size of the active electrode.[16,17] When 1 electrode is large (dispersive) and the other is small (active), the current flowing between the 2 is not evenly dispersed but attains sufficient density at the small active electrode to result in local tissue heating (Figs 2, 3). Clearly, holding other factors constant, the larger the active electrode, the lower the current density at that active electrode.

HISTOLOGY

The tissue temperature differences among various surgical heating processes vary; they can be as low as 45°C or well over 500°C. Accordingly, the biological effects significantly differ, ranging from gentle tissue dehydration to burning, charring, and carbonization. The final histology depends heavily on the ultimate tissue temperature and the duration at that temperature. Previous studies have shown this temperature-dependent effect.[18,19] The earliest evidence of hyperthermal injuries is functional rather than structural. Capillaries become dilated as tissue temperature rises, the permeability of capillary walls increases, and tissue edema results. Injury during periods of minimal temperature rise (40 to 45°C) is the result of accelerated metabolism of hyperthermal tissue and many hours are ordinarily required before irreversible changes occur. The temperature at which many animal cells die rapidly because of the denaturation of heat-sensitive proteins and enzymes appears to be 45°C. At 60°C for 50 seconds, cell polarization, dissociation with nuclear damage, edema, and hemorrhage are noted. At 70°C, these changes are intensified, in addition to focal necrosis and peripheral edema. At 80°C, necrosis and edema are more pronounced. The margins of the lesion are well demarcated after H&E staining at these temperatures. Beyond this border of injury is an extensive zone of edema. Temperatures above 100°C lead to water vaporization and cell explosion. Tissue charring and carbonization can occur above this temperature.[14]

ADVANCES IN ELECTROSURGERY

Some recent developments in the field of electrosurgery for otolaryngologists have involved minimally invasive techniques to electrosurgically ablate excess tissue thought to be responsible for upper airway obstruction.[5-8] In animal models, significant volumetric reduction of tongue tissue was seen at the specific ablation site.[13] Clinical trials have studied effects of tissue reduction and vibratory reduction

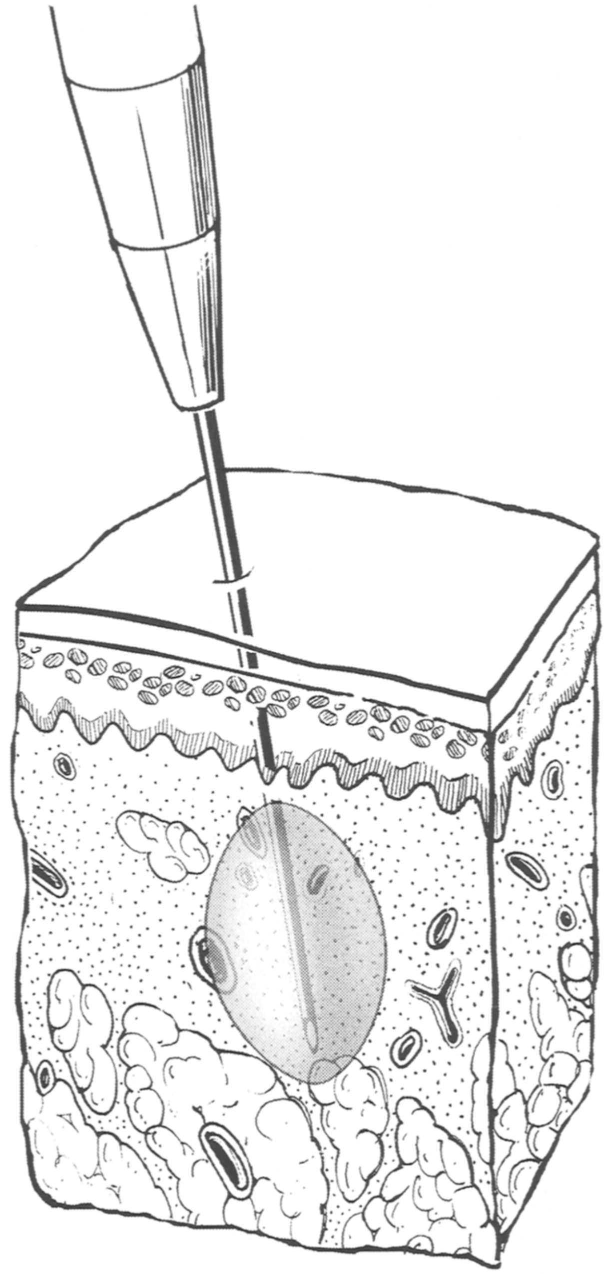

FIGURE 4. Subsurface lesion is produced around the active portion of the needle electrode. The proximal portion of the needle is insulated.

of the palate as well as nasal turbinate reduction. These electrosurgical devices use a monopolar needle electrode to deliver low levels of radiofrequency energy to create controlled necrotic lesions in soft tissue structures (Figs 6-8). Current flows from the active needle electrode through the patient to a dispersive pad, making this technique a type of electrosurgery. Low voltage (approximately 80 V) and low power (under 15 W) generate relatively low-tissue temperatures (generally under 90°C). Thermocouples located within the needle electrode allow continuous monitoring of tissue temperature. Based on continuous feedback information from the electrode thermocouples, power is varied so that maximum tissue temperature can be controlled by the surgeon. Temperatures need to be kept under 100°C to prevent boiling at the electrode-tissue interface, which creates charring and coagulation of the needle, insulating it, and preventing proper current flow. The electrosurgical generator provides continuous real-time information not only on tissue temperature but also on circuit impedance, power level used (W), time of application, and total energy delivered to the tissue (Js).

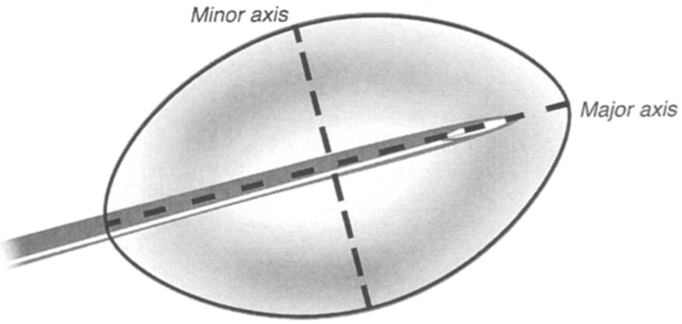

FIGURE 5. A 3-dimensional prolate spheroid lesion produced around the active portion of the needle electrode.

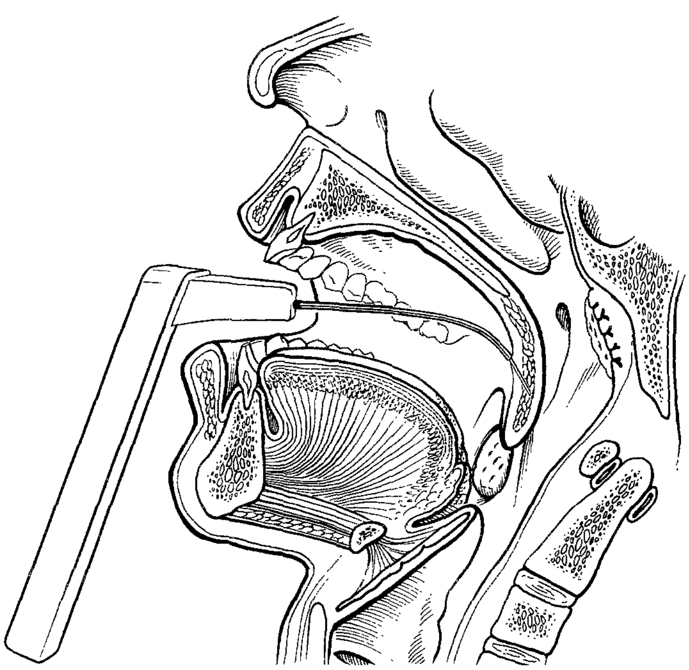

FIGURE 6. Placement of the electrode within the palate. The distal 1 cm of the needle is "active."

CONCLUSION

Electrosurgery has proliferated since its original application by Bovie and Cushing in the 1920s. Electrosurgical units operate on basic fundamental principles of physics

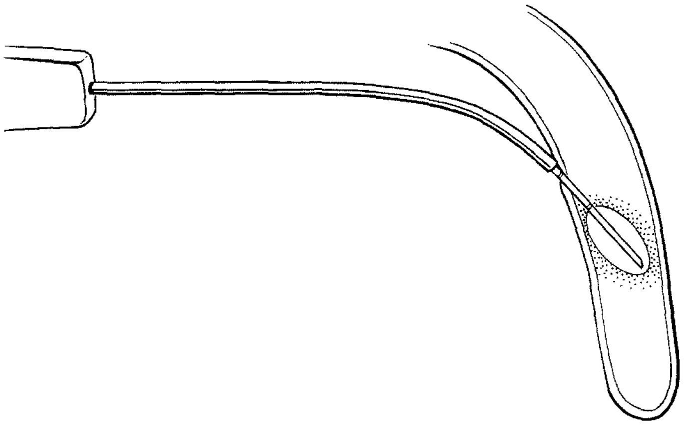

FIGURE 7. Lesion produced within the palate around the active portion of the needle electrode.

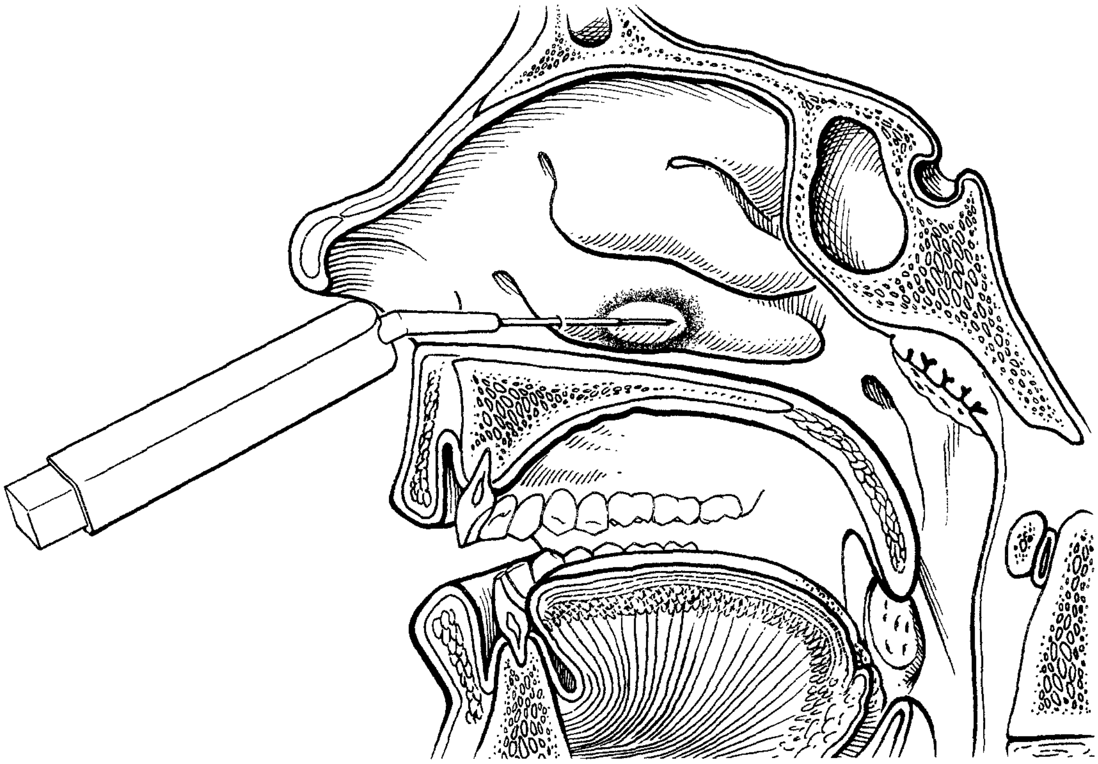

FIGURE 8. Lesion produced within the turbinate tissue around the active portion of the electrode.

and involve the passage of electrical current through tissue to create the desired tissue effect. The probe does not heat, as in electrocautery; rather, the tissue heats in response to the radiofrequency current passing through it.

The electrosurgical circuit includes the electrosurgical unit (radiofrequency generator), active electrode, dispersive electrode (grounding pad), and the patient. The fundamental techniques of electrosurgery are electrosection (cutting), coagulation (contact or spray), and needle ablation. Each of these modes uses a combination of frequency, power, waveform, electrode size, and time of application to produce a tissue temperature that will result in a relatively predictable histological effect.

Passing electrical current through the patient creates unique hazards for electrosurgery. Burns may be produced by faulty dispersive pads or faulty application of the pads. Undesirable alternate current pathways can increase current density and produce burns at any site where a potential conductor is in contact with the patient. Capacitively-coupled instruments can inadvertently burn the tissues they contact. Electromagnetic interference results when instrumentation in the operating suite creates electrical fields that interact and create distortion. Patient monitoring devices can be affected, as can implantable cardiac devices. The biomedical engineering department and the patient's cardiologist can help ensure the safety of electrosurgery in these patients.

Advances in electrosurgery are best discerned and properly evaluated by those who understand the basic concepts. With knowledge of the history, physics, techniques, histological effects, and safety issues of electrosurgery, the surgeon can use electrosurgery appropriately to alleviate human suffering, and the field will continue to proliferate.

REFERENCES

1. O'Connor JL, Bloom DA, William T: Bovie and electrosurgery. Surgery 119:390-396, 1996
2. Kramolowsky EV, Tucker RD: The urological application of electrosurgery. J Urology 146:669-674, 1991
3. Peltier LF: Preliminary note on a new surgical-current generator. Clin Orthop 310:3-5, 1995
4. Bovie WT: From Cushing H. Electrosurgery as an aid to the removal of intracranial tumors with a preliminary note on a new surgical-current generator. Surg Gynecol Obstet 47:751-784, 1928
5. Coleman S, Smith TL: Radiofrequency tissue reduction of the palate for bothersome snoring and sleep disordered breathing: A clinical trial. Otolaryngol-Head Neck Surg (in press)
6. Smith TL, Correa AJ, Kuo T, et al: Radiofrequency tissue ablation of the inferior turbinates using a thermocouple feedback electrode. Laryngoscope 109:1760-1765, 1999
7. Powell NB, Riley RW, Troell RJ, et al: Radiofrequency volumetric tissue reduction (RFVTR) of the palate in subjects with sleep disordered breathing. Chest 113:1163-1174, 1998
8. Li KK, Powell NB, Riley RW, et al: Radiofrequency volumetric tissue reduction for the treatment of turbinate hypertrophy: A pilot study. Otolaryngol Head Neck Surg 119:569-573, 1999
9. Bernstein T: Electrical injury: Electrical engineer's perspective and a historical review. Ann N Y Acad Sci 720:1-10, 1994
10. Reilly JP: Scales of reaction to electric shock. Ann N Y Acad Sci 720:21-37, 1994
11. Lacourse JR, Miller WT III, Vogt M, Selikowitz SM: Effect of high frequency current on nerve and muscle tissue. IEEE transactions on biomedical engineering. Biomed Engineering 32:82-86, 1985
12. Harrington DP: Electrosurgery fact and fiction. Biomed Instrum Technol 28:331-333, 1994
13. Powell NB, Riley RW, Troell RJ, et al: A porcine pilot study for the treatment of obstructive sleep apnea syndrome. Chest 111:1348-1355, 1997
14. Dinerman JL, Berger RD, Calkins H: Temperature monitoring during radiofrequency ablation. J Cardiovasc Electrophysiol 7:163-173, 1996
15. Organ LW: Electrophysiologic principles of radiofrequency lesion making. Appl Neurophysiol 39:69-76, 1976/77
16. Krejci RF, Kalkwarf KL, Krause-Hohenstein U: Electrosurgery—a biological approach. J Clin Periodontol 14:557-563, 1987
17. Erez A, Shitzer A: Controlled destruction and temperature distributions in biological tissues subjected to monoactive electrocoagulation. J Biomech Eng 102:42-49, 1980
18. Zervas NT, Kuwayama A: Pathological characteristics of experimental thermal lesions. J Neurosurg 37:418-422, 1972
19. Cosman ER, Nashold BS, Ovelman-Levitt J: Theoretical aspects of radiofrequency: Lesions in the dorsal root entry zone. Neurosurgery 15:945-950, 1984