International Journal of Biomedicine 15(4) (2025) 645-648
http://dx.doi.org/10.21103/Article15(4)_RA4

MINI REVIEW

INTERNATIONAL JOURNAL OF BIOMEDICINE

Electrosurgery: Principles, Risks, Safety Considerations, and Modeling of Thermal Effects

Branislav Radjenović, Marija Radmilović-Radjenović*

Institute of Physics, University of Belgrade, Belgrade, Serbia

Abstract

Electrosurgery has significantly transformed modern surgical practices, offering a versatile and effective approach for cutting, coagulating, and desiccating biological tissue with remarkable precision. This review provides a comprehensive exploration of the fundamental principles that underpin electrosurgery, including the electrical mechanisms, tissue interactions, and the various types of thermal injuries that may arise during procedures. It categorizes thermal injuries into direct and indirect types, elucidating the unique risks associated with patients who have implantable electromagnetic devices. Furthermore, the review emphasizes the critical role of modeling thermal effects in electrosurgical procedures, highlighting how computational simulations can predict tissue damage and enhance safety measures. By deepening the understanding of these intricate concepts, surgeons are better equipped to optimize patient outcomes, minimize complications, and ensure the safe application of electrosurgical techniques. Ultimately, this review aims to bridge existing knowledge gaps and promote best practices in the field of electrosurgery, reinforcing its role as a vital tool in contemporary surgical settings.(**International Journal of Biomedicine. 2025;15(4):645-648.**)

Keywords: electrosurgery • thermal injures • electromagnetic devices

For citation: Radjenović B, Radmilović-Radjenović M. Electrosurgery: Principles, Risks, Safety Considerations, and Modeling of Thermal Effects. International Journal of Biomedicine. 2025;15(4):645-648. doi:10.21103/Article15(4)_RA4

Introduction

Electrosurgery has revolutionized surgical practices by providing a versatile and effective tool for cutting, coagulating, and desiccating biological tissue.[1-3] By harnessing the effects of electric current, this technique enhances precision and efficiency in a wide range of surgical procedures, from minimally invasive laparoscopic surgeries to complex open surgeries. The ability to manipulate tissue with high accuracy not only improves surgical outcomes but also reduces recovery times and complications associated with traditional surgical methods.

However, the use of electrosurgery is not without its challenges. As with any surgical technology, it introduces inherent risks and complications, particularly in the form of thermal injuries.[4,5] These injuries can have significant consequences for patient safety, ranging from minor burns to severe internal damage. Understanding the underlying principles of electrosurgery—including electrical fundamentals, tissue interactions, and the mechanisms of potential hazards—is essential for surgeons striving to optimize patient outcomes and minimize risks.

Electric currents flowing through the human body can lead to severe tissue injuries, commonly classified as direct and indirect thermal injuries.[6] Direct injuries occur when an active electrode inadvertently contacts any part of the body outside the intended surgical site. In contrast, indirect injuries occur when the electrode unintentionally comes into contact with other metal instruments, causing the current to divert and affect surrounding tissues. Additionally, patients with implantable electromagnetic devices face unique risks, as electrosurgical devices can interact adversely with these implants, leading to specific injuries.

Given these complexities, this review aims to explore the principles of electrosurgery, examine the factors that influence its effectiveness, and emphasize the importance of safety considerations in its application. By enhancing our understanding of electrosurgery, we can better equip surgeons to utilize this powerful tool safely and effectively, ultimately improving patient care in surgical settings.

***Corresponding author**: Dr. Marija Radmilović-Radjenović, Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia, E-mail: marija@ipb.ac.rs*

Principles of Electrosurgery

Electrical Fundamentals

The mechanics of electrosurgery are grounded in electrical principles. It employs alternating current, which causes cellular ions to oscillate, generating frictional heat. This process transforms electrical energy into mechanical and then thermal energy within the cells. Electrode arrangements used in electrosurgery can be roughly divided into two categories: unipolar and bipolar (Figure 1).[7,8]

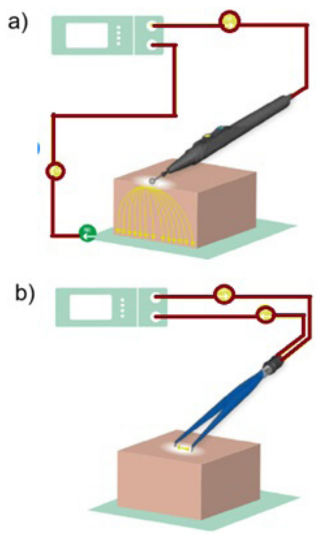

Figure 1. *Schematic view of dipole circuits: a) a small active electrode - unipolar (monopolar) and b) two equal-sized electrodes - bipolar.*

The primary difference between these modalities lies in the pathway of the current. The unipolar circuit consists of a small active electrode placed at the surgical site and a patient return electrode placed on the patient's body. The current's likely path is from the active electrode to the ground electrode and back to the electrosurgical generator, completing the circuit. The high current density produced at the active electrode creates a pronounced diathermic effect, causing tissue destruction at the operative site. On the other hand, a bipolar circuit uses two electrodes of equal size, creating a dipole circuit at the site of application. Upon applying a high current density through bipolar forceps, the small amount of tissue contained between the tips of the forceps is coagulated with minimal effect on surrounding tissue.

Thermal Tissue Effects

Figure 2 illustrates thermal tissue effects, which refer to the changes that occur in biological tissues when they are exposed to heat or cold.[9] Electrosurgical cutting occurs when temperatures exceed 100°C, leading to cellular vaporization. The gradual temperature rise between 60°C and 95°C results in desiccation and coagulation. Desiccation is achieved through the loss of cellular water, while coagulation arises from thermal protein denaturation. The use of wider active electrodes generally reduces current density, making it more conducive to coagulation and desiccation. Fulguration is a specialized application of the coag waveform, executed with the active electrode positioned away from the tissue. This technique generates electric arcing that bridges the air gap, producing temperatures above 200°C and resulting in carbonization. The low duty cycle ensures rapid diminishment of current, thus preventing excessive heat accumulation in deeper tissues. Fulguration proves effective in controlling bleeding from raw surfaces, providing a valuable tool for surgical hemostasis.

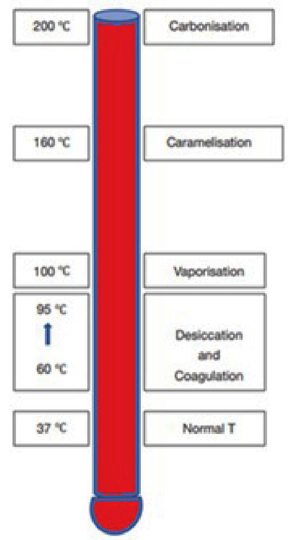

Figure 2. *Tissue effects result from the changes that biological tissues undergo when exposed to heat or cold.*

Tissue Factors

Tissues with high impedance, such as fat and scar tissue, will require higher power to achieve the desired tissue effects compared to those with low impedance, such as muscles and skin.[10] Generally, obese or emaciated patients need more power output to cause the same tissue effects as in lean and muscular patients. Patients with vascular diseases such as atherosclerosis, liver cirrhosis, diabetes, and collagen disorders may not be suitable for electrosurgical hemostasis, and alternative hemostatic techniques may be required. Eschar build-up on the active electrode poses a high impedance to current; hence, higher power will be needed to achieve the desired tissue effects. It is good practice to keep the electrode clean at all times or to use non-stick electrodes (Teflon or silicone-coated).

Hazards of Electrosurgery

Although advanced technology has significantly reduced electrosurgical complications, severe internal burns still occur.[11] The estimated incidence of such burns is 3.6 per 1,000 laparoscopic procedures. The majority of such burns are not recognized at the time of surgery, which can lead to severe morbidity or even mortality postoperatively. Additionally, they are associated with increased costs due to repeated surgeries, prolonged hospitalizations, and malpractice claims. Table 1 shows a practical classification of electrosurgical hazards.

Table 1.

Overview of the electrosurgical hazards (unintended burns, electrical shock and glove burns, surgical plume, explosion, surgical fire, and electromagnetic interference with other devices).

Unintended burns		
Active electrode	***Dispersive electrode***	***Current diversion***
Lateral thermal spread	Poor skin contact	Insulation failure
Residual heat	Poor lead connection	Direct coupling
Inadverten activation		Capacitive coupling
Direct thermal extension		Antenna coupling
		Alternate site injury
Electrical shock and glove burns		
Surgical plume		
Explosion		
Surgical fire		
Electromagnetic interference with other devices		
Implantable electronic devices	***Electrocardiogram***	***Video imaging system***

Modelling of Thermal Effect

Accurate modeling of electrosurgical heating of soft tissues requires a fundamental understanding of how the applied energy distributes and dissipates within the tissue. Electrosurgery involves the application of an alternating current to cut and coagulate tissues simultaneously.[12] When higher power settings are applied, the tissue is rapidly heated to 100°C within seconds. In an electrosurgical procedure, the vicinity of the electrode is a region of high-power density as the electric field intensity drops off as the square of the distance from it, resulting in sharp temperature and pressure gradients with large evaporation losses.[13] The challenge of accurately modeling electrosurgical heating of hydrated soft tissues arises from the need to capture energy dissipation that is significantly affected by changes in temperature-dependent properties, latent heat loss, and phase change within the tissue that is heterogeneous and contains than 70% water by mass. Computational models are frequently employed to evaluate the safety of electrosurgical procedures, predict tissue damage, and inform the development of new instrument designs.[14,15] In the modeling of thermal effects on the tissue, several factors have to be considered:

• *Penetration of Electric Field into Tissue* – The distribution of the electric field is determined by the geometry of the electrodes. For spherical and cylindrical electrode configurations, the penetration depth of the electric field in tissue is approximately equal to the electrode radius.

• *Heat Diffusion* – The penetration of heat into the tissue by diffusion depends on pulse duration. If repetitive pulses are applied, heat accumulation should be prevented by providing a sufficient delay between pulses for energy dissipation from the heated area.

• *Cavitation* – In pulsed ablation, tissue can also be damaged by the mechanical effects of the rapidly expanding and collapsing cavitation bubbles. During the collapse of the cavitation bubbles, fast water jets can form near the tissue boundaries, extending the range of mechanical tissue damage.

• *Electroporation* – Another potentially damaging mechanism is the direct effect of the electric field on cellular membranes. Due to the polarization of the cell in an electric field, its transmembrane potential is increased on the anodic side (hyperpolarization) and decreased on the cathodic side (depolarization).

• *Tissue Modelling* – The significant discrepancies found between model predictions and experimental data in the literature show that accurately modelling the radio-frequency heating of soft tissue requires capturing the interactions between the heterogeneous phases that comprise soft tissue, including heat transfer, mass transport, phase change, and mechanics.

• *Evolution of Tissue Damage* – Modeling of electrosurgical procedures is complicated because the models must also include the motion of the electrosurgical tool. The actual depth and extent of tissue injury depend on several factors, including power density, electrode size and shape, and the nature of the tissue being dissected.

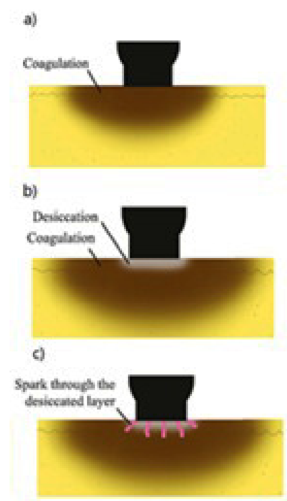

Figure 3. *Graphical illustration of the sparking that occurs during the electrocoagulation with desiccation.*

The computational model plays a significant role in predicting electrosurgical outcomes, thereby enhancing electrosurgery, as illustrated in Figure 3, which depicts the stages of electrocoagulation. a) The process starts with coagulation. b) At the end of coagulation, the more superficial coagulated tissue dries out (desiccation) and becomes less electrically conductive, potentially preventing the current from continuing to flow. c) Sparking may then occur through the nonconductive desiccated layer, leading to disruption of this layer, passage of more current, more heat production, and deeper thermal damage. The timing of desiccation occurrence during coagulation depends on the current density. With lower current density, there may be deep coagulation before desiccation happens. Therefore, for deep coagulation, a relatively low power should be chosen to provide slow coagulation and a late occurrence of desiccation, keeping in mind that a very low power may not be able to ensure the coagulation. In such cases, simulations may provide accurate values of the current density that enable the desired coagulation with late desiccation.

Conclusions and Future Outlook

In conclusion, electrosurgery represents a significant advancement in surgical technology, enabling the performance of complex procedures with greater efficiency and precision. The capability to simultaneously cut and coagulate tissue has transformed surgical protocols, reducing operation times and improving patient recovery. However, risks such as thermal injuries and complications for patients with implantable devices remain concerns.

This review highlights the importance of ongoing research in enabling surgical teams to understand the complexities of electrosurgical techniques and their associated risks. Implementing rigorous safety protocols and updating best practices based on current research will be vital in mitigating complications. Looking ahead, advancements in technology and computational modeling promise to further enhance the capabilities of electrosurgery. An improved understanding of tissue interactions and thermal dynamics through simulation may enable more tailored surgical approaches, thereby minimizing damage to surrounding tissues. The integration of artificial intelligence and machine learning could also revolutionize precision and safety, offering real-time feedback for dynamic adjustments during procedures.

As the field evolves, interdisciplinary collaboration among engineers, surgeons, and researchers will drive innovation, keeping electrosurgery at the forefront of surgical technology and ultimately enhancing patient care and outcomes. The future of electrosurgery is promising, with potential for even greater advancements in surgical practices and patient safety.

Sources of Funding

Marija Radmilović-Radjenović acknowledges that this research was supported by the Slovak Academic Information Agency through the National Scholarship Program of the Slovak Republic.

Conflicts of Interest

The authors declare that they have no competing interests.

References

1. Meeuwsen F, Guédon A, Klein J, Elst MV, Dankelman J, Van Den Dobbelsteen J. Electrosurgery: short-circuit between education and practice. Minim Invasive Ther Allied Technol. 2019 Aug;28(4):247-253. doi: 10.1080/13645706.2018.1513945.

2. Biradar M, Dode P. Principles of electrosurgery in laparoscopy - A review. International Journal of Biomedical and Advance Research. 2019;10:e5163. Doi:10.21037/gpm

3. Radmilović-Radjenović M, Sabo M, Radjenović B. Application of multi-component fluid model in studies of the origin of skin burns during electrosurgical procedures. Comput Methods Biomech Biomed Engin. 2021 Oct;24(13):1409-1418. doi: 10.1080/10255842.2021.1890721. Epub 2021 Mar 5. PMID: 33667151.

4. Bisinotto FMB, Dezena RA, Martins LB, Galvão MC, Sobrinho JM, Calçado MS. Queimaduras relacionadas à eletrocirurgia – Relato de dois casos [Burns related to electrosurgery - Report of two cases]. Rev Bras Anestesiol. 2017;67:527-534. Portuguese. doi: 10.1016/j.bjan.2016.03.003.

5. Ho CWG, Yang SH, Wong CH, Chong SJ. High-voltage electrical injury complicated by compartment syndrome and acute kidney injury with successful limb salvage: A case report and review of the literature. Int J Surg Case Rep. 2018;48:38-42. doi: 10.1016/j.ijscr.2018.04.039. Epub 2018 May 16.

6. Huschak G, Steen M, Kaisers UX. Elektrochirurgie--Grundlagen und Risiken [Principles and risks of electrosurgery]. Anasthesiol Intensivmed Notfallmed Schmerzther. 2009 Jan;44(1):10-3. German. doi: 10.1055/s-0028-1128179. Epub 2008 Dec 29. PMID: 19115182.

7. Vilos GA, Rajakumar C. Electrosurgical generators and monopolar and bipolar electrosurgery. J Minim Invasive Gynecol. 2013 May-Jun;20(3):279-87. doi: 10.1016/j.jmig.2013.02.013.

8. Takahashi Y, Enatsu R, Kanno A, Imataka S, Komura S, Tamada T, et al. Comparison of Thresholds between Bipolar and Monopolar Electrical Cortical Stimulation. Neurol Med Chir (Tokyo). 2022 Jun 15;62(6):294-299. doi: 10.2176/jns-nmc.2021-0389. Epub 2022 Apr 22.

9. El-Sayed MM, Saridogan E. Principles and safe use of electrosurgery in minimally invasive surgery. Gynecol Pelvic Med 2021;4:6(1-14). doi: 10.21037/gpm-2020-pfd-10

10. Frivalssky M, Pavlek M. Electro-Thermal Model of Liver Tissue and its Approximation. Biomedical Eng. 2019; 17:187-193. doi: 10.15598/aeee.v17i2.2872

11. Hurst RD, Stewart CL. Hazards of surgical smoke from electrocautery: A critical review of the data. Am J Surg. 2024 Jul;233:29-36. doi: 10.1016/j.amjsurg.2024.02.017. Epub 2024 Feb 9.

12. Dufaye G, Cherouat A, Bachmann JM. Advanced modelling of the mechanical behaviour of biological tissues: application to 3D breast deformation. Comput Methods Biomech Biomed Engin. 2013;16 Suppl 1:305-7. doi: 10.1080/10255842.2013.815917. PMID: 23923952.

13. Morrison TM, Dreher ML, Nagaraja S, Angelone LM, Kainz W. The Role of Computational Modeling and Simulation in the Total Product Life Cycle of Peripheral Vascular Devices. J Med Device. 2017;11(2):024503. doi: 10.1115/1.4035866. Epub 2017 Jan 23. PMID: 29479395; PMCID: PMC5823268.

14. Lin CL, Lan GJ. A computational approach to investigate optimal cutting speed configurations in rotational needle biopsy cutting soft tissue. Comput Methods Biomech Biomed Engin. 2019 Jan;22(1):84-93. doi: 10.1080/10255842.2018.1535060. Epub 2018 Nov 6. PMID: 30398374.

15. Radmilović-Radjenović M, Radjenović B. 2020. Studies of the origin of skin burns during electrocautery based on a multi-component plasma fluid model. J. Surg. Surgical Research 2020;6:27-29. doi:10.17352/2455-2968.000091