Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

Material Removal Mechanisms in Monopolar Electrosurgery

Arlen K. Ward, *Member, IEEE*, Casey M. Ladtkow, and George J. Collins, *Fellow, IEEE*

***Abstract*— The underlying mechanisms that cause the observed tissue differences in monopolar electrosurgery under different electrical excitation conditions have not been accurately identified to date. Without an understanding of the mechanisms behind the observed differences in tissue effect, advances in electrosurgical technology are reduced to empirical trial and error. The numerical method we present herein allows single arc events and two ensuing vaporization mechanisms and thermal damage to surrounding tissues to be modeled. It also allows for a realistic prediction of the effect of different electrical waveforms employed in monopolar electrosurgery.**

The method presented here models both explosive boiling and confined boiling as mechanisms for observed material removal. It uses an Arrhenius damage calculation to predict both tissue cutting rates and adjacent thermal damage to peripheral tissue. All results agree with experimentally observed results. To our knowledge this agreement has not been accomplished with previous models. While not a complete description of the physical events surrounding tissue division and coagulation in electrosurgery, modeling single arc events is the initial step towards understanding the mechanisms of monopolar electrosurgery.

I. Introduction

ELECTROSURGERY involves the use of high frequency (>100 kHz) alternating current passed through biological media to cut and coagulate tissues at the surgical site. This is a tool used by surgeons to divide tissue while providing hemostasis (coagulation to arrest blood flow), a benefit that is unavailable with a standard cold steel scalpel. Controlling bleeding during surgery is important to both patient health and to the ability of the surgeon to complete their work unimpeded.

In monopolar electrosurgery, there are two traditional waveforms that create very different tissue effects, pure cut and coag as shown in figure 1. While both operate at the same frequency and power levels, changing the duty cycle of the applied waveform produces a noticeably different effect on biological tissue, when using the same RMS power

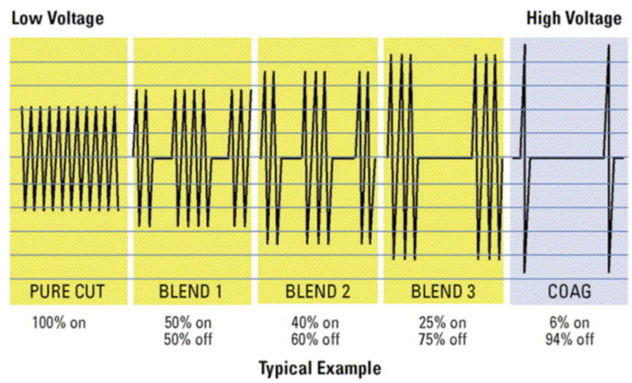

Fig. 1. Typical waveforms used in monopolar electrosurgery. The change in duty cycle corresponds to a change in tissue effect.

setting, shown in figure 2. A continuous wave (100% duty cycle) sinusoidal wave divides tissue very well, but does not provide the hemostasis necessary to keep an incision clear from bleeding. The second waveform is an interrupted sinusoid, at typically a 5% duty cycle. The interrupted waveform provides better hemostasis, but the rate of tissue division is slower than the first case. By reducing the duty cycle by a factor of 20, the peak voltage and current changes by a factor of $\sqrt{20}$.

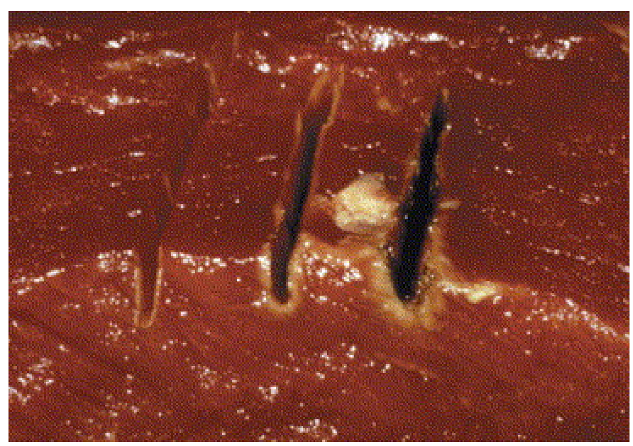

Fig. 2. Illustrative tissue effects and surrounding thermal damage for different duty cycles. The CW waveform effect is on the left, while the center and right samples are 50% and 5% duty cycles respectively. Note the increase in surrounding thermal damage for the lower duty cycles.

While the macroscopic tissue effect differences have been well known for nearly a century, the mechanism behind the observed effects has not been completely understood. If the underlying mechanisms that drive these differences can be better determined, this opens the possibility of engineering

Manuscript received April 2, 2007. This work was supported in part by Valleylab, a division of Tyco Healthcare.

A. K. Ward is with the Department of Mechanical Engineering at Colorado State University, Fort Collins, CO 80523 USA (corresponding author phone: 303-530-6281; fax: 303-581-6648; e-mail: arlen.ward@gmail.com).

C. M. Ladtkow is with Tyco Healthcare in Boulder, CO 80301 USA (e-mail: casey.ladtkow@tycohealthcare.com)

G. J. Collins is with the Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523 USA (e-mail: gcollins@engr.colostate.edu).

an applied waveform for a specific desired tissue effect. This understanding and modeling will provide opportunities for new electrosurgical devices that give surgeons finer control of tissue effects during procedures.

While it is well understood that vaporization of biological tissue caused by resistive heating is the physical basis for dividing tissue, previously implemented models were unable to match the cutting rates that were observed in experimental settings for an identical RMS power. In early models using contact between the electrode and the tissue [1] the current density magnitudes were too low to cause vaporization at the rates observed. This lead Pearce [2] to hypothesize that the electrical arcs in atmospheric air between the surgical instrument and the tissue provided the needed spatial transform from a wide to narrow area in order to reach the higher current densities. However, when this was simulated with a nucleation and growth vaporization model, the cutting rates were still much lower than those observed experimentally [3].

II. Theoretical Model

In the present simulation we apply two specific vaporization models to the problem, and determine if the material removal correlates to the observed behavior during application of waveforms characteristic of both cut and coagulation electrosurgical modes as described below.

A. Electrical Heating of Tissue

The primary mechanism of electrosurgery is the resistive heating caused by passing current through a volume of tissue. The spatially deposited power distribution is a function of the resistivity of the tissue volume as well as the current density profile. When arcs apply the current instead of conduction through physical contact of the electrode to the tissue, the current is more concentrated into the limited arc strike area by the surrounding atmosphere. Electrosurgical generators often operate with frequencies around 500 kHz, so the maximum duration of any single arc is less than 1 μs. When coupled with the small area (~0.15 mm diameter) of current application for an arc strike, the resulting volumetric power densities can be on the order of 10^{12} to 10^{16} W/m^3.

B. Thermal Conduction

While many applications of heat require the consideration of thermal diffusion into surrounding tissue, the high heating rates and short application times in electrosurgery help to isolate the thermal effects to the area being actively heated. This approximation was originally applied to laser tissue ablation [4], but we find that the conditions for an individual arc strike are such that again the characteristic thermal diffusion time, τ_d, of the heated volume provides the same criteria for neglecting thermal diffusion into surrounding tissue [5].

$$\tau_d = \frac{d^2}{\kappa} \quad \tau_p < \tau_d \tag{1}$$

Using the heating depth, d, of 100 μm and a tissue thermal diffusivity of $\kappa=4.8\times10^{-8}$ m$^2\cdot$s^{-1} [6], τ_d is 0.21 s. Employing the criteria of (1) the arc duration is thus shown to be sufficiently short to neglect thermal diffusion from the heated volume.

C. Tissue Removal

The two vaporization models used in this simulation are explosive and confined boiling. Each model is outlined below. Explosive boiling, or spinodal decomposition, is an effect that is associated only with very high heating rates. That is where water vapor is heated past the metastable region of nucleate boiling and reaches the unstable region where all liquid in the given volume flashes to vapor. At atmospheric pressure, this happens with heating rates allow temperatures to reach 585 K [7], well within the predicted heating rates for monopolar electrosurgery. In this model, we can assume that any material heated at this rate is vaporized completely. The second vaporization model is based on the confinement of water vapor inside tissue structures until the pressure buildup exceeds the tensile strength of the tissue. In the dermal layers, the material rupture strength can reach 1.7×10^7 Pa [8]. The increased pressure allows the liquid water constituents of the tissue to remain liquid to a higher temperature. When the pressure is released upon material failure the pressure drops and the rapid vaporization of the water results in material ejection, including the remaining liquid water. Therefore, confinement during vaporization is a mechanism for material removal via several pathways. Since confined boiling is not heating rate dependant, the calculated lower limit for material removed by this method was set at the heating rate necessary to cause vaporization at the pressure equivalent to the tissue tensile strength. Volumetric heating rate determines the volume that reacts with explosive vaporization and which volume undergoes confined boiling.

D. Thermal Damage

The third zone of tissue effect is thermally damaged tissue in the periphery of the electrical deposition zone. Thermal damage is often modeled as a first order kinetic process [9]. The Arrhenius damage integral takes into account the tissue damage dependance on time and temperature.

$$\frac{d\Omega}{dt} = A\, e^{-\Delta E / R \cdot T(t)} \tag{2}$$

The values for A and ΔE used in this simulation are from the original study by Henriques correlating values greater than unity to epidermal necrosis [9]. With the damage parameter Ω it is possible to predict the extent of thermal damage to the remaining tissue during electrosurgery.

Using the calculated volume of removed material and including the volumes with denatured proteins provides an overall picture of the tissue effect. The vaporized volume can then be extrapolated to cutting rates when multiplied by the number of arc events in the waveform.

The thickness of the damaged margin for divided tissue is calculated for reaching the given Arrhenius value. The distance from the last vaporized area to that value gives the amount of surrounding thermal damage.

III. Simulation Method

In order to determine the behavior of the mathematical models of the individual physical processes while maintaining the coupled nature of the descriptive differential equations a simultaneous solution of models describing widely varied physical processes is necessary. A numerical solution of a finite element implementation will best provide an understanding of the tissue behavior related to single arc strikes.

The COMSOL software package (COMSOL AB, Stockholm Sweden) was used to couple the mathematical models described above into a time dependent solution of multiple partial differential equations.

We implemented this model in finite element code to both determine the material removal rates and to extrapolate the cutting rates. Since the behavior of the water drives the vaporization mechanism, and structurally modified proteins determine the thermally damaged area, both material effects must be taken into account.

Volumetric heating rate determines the volume that reacts with explosive vaporization and which volume undergoes confined boiling.

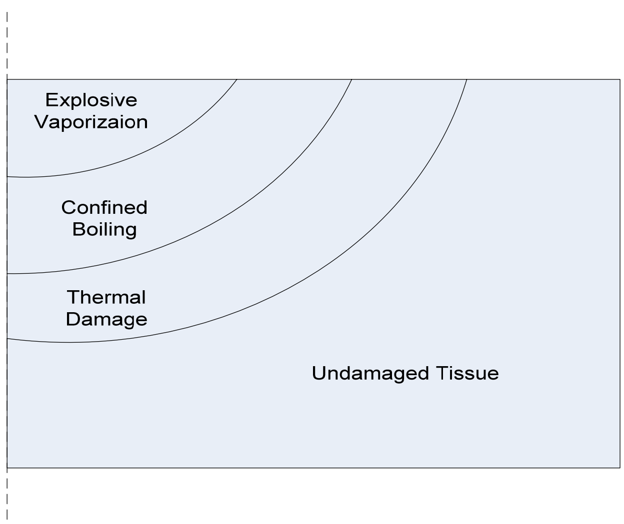

Fig. 3. Illustrative spatial zones for the tissue effects we propose. Vertical axis is relative depth into tissue while horizontal axis is distance from the electrode. The axis of symmetry for the model is along the left side. See Figure 4 for scale of the effects.

The finite element model is implemented as a 2D axi-symmetric geometry, with the center axis corresponding to the centerline of the arc. For these simulations, an RMS power of 80 W is used as a typical power setting used on the dermal tissue layers. This was used to calculate the characteristics of the arc for each waveform. The two waveforms used were a CW waveform and an interrupted waveform with a 5% duty cycle.

TABLE I
Input Parameters Employed for Simulation

Symbol	Property	100% Duty Cycle Waveform	5% Duty Cycle Waveform
ρ	Density [kg/m3]	1200	1200
C_p	Specific Heat [J/kg·K]	3600	3600
A	Frequency Factor [1/s]	3.1×10^{98}	3.1×10^{98}
ΔE	Activation Energy [J/mol]	627000	627000
	Arc Diameter [mm]	0.15	0.15
	Current Density [A/m2]	1.5×10^{7}	6.7×10^{7}

The first simulation uses arc characteristics of a CW waveform, using the parameters shown in Table I. The results of this simulation are shown figure 4, with the corresponding zones from figure 3 shown in solid colors.

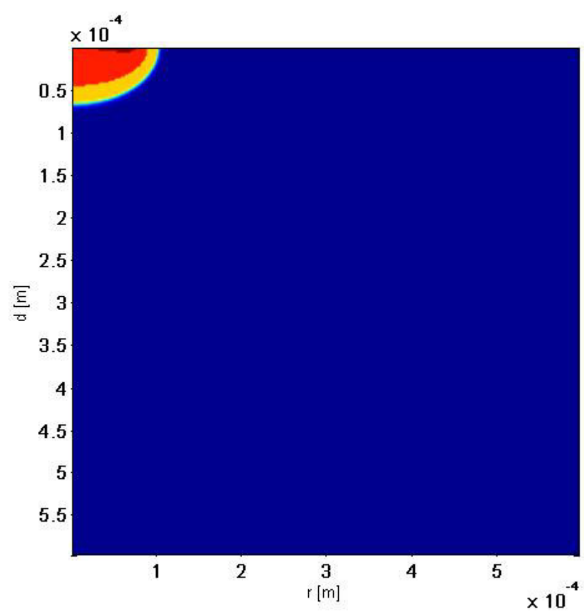

Fig. 4. Calculated tissue effect zones for a single arc strike characteristic of a CW waveform. Note that the red areas are predicted to be material vaporized by the confined boiling method and the yellow zone thermally damaged tissue. Dimensional units are in meters.

The second simulation uses arc characteristics of the interrupted waveform, using the parameters shown in Table I. The varied tissue effects are shown in solid colors in figure 5.

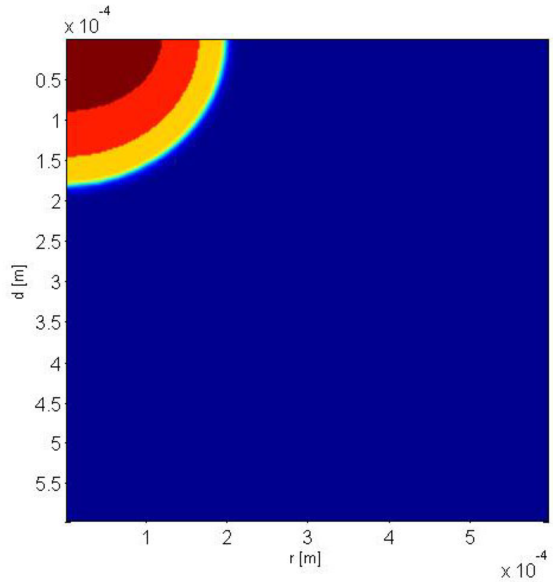

Fig. 5. Calculated tissue effect zones for a single arc strike characteristic of an interrupted waveform. Note that the red areas are vaporized material and the yellow zone is thermally damaged tissue. Dimensional units are in meters.

Using the calculated zones for explosive boiling and confined boiling as determined by the simulations, the rate of tissue division is determined by the width and depth of the calculated volume of removed tissue. Distance from the last vaporized material to the point where the damage integral equaled unity determined the thermal damage areas.

Division rates were determined by a function of the amount of material removed and the frequency of the arc events.

$$v_{Division} = f_{Arc} \frac{w_{Vap} \bullet d_{Vap}}{d_{Cut}} \quad (3)$$

The widths of the vaporized region, w_{Vap}, and the depth of the vaporized region, d_{Vap}, are determined from the simulation results. The depth of the cut, d_{Cut}, was assumed to be 1 cm. The arc event frequency, f_{Arc}, is based on the number of half cycles per second for each waveform.

TABLE II
MATERIAL REMOVED AND DAMAGE THICKNESS

Parameter	100% Duty Cycle Waveform	5% Duty Cycle Waveform
Arc Event Frequency [1/s]	1.0×10^{6}	5.0×10^{4}
Tissue Division Rate [cm/s]	7.2	2.3
Damaged Tissue Thickness [mm]	0.011	0.035

IV. RESULTS

Material vaporization has been identified as the mechanism for tissue division for a long period of time [1] and [2]. However, when other attempts have been made to model the material removal, discrepancies between the predicted and observed results highlighted the possible contribution of multiple methods.

While the simulation does not model all the physical processes present during an atmospheric arc strike on biological tissue, the reasonable behavior extrapolated from the initial results is promising.

V. CONCLUSION

We judge that the changes in the arc characteristics are primarily due to breakdown in atmosphere that occurs at a further distance from the tissue for the interrupted waveform as compared to the continuous waveform. More area constriction of the current flow occurs both due to self induced magnetic fields from the high current density as well as the electron capture at the outer surface of the cylindrical arc volume, both of which increase the difference in current density seen between the CW and interrupted waveforms.

The extrapolation in this work did not take into account the changes in vaporization volumes and damaged areas that would result from arcs to tissue that has previous strikes already. This is important because the electrical properties of the tissue change with temperature and water content, so the heating pattern for repeated arc strikes after the first one will require a model that takes into account the changing material properties for the remaining biological material.

REFERENCES

[1] W. M. Honig, "The mechanism of cutting in electrosurgery," *IEEE Trans. Biomed. Eng*, vol. 22, no. 1, pp. 58-62, Jan.1975.

[2] J. A. Pearce, *Electrosurgery* Wiley Medical, 1986, pp. 1-218

[3] D. E. Protsenko and J. A. Pearce, "Thermo-electrical numerical model of electrosurgical RF cutting," *Proceedings of the SPIE - The International Society for. Optical. Engineering*, vol. 4247, pp. 203-209, 2001.

[4] R. R. Anderson and J. A. Parrish, "Selective Photothermolysis: Precise Microsurgery by Selective Absorption of Pulsed Radiation," *Science*, vol. 220, no. 4596, pp. 524-527, Apr. 1983.

[5] S. L. Jacques, "Role of tissue optics and pulse duration on tissue effects during high-power laser irradiation," *Appl. Opt.,* vol. 32, no. 13, pp. 2447-2454, May 1993.

[6] M. L. Cohen, "Measurement of the thermal properties of human skin. A review," *J. Invest. Dermatol.,* vol. 69, pp. 333-338, 1977.

[7] S. aus der Wiesche, C. Rembe, E. P. Hofer, "Boiling of superheated liquids near the spinodal: II Application," *Heat and Mass Transfer,* vol. 35, pp. 143-147, 1999.

[8] H. Yamada, *Strength of Biological Materials*, Robert E. Krieger Publishing Co., Huntington, NY, 1970.

[9] F. C. Henriques, "Studies of Thermal Injury V. The Predictability and the Significance of Thermally Induced Rate Processes Leading to Irreversible Epidermal Injury" *Arch. Pathol.,* vol. 43, pp. 489-502