Electrical Characteristics of the Sparks Produced by Electrosurgical Devices

Bertoldo Schneider, Jr.* and Paulo José Abatti

***Abstract*—The electrical characteristics of the sparks produced between the active electrode and the biological tissue during electrosurgical procedures have been experimentally investigated. The results have shown that the minimum voltage required to initiate a spark depends on the applied voltage polarity resulting in electrosurgical voltage asymmetry. This voltage asymmetry is capable of producing dc levels that can result in tissue electrostimulation or direct current burns as discussed in this paper. The experimental setup and the conditions, under which the results have been obtained, including the techniques used to improve experimental reproducibility, are reported in detail.**

***Index Terms*—DC burns, electrical discharge, electrostimulation, electrosurgical devices.**

I. INTRODUCTION

ELECTROSURGICAL devices are widely used for producing tissue incisions, hemostasis through coagulation of blood and protein, or performing a blend of both effects. These electrosurgical effects are caused by the tissue heating. While moderate temperatures ranging from 50 °C to 70 °C can enhance hemostasis, temperatures above 100 °C can blow the cells up resulting in tissue incisions [1]. The volume of vaporized cells and fluids as well as the degree of hemostasis on the surrounding tissue depend on the control over the power and time of the electrosurgical signal applied. Nondesired effects such as tissue carbonization, which makes cicatrisation more difficult, should be avoided by preventing tissue temperatures above 200 °C [2]. These electrosurgical effects can be obtained generating a spark between the tissue and an active electrode, which is generally a metal ball, needle or knife-shaped tip used to apply the electrosurgical energy in a very small area of the body. Moreover, coagulation can also be obtained without spark through an ohmic contact in a process called desiccation.

The features of the electrosurgical signal delivered to the tissue (e.g., energy, waveform, time) determine the degree of each electrosurgical effect. However, this electric energy must be delivered free of direct current (dc) bias and low frequency components to prevent undesirable effects such as dc burns [3] at the reference electrode, which is a conductive plate attached to the patient used for providing a closed loop for the electrosurgical current and/or electrostimulation [4]. In practice, the circuit involving the patient is isolated from other circuits in the electrosurgical device using a transformer and recommended operating frequencies higher than 300 kHz [5]. In addition, a capacitor in series with the patient with value equal or less than 15 nF [6] is necessary to prevent dc current component in the patient circuit.

To generate a spark, the developed electric field should reach a value which is high enough to produce the medium dielectric breakdown and, consequently, to generate a spark. The minimum voltage amplitude applied between the active electrode and tissue necessary to generate such an electric field depends on the local temperature, electric characteristics of the medium, and on the materials, geometry, and positioning of the active electrode with respect to the tissue which is typically considered flat [7]–[9]. After sparking begins, the active electrode-to-tissue distance is not so important to maintain it [9].

During a typical electrosurgical procedure none of those factors can be controlled in an effective manner. The surgeon usually holds the active electrode with the hand so that the distance to the tissue is variable. Surgeon can also freely choose among several active electrode tip geometries, which will dictate the minimum electric field for sparking, mainly due to their radius of curvature [10]. Finally, electrosurgical procedure itself modifies the temperature and characteristics of the medium as well as of the tissue due to, for instance, introduction of liquid vapors and blood coagulation, respectively [6]. Moreover, the physical processes involved in the generation of a spark depend on the frequency of the applied voltage. The low frequency and dc voltages generate sparks based on electrons which have enough time to travel from the active electrode to the tissue and vice versa. According to Townsend effect, a free electron can generate other ones by ionization, leading to a breakdown that would cause an avalanche of electrons traveling at a typical velocity of 1 km/s. Therefore, sparks created with high frequency voltages (e.g., frequencies higher than 250 kHz for a 2 mm gap) cannot be explained assuming only electron avalanches. Hence, a different reasoning is needed to explain these sparks (e.g., streamer effect [11]).

Under the previous conditions it is not a surprise that the electrosurgical parameters such as the applied voltage amplitude and frequency have been empirically determined through the last 100 years [12]–[14]. Therefore, any optimization on the electrosurgical procedures, safety conditions, or even in the technical aspects of the equipment is difficult to be implemented and/or justified without better understanding of the sparking phenomenon.

The aim of this paper is to present the electric characteristics of the sparks produced between an active electrode and a tissue

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*B. Schneider, Jr. is with the Federal University of Technology, Paraná, Av. Sete de Setembro, 3165, DAELN, CPGEI, CEP 80230-901, Curitiba, PR, Brazil (e-mail: bertoldo@utfpr.edu.br).

P. J. Abatti is with the Federal University of Technology, Paraná, CEP 80230-901, Curitiba, PR, Brazil (e-mail: abatti@utfpr.edu.br).

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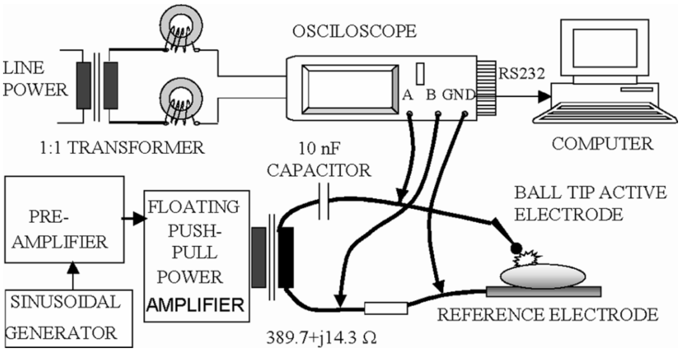

Fig. 1. Experimental setup used to investigate the spark electrical characteristics produced during electrosurgical procedures.

during a simulated electrosurgical procedure. The experimental setup and the conditions under which these characteristics have been observed are described in detail. Possible explanations for the electrostimulation and/or dc burns intermittently observed during electrosurgical procedures are also discussed.

II. EXPERIMENTAL SETUP AND MATERIALS

Fig. 1 shows the schematic view of the experimental setup. The generator (Tektronix CFG253), the preamplifier, and the class B push-pull power amplifier provide an almost sinusoidal output at desired frequency. However, a maximum operating frequency of about 450 kHz is imposed by the characteristics of the transistors (MJL3281; $\mathrm{Vce}_{\max} = 200$ V; $\mathrm{Ic}_{\max} = 15$ A and maximum power = 200 W) used in the power amplifier [15].

The power transformer has been constructed using a ferrite core (Thornton IP12R EE, with $66.5 \times 52.4 \times 64.4$ mm^3) and “Litz” cables consisting of 3.5 turns of two 0.52 mm^2 enameled copper wires at the primary winding and 13 turns of four 0.13 mm^2 wires at the secondary winding. The primary and secondary windings were separated by a plastic tape with thickness of about 0.2 mm to reduce the coupling capacitance. In addition, the stray capacitances in the secondary solenoid were reduced using a polyester thread with diameter of 2.0 mm to separate the coils. The constructed transformer was created to present the lowest resonance frequency at about 650 kHz such that the experimental setup did not require filters, simplifying the output circuit [15].

An oscilloscope (Tektronix TDS220) has been used to register the voltage V and current I (through a resistor with 119.5 Ω and +j11.5 of inductive reactance, measured at 400 kHz) during the spark formation. To prevent damage to the experimental setup, the output circuit where the sparks were being generated was kept isolated from the other parts. The oscilloscope was powered through a 1:1 transformer in series with two RF chokes inductances of 5.5 mH, and the RS 232 serial link between oscilloscope and personal computer remained disconnected during the experiments. Thus, the voltage and current waveforms were initially acquired and stored in the oscilloscope to be transferred to the personal computer afterwards. In addition, the experimental setup had been carefully arranged, particularly the cables, to reduce the parasitic capacitances.

The experiments were performed using 2-cm-thick slices of pork loin, because swine’s flesh can be considered essentially identical to human’s flesh during electrosurgery [16], as well as 2-cm-thick slices of chayote (Sechium edule Sw.) [15] for comparison purposes. Three shapes of active electrodes including a ball tip (see Fig 1) with curvature radius of about 1.0 mm, a needle tip with radius of curvature of about 0.1 mm and knife tip with main curvature radius of about 0.25 mm and width of 1.5 mm were used. All the electrodes, including a plate with 10×18 cm^2 used as reference electrode, were made using stainless steel alloys.

The experiments were carried out at room temperature of approximately 20 °C. The temperature at the very electrosurgical site had not been measured.

III. RESULTS

During the experiments, desiccation could be obtained only if the active electrode was pressed against the tissue with a force equal or higher than 0.5 N. For forces smaller than 0.5 N, even with the active electrode touching the tissue, sparks could be generated. This peculiar behavior had been experimentally observed using voltages with frequencies ranging from 50 to 450 kHz, and can be used to eliminate part of the experimental variables. First, the distance between the active electrode and tissue is not anymore a variable, since it is kept constantly touching the tissue (minimum value). Second, electron avalanches (Townsend Theory) suffice to qualitatively explain the spark process for this setup.

In addition, the electrode shape influence on the electric field strength necessary to generate a spark is minimized (by using ball-type active electrode). The starting-voltage characteristics of sparks produced using ball, needle and knife-type electrodes were experimentally investigated, showing that the geometric differences among them were less than 12%. However, it was also experimentally observed that the electrical parameters evaluated depend on other factors such as cutting depth and applied force, as well as on the applied power and the time that the active electrode is maintained at same site. In addition, it was observed that the slicing orientation of the pork loin (longitudinal or transversal cut in relation to its muscle fibers direction) influence the electrical parameters registered. Thus, in order to improve reproducibility, the experiments were performed sliding a ball electrode over the tissue (“transversal cut”) with a velocity of about 7 mm/s and a force of 0.15 N, while applying a maximum power of 35 W, which resulted in a cutting depth of about 1.5 mm.

Fig. 2 presents the 1) V and I waveforms and the 2) correspondent V versus I (V×I) diagram of a spark generated on the swine’s flesh, along with the open circuit and desiccation V×I diagrams. Fig. 2 clearly shows that the voltage required to initiate a spark depends on its polarity, i.e., about 600 V for the positive cycle (positive at the active electrode and “negative” at the swine flesh) and about −370 V for the negative cycle under the conditions previously presented. In the case of a purely resistive impedance, the V versus I diagram would be a single line. Therefore, Fig. 2 also shows a relative high capacitive component in the experimental setup, with impedance phase of approximately 30°, measured at 300 kHz using the Lissajous Technique.

Fig. 3(a) illustrates the V×I spark diagram obtained using a ball-type active electrode and transversal slices of pork loin and

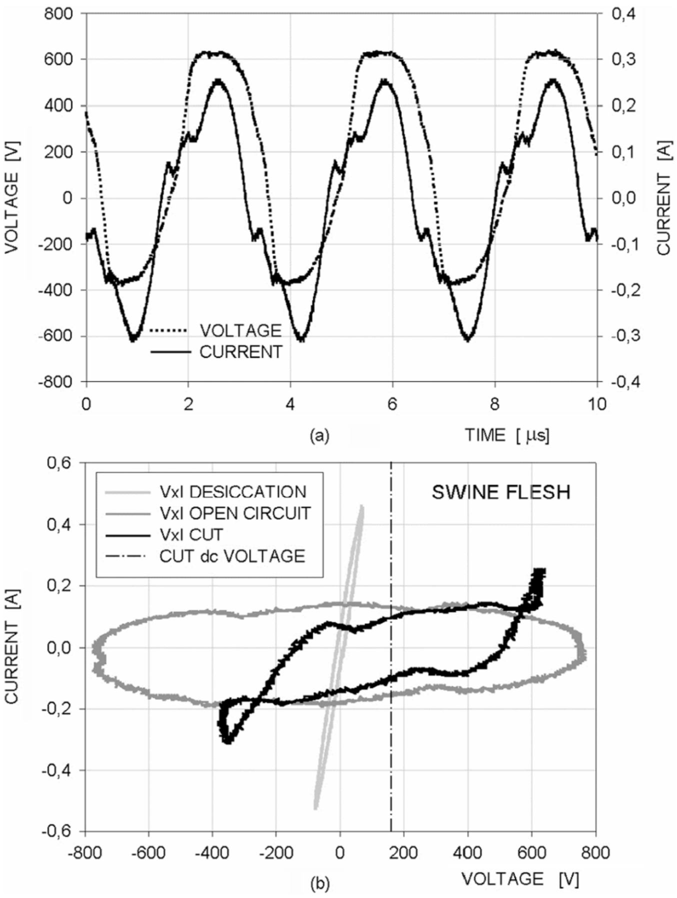

Fig. 2. (a) Typical voltage (dotted line) and current (full line) waveforms registered during electrosurgical cut procedure on swine flesh; (b) correspondent voltage versus current diagram (black line), open circuit diagram (dark gray line), and desiccation (light gray line).

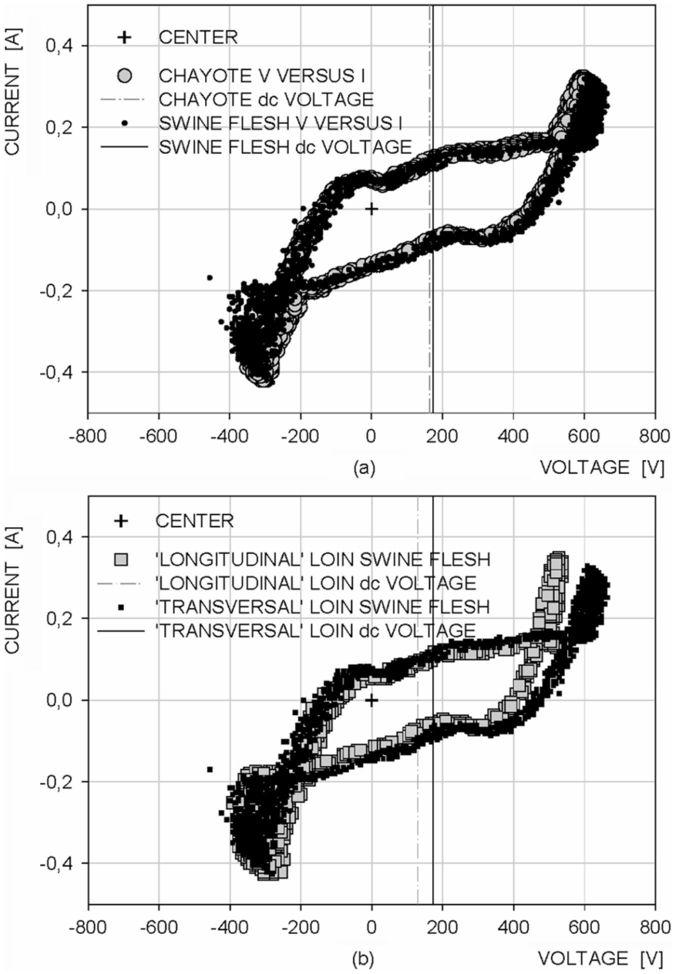

Fig. 3. (a) Voltage versus current diagram registered using Chayote (gray circles) and "transversal cut" loin swine flesh (dark points). (b) Voltage versus current diagram registered using loin swine flesh sliced longitudinally (gray squares) and transversally (black squares) cut in relation to its muscle fibers.

Chayote. To demonstrate the dependence on cutting direction, Fig. 3(b) illustrates the V×I diagram for slices of transversal and longitudinal cuts of pork loin. This figure shows that the values for chayote (gray circles) are practically the same of those for the transversal cut of pork loin (dark points). However, both are quite different from those obtained using longitudinal cut of pork loin. In addition, it could not be observed any influence of tissue thickness ranging from 0.8 to 4.6 cm on the recorded V and I parameters. Additional experiments have neither shown influence of the time elapsed of chayote harvesting from few hours to weeks nor modifications on the electrical characteristics of sparks due to the dehydration after chayote slicing throughout 21.5 hr at 25 °C. Moreover, it is important to point out that these V×I diagrams are obtained using (V, I) pairs obtained along several cycles (equivalent-time sampling). Therefore, the deformation seen in the region close to −370 V in Fig. 3 may be explained assuming that depending on local conditions the spark could start at different voltage levels at each cycle. However, though initiating at different voltage levels, the V×I curves behavior is in general resumed.

Due to the risks to the patients, it must be emphasized that due to the observed asymmetry there is a dc component in the measured voltage, about 160 V [see Fig. 3(a)] for chayote and transversal cut of pork loin and about 120 V for longitudinal cut of pork loin [see Fig. 3(b)], while current presents a nearly null average value.

IV. DISCUSSION AND CONCLUSION

The electrical characteristics of the spark under conditions quite similar to those found in practical electrosurgery have been investigated. The experiments demonstrated that the voltage levels required to initiate a spark are polarity-dependent, showing that it is easier to take electrons from a metal than from a biological tissue under the conditions found on an electrosurgical procedure. In addition, it was also demonstrated that sparking can be obtained even when the active electrode is gently touching the tissue. It was observed that differences between tissue and electrode tip temperatures during electrical discharge do not account for this voltage asymmetry. To confirm this finding, no significant difference could be observed when the active electrode temperature was raised till incandescence. In addition, it was observed that this voltage asymmetry is influenced by tissue characteristics, including tissue cut in relation to its muscle fibers as shown in Fig. 3.

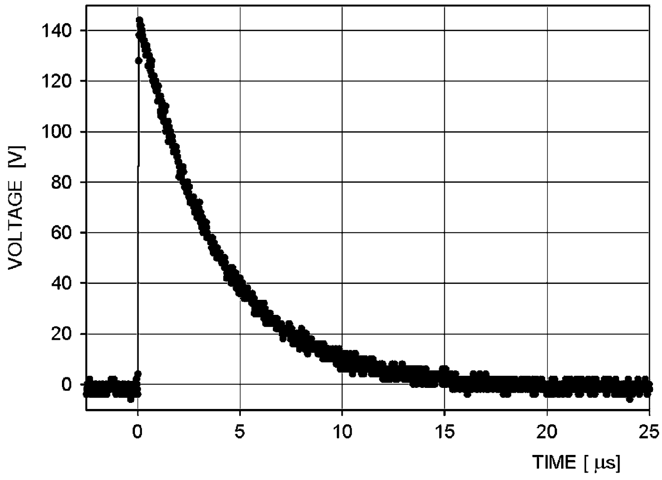

Fig. 4. Series capacitor voltage discharge curve on a 390 Ω test resistor.

That saturation in Fig. 2 is due exclusively to the spark process. When no spark was present, no saturation could be observed, even for higher delivered power (desiccation). In addition, no saturation from the electrosurgical device circuitry (e.g., output power amplifier) could be reflected in the results found since such saturations create dc components that would not be driven through the transformer.

For practical electrosurgical purposes, perhaps the most important result is the observed dc voltage level which can produce electrostimulation and/or dc burns at the reference electrode to tissue contact area. Both of these dc-generated effects could result in serious damage to the patient. This dc voltage level can be higher than 160 V (see Fig. 3), charging the recommended series capacitance [6]. If surgeon stops the procedure when the active electrode is not in contact with the patient, that charge remains stored in the capacitor, and it is known that stored energy can be later discharged at the next touch of the electrode with the tissue [17]. A range from 6.7 to 67 mC delivered in 100 ms or less is the threshold for electrostimulation [18], [19]. Fig. 4 shows the initial dc voltage level stored in the output capacitor and its discharge over a test resistance of 390 Ω mimicking the human tissue. For a 10 nF test capacitor, the typical output capacitance in electrosurgical procedures, a charge of 1.4 μC was observed. For the maximum allowed 15 nF capacitance [6] that would be 2.1 μC, approximately one third of the electrostimulation threshold. It is important to note that these experiments were carried out using less than 35 W. In electrosurgical procedures, higher power levels would generate higher dc voltages. Therefore, that threshold could be reached, causing the undesirable electrostimulation. Moreover, dc burns could also result from these charges since dc voltage level as low as 3 V can cause such burns [3]. Provided the time sufficiently long, and remembering that the capacitor is not ideal (practical capacitors present leakage, represented by a parallel resistance), part of the dc voltage stored at capacitor can be transferred to the reference electrode-to-tissue interface, particularly when the active electrode is touching the tissue, causing dc burns.

In conclusion, the presented experimental results show that different materials generate asymmetry when sparks are involved (no asymmetry had been detected when the sparks took place between the active electrode and a same material piece of metal stuck into the flesh or chayote). The dc voltage produced by the electrosurgical procedure, and stored at the series capacitance, could, in principle, explain both the electrostimulation and the dc burns [3], [4] reported by surgeons.

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REFERENCES

[1] C. F. P. van Swol, R. J. Hillenius, R. J. van Vliet, R. M. Verdaasdonk, and T. A. Boon, "Vaporization and coagulation potentials of new electrovaporization devices for transurethral prostatectomy," in *Proc. 18th Ann. Int. Conf. IEEE Eng. Med. Bio. Soc.*, 1997, pp. 1709–1710.

[2] ERBE, Atlanta, GA, "Operator manual ERBOTON ICC 350," ERBE, V1.06, code 10128-200 e 10128-206, 1994.

[3] M. N. Leeming, C. Ray, Jr., and W. S. Howland, "Low-voltage direct-current burns," *J. Amer. Med. Assoc.*, vol. 214, no. 9, pp. 681–1684, Nov. 30, 1970.

[4] *An International Codes and Standards Organization, Standard for Health Care Facilities, Addendum D*, NFPA 99, National Fire Protection Association, 2002.

[5] *Equipamento Eletromédico, Parte 2-2: Prescrições particulares para Segurança de Equipamento cirúrgico de alta freqüência*, ABNT NBR IEC 60601-2-2, Associação Brasileira de Normas, Apr. 1998.

[6] *International Standard, Medical Electrical Equipment, Part 2: Particular Requirements for the Safety of High Frequency Surgical Equipment*, CEI/IEC 601-2-2, 1991.

[7] Y. Takahashi, S. Kato, and S. Kobaiashi, "Discharge voltage of dielectric gaps and the generalized secondary ionization coefficient n of the dielectric cathode, properties and applications of dielectric materials," in *Proc. 2nd Int. Conf. Properties Appl. V2*, 1988, pp. 550–553.

[8] J. A. Pearce, *Electrosurgery*. New York: Wiley, 1986, p. 270.

[9] J. R. LaCourse, A. D. Rothwell, and S. M. Selikowitz, "II. Voltage-current characteristics of an AC arc for different electrode separations with application to electrosurgery," in *Proc. IEEE 19th Ann. Northeast Bioeng. Conf.*, 1993, pp. 37–39.

[10] F. W. Sears and M. W. Zemanski, *Física, Eletricidade, Magnetismo e tópicos de Física Moderna*, 1st ed. Portugal: Livros Técnicos e Científicos Editora S.A., p. 471.

[11] B. H. Crichton, "Gas discharge physics," *IEE Colloquium Adv. HV Technol.*, pp. 3/1–3/5, Oct. 4, 1996, Digest No. 1996/173).

[12] L. A. Geddes, L. F. Silva, and D. P. Dewitt, "What's new in electrosurgical instrumentation?," *Med. Instrum.*, vol. 11, no. 6, pp. 355–361, Nov./Dec. 1977.

[13] J. G. Webster, *Encyclopedia of Medical Devices and Instrumentation*. New York: Wiley, 1988, vol. 2, pp. 1180–1203.

[14] J. R. LaCourse, A. D. Rothwell, and S. M. Selikowitz, "Development of electrosurgery: A historical perspective," in *Proc. IEEE 19th Ann. Northeast Bioeng. Conf.*, 1993, pp. 35–36.

[15] B. Schneider, Jr. and P. J. Abatti, "Development of an electrosurgical device with a non switched power output," *Brazilian J. Biomed. Eng.*, vol. 21, no. 1, pp. 17–26, 2005.

[16] H. F. Bowman, E. G. Cravalho, and M. Woods, "Theory, measurement, and application of thermal properties of biomaterials," *Ann. Rev. Biophys. Bioeng.*, vol. 40, pp. 43–80, 1975.

[17] C. Chu, J. G. Webster, P. Hua, P. , and T. Au, "Minimizing interference caused by electrosurgical units," in *Proc. IEEE 7th Ann. Conf. Eng. Med. Bio. Soc.*, 1985, pp. 775–778.

[18] B. Katz, *Nerve, Muscle & Synapse*. New York: McGraw-Hill, 1966, p. 193.

[19] J. G. Webster, *Medical Instrumentation*. Boston, MA: Application and Design, Houghton Mifflin Company, 1978.

Bertoldo Schneider, Jr. was born in Apucarana, Paraná, Brazil, on June 25, 1962. He received the B.S. degree in electronics and telecommunication engineering and the M.Sc. degree in biomedical engineering (biotelemetry) from Paraná Federal Center of Technological Education, Paraná, Brazil, in 1986 and 1994, respectively, and the D.Sc. degree in electrical and electronic engineering from Federal University of Technology-Paraná (UTFPR), Paraná, Brazil, in 2004.

Since 1987, he has been with the Federal University of Technology, where he is currently a Professor and a Professor-Research with the Electrical Engineering and Computing Program, the Post-graduate School. His present research interests include biotelemetry systems, biomedical instrumentation, electrosurgical theory, modeling of electrosurgical phenomena, and high-frequency high-power transformers design.

Paulo José Abatti was born in Curitiba, Paraná, Brazil, on January 3, 1958. He received the B.S. degree in electrical engineering from the Federal University of Paraná, Paraná, Brazil, in 1980, the M.E.E. degree in biomedical engineering from the State University of Campinas, São Paulo, Brazil, in 1983, and the Doctor of Engineering degree in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1991.

Since 1977, he has been with the Federal University of Technology-Paraná, Brazil, where he is currently a Professor and Pro-Rector for Post-Graduation and Research Affairs. His present research interests include development of communication techniques and electronic circuits for implantable biotelemetry Systems and modeling of biological phenomena.