Novel Technologies for Reducing the Occurrence of Accidental Burns During Electrosurgery

3MA100 - Physics Behind Medical Technology

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Abstract

Electrosurgery is a widely used surgical technique for cutting and coagulating tissue, but there are several risks related to incorrect use. To reduce adverse effects, an option is to develop more advanced generator control systems. These systems monitors the tissue temperature and/or impedance during use. The generator switches between operation modes and adjusts power outputs according to tissue feedback parameters or, avoiding feedback, using models to fit necessary parameters. Another (complementary) option is to develop representative models that accurately captures the physical processes occurring at the interface between active electrode and tissue. To handle the big data sets of input parameters necessary to develop such models, the prospect of using machine learning is interesting. Implementing machine learning could speed up simulation processes and outperform humans in mapping input to output parameters. This may increase health personnel knowledge, and can help optimise settings of the electrosurgical generator according to simulation(s), reducing the amount of accidental patient burns.

In this review paper, we first present the physical working principles and operational modes of the electrosurgical unit, and the risks related to incorrect or non-optimal instrument use. Thereafter, current research performed on generator control systems and tissue behaviour modelling will be presented, followed by an evaluation of which of the two approaches would be more convenient to invest time and resources in for the sake of reducing occurrence of accidental burns. Developing more accurate models for tissue behaviour would be a useful tool in increasing knowledge among surgeons for safer handling of equipment, whereas improved generator control systems increase the ease of use and inherit automatic mechanisms for burn prevention.

1 Introduction

Electrosurgery is a surgical technique where high frequency alternating electric current is used to desiccate, coagulate, and/or fulgurate biological tissue. Due to impedance of tissue, heat is generated when an electric flow is applied. Hence, the technique can be used in surgery to control bleeding and/or to dissect soft tissue. An electrosurgical device consists of two electrodes and a high frequency (HF) electrical generator, in addition to components facilitating sterility and safety. Clinical relevance and cost-effectiveness make electrosurgery one of the most important surgical technologies [1]. Electrosurgery is commonly used in dermatologic procedures to remove abnormal skin growths or for cosmetic indications, gynecological procedures such as laparoscopy and hysteroscopy, and also in gastroenterology, tissue resection and for hemostasis [1][2][3].

Although electrosurgery is extensively used today, there exists a knowledge gap and a lack of surgeon expertise on the field. The risk of complications is tightly related to the surgeon's knowledge on possible complications and technical faults that may occur [1], but also to the lack of understanding on tissue response to large current levels [4]. The most common adverse effects are skin or visceral burns, which can do serious damage to the patient and has high morbidity if not recognised early enough [5]. For laparoscopic applications, the reported incidence of severe burns is 3.6 out of 1,000 procedures [6]. The injury could be a result of instrumental issues or failure, such as direct or capacitive coupling or insulation failure, but it could also be due to direct application. If an excessive amount of power is used for too long time, tissue injury could occur [5]. One rationale for non-optimal generator settings is the lack of a purely representable model of tissue behaviour to electric current at different anatomical sites. Different tissue types will have distinct impedance and current responses, which makes it hard to predict and control the thermal spread. Modelling of tissue behaviour in response to electric current applied during electrosurgery is complex, and there is not yet a model that efficiently captures all relevant effects [7].

This paper aims to review recent technologies developed to prevent accidental burns from occurring during electrosurgery. There are mainly two approaches that will be discussed: improving generator control systems that may adapt to changes in tissue conductance during surgery, and developing more realistic models of tissue behaviour and thermal spread to increase understanding and knowledge among clinicians. Thereafter the two approaches will be compared and evaluated based on ease and feasibility of implementation, and their prospect of reducing the number of accidental burns.

2 First aspects on Electrosurgery

2.1 Historical background

The use of heat for medical purposes has a long history, as documents from 980 BC prove, describing the use of hot iron to control bleeding in patients [1]. As the development of electrosurgery is obviously linked with increasing knowledge concerning electricity, it has known a rapid expansion in the 19th century [8]. In the 19th century, for the first time, heat was generated in biological tissue without stimulating the neurons and muscles. The medical device was made by Morton in 1881, when he showed that an alternating current of 100 kHz did not cause any neuromuscular stimulation. Later, the effect of destroying biological tissue was described [1].

The fundamental of today's electrosurgery is much based on the collaboration between the physicist William T. Bovie and the neurosurgeon Harvey Cushing in late 1920. They developed the first modern electrosurgical unit. The model offered the possibility to cut and coagulate [5]. Bovie's generator was the first milestone for the development of electrosurgery, and his name is still used to name the generators used today.

2.2 Basic Principles of Electrosurgery

Electrosurgery is a surgical technique where an alternating radiofrequency (RF) current is applied to perform either cutting or coagulation. It is essential to keep the alternating current high (> 100,000 Hz) to avoid interference with electrical signalling of the nervous system [8]. Tissue impedance is a result of oscillation of cellular ions when an alternating current is applied. Frictional heat is produced when the electric flow encounters this inherent impedance in tissue, which result in either vaporisation or dehydration of cells present due to the heat generated from energy dissipation. This will again elicit dissection or coagulation, depending on the settings. Coagulation can also be performed using fulguration, where the active electrode is not in direct contact with the tissue. Electric sparks are created between electrode and tissue, giving rise to temperatures up to 200 °C [6]. Temperatures must be tightly controlled in order to assure that the desired tissue effect is obtained. The various thermal effects on skin as a function of temperature are visualised in Fig. 1, emphasising the importance of tight temperature control.

The efficient temperature rise in the tissue, and hence the resulting effect of electrosurgery, is dependent on several parameters, such as the applied current density and

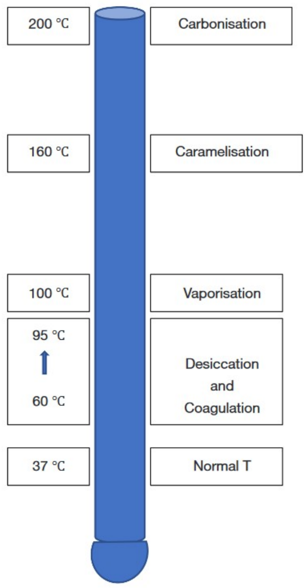

Figure 1: Figure illustrating temperature effects on the human skin as a function of temperature applied. Vaporisation occurs at around 100 °C, whereas highly elevated temperatures result in carbonisation, efficiently insulating below areas from heat spread. The image is adapted from [6].

waveform, size and type of electrode, conductivity of the tissue and time [5]. This is mostly controlled by the generator. The generator, that will be presented more in depth later, adjusts the voltage and the duty cycle of the current, and can produce distinct types of current waveforms. There are three main structural types of current waveforms that can be applied, each yielding distinct tissue effects, being either cut, blend or coagulation mode[6]. Fulguration is not listed among the main current waveforms, as it is a type of coagulation mode. The pattern will be similar to coagulation mode, but with a larger peak voltage to create electrical arches. The basic shape of the three waveform types are visualised in Fig. 2.

The electrosurgical unit (ESU) consists of a generator and two electrodes, and the device can be controlled by a switch, which is either handheld or steered by the surgeons foot. The equipment further consists of components to improve safety, including sterile sleeves to cover the handle, disposable electrode tips and a smoke evacuator to safely remove the mutagenic smoke plume [2]. The generator is used to apply a constant voltage or power, depending on the settings. The operating currents are high and can be damaging to the patient if not used correctly, resulting in burns or other injuries. Present day generators can use algorithms that adjust the output power or current depending on patient return functions, as a measure to prevent damage to the patient, as explained in section 3. There also exist general safety procedures that should be followed by the operating surgeons [8].

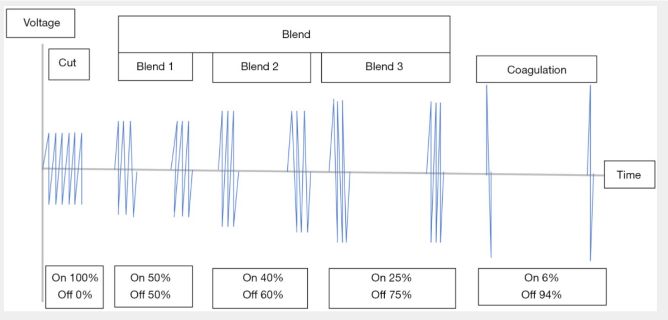

Figure 2: Electrosurgical generators may produce different waveforms depending on application. One can distinguish three main waveforms yielding distinct tissue effects: cut, blend and coagulation. Fulguration mode has the same pattern as coagulation, but a larger peak voltage. The image is adapted from [6].

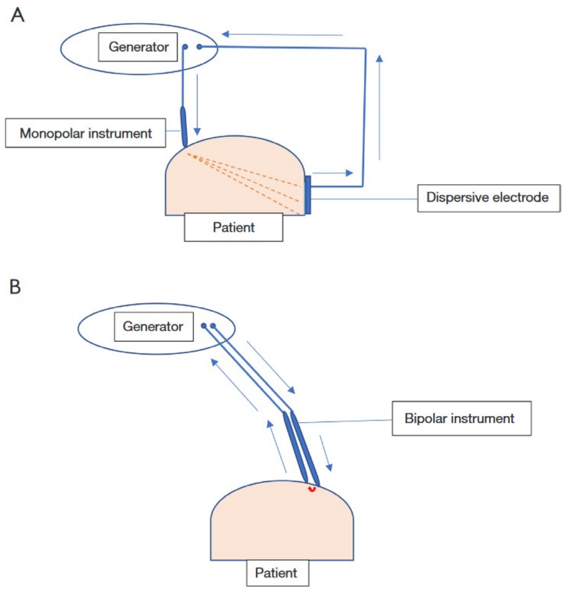

Figure 3: Schematic of the two electrosurgery modalities: A) monopolar mode and B) bipolar mode. In monopolar mode, the patient is integrated into the circuit, with a dispersive electrode placed remote from surgical site. For bipolar mode, both active and return electrode are located at surgical site. Image is adapted from [6].

Electrosurgery devices can be operated in two different circuit modes: monopolar or bipolar, as can be seen in Fig. 12. For a monopolar circuit, the return electrode is placed somewhere on the patient, remote from the surgical site. Hence, current will flow through the patient and back to the generator. The return electrode has a large surface area to reduce the current density. For a bipolar approach, two electrodes are used at the site of the wound, and hence the current is only applied locally, between the two electrodes. The monopolar mode is the most versatile approach for switching between cutting and coagulation modes. The bipolar mode is convenient for precisely delivering intense energy to a small spot [3].

For the time being there is limited understanding of the exact processes occurring at the interface between active electrode and tissue. Current conducting through tissue results in resistive heating as ions and/or electrons travels with the potential gradient. The simplest equation to describe electrosurgical effect is given by

$$Q = I^2 \cdot R \cdot t \tag{1}$$

where Q is the heat dissipated in the tissue, I is the current, R is the tissue resistance and t is the amount of time for which the current is applied [8]. However, it is not well known how tissue impedance changes as a function of applied voltage, time and power/current output from the generator. The above equation gives an excessively simplistic view of tissue response to electrosurgery, as there are several effects taking place at tissue-electrode interface. To describe this complex process, researchers are actively trying to seek out fitting and representative models for tissue behaviour. Knowledge on electrical circuits is used to describe the conduction of currents, whereas thermodynamic and thermal models are used to account the heat spreading, and chemistry and biomechanics is used to further describe the reaction of human tissue to changes in both membrane voltage and ions concentration. The above science fields are dissimilar, but however still tightly intertwined in practical applications. Combining knowledge from all these fields is essential, and is what the scientific community is trying to achieve for developing new and improved models for electrosurgery [3].

It is also important to highlight that correct handling electrosurgical equipment by surgeons is essential to improve efficiency and to reduce complications, supplementing the strong need of understanding the basic as well as physical principles of electrosurgery [8]. There is a lack of both systematic training and established models for tissue response. If the physical response of tissue can be modelled in a more realistic and representative manner, routines for systematic training may also be improved, and postoperational complications of electrosurgery are more likely to be reduced [5].

2.3 Risks

Though electrosurgery offers several advantages over the use of a scalpel and improves quality of homeostasis, the technique is associated with a risk of complications. Approximately 40,000 unintended patient burns occur every year, and several million dollars are paid out in compensation. Some of the injuries are harmless, but severe and possible lethal burns happen [9]. Some risks can easily be avoided by taking proper safety precautions and following safety guidelines correctly, being

- Presence of flammable gases and/or liquids (cleansers)
- Patient is not properly insulated from grounded objects
- Poor removal of surgical smoke plume
- Fire hazard and/or explosions
- Poor electrical contact at return electrode
- Non-optimal placement of return electrode
- Transmission of infections
- Electromagnetic interference with other devices and/or implants

The above listed risks can be prevented by proper preparation, and will presumable not be affected by improved modelling of electrosurgery or generator control system. One exception is poor electrical contact at the return electrode, which can be detected by modern smart generator designs [5]. This is already well implemented in clinical use [8]. However, the largest risks of electrosurgery is related to direct application and the current diversions [9]. These risks are especially relevant during laparoscopy. As the surgeon has no direct line of sight, but depend purely on a monitor image and anatomy knowledge, there is also a lower probability of detecting burns during the surgical procedure [8]. The six most common complications are listed below, sorted in the order of more to less clinical relevance [9]

- Direct application (lateral thermal spread)
- Insulation failure
- Antenna coupling
- Residual heat
- Direct coupling
- Capacitive coupling

Direct application injuries are a result from the thermal spread from the tip of the electrosurgical device to surrounding tissue structures. The thermal spread in the relevant tissue is dependent on many factors, such as instrument type and parameters, power settings, duration of the treatment and tissue impedance [6]. This is not a matter of current diversion, but rather a lack of complete understanding on the exact tissue response when electrosurgery devices is used [10]. The next major risk is insulation failure, which result in adverse current pathways remote from the surgical site. Cracks in the insulation layers may be due to frequent sterilisation and/or use of the equipment [5]. Antenna coupling is electromagnetic coupling of the cord of the electrosurgery electrode to the cord of another device, like a camera or ECG wire, resulting in undesired activation [9]. Residual heat may be present in devices after deactivation, and hence surgeons must be careful with device handling also after intended use. Lastly one has the effects of coupling. Current will always find the way of least resistance, and if the active electrode is in too close proximity to another metal device, adjacent organs and/or structures may be subject to an unintended electric current pathway, also known as direct coupling [6]. Capacitive coupling occurs when another conductive material is in close proximity. There is a high risk of spark formations if distances are small and the surface areas are large [8].

To reduce the amount of accidental patient burns, the above complications should ideally be eliminated. For the effects of coupling and insulation failure, modern active electrode monitor (AEM) systems may be used for early detection [5][6]. However, occurrence lateral thermal spread from direct application cannot be eliminated by AEM in the same manner, but is rather a question of correctly adjusting ESU parameters [9]. If one is able to predict and/or adjust to how thermal spread occurs as a function of ESU settings, time and tissue parameters, surgical procedures can be performed thereafter and burn incidences can be reduced. In the following sections, two different approaches for achieving this will be presented and discussed. This includes implementation of smart generator control systems, that can sense and adapt to changes in tissue parameters during the surgical procedure, and multiphysics modelling of tissue to predict behaviour and response to electrosurgical treatment.

3 Generator Controllers

Since electrosurgery is a technique based on delivery of high frequency alternating current, generators are main components of the circuit. It is also important to note that the body of the patient is part of the circuit, thus affecting the final outcome through inherent tissue impedance. Together with this parameter, there are also other factors coming into play, such as distance between tissue and electrode, position of passive electrode, power, voltage and current density. These parameters have to be considered when designing an electrosurgical unit, and monitored through a feedback control loop on the generator for appropriate adaption to the changing conditions [11]. The main problem often encountered in literature is the difficulty of keeping the power output of the generator constant, since fluctuations of this parameter lead to thermal spreading. There could be misunderstanding on the definition of constant power output for an AC output, now clarified: average power delivered in each switching cycle [12]. The problem arises from the changes in tissue impedance during electrosurgery – tissue impedance is initially low, but progressive tissue desiccation increases the impedance. Therefore it is challenging to face changes in voltage in order to maintain the same power output [13]. To deal with the problem, innovative solutions are proposed – such as specialised proprietary output modes to control the process.

3.1 Dual Control Mode Controller

We first cite a controller, switching between constant power, current and voltage output, that can be applied to different converters by Friedrichs et al [12], prototyped using a field-programmable gate array (FPGA). The outcomes are listed below:

- When constant power mode is applied, changing the load, voltage and current changes, but their product, i.e. power, remains constant.
- Operating in voltage limited mode, when the impedance of the tissue being cut changes, the converter switches to constant power mode. Since the load impedance increases, the increasing output voltage triggers current to power to voltage transitions.

Transitions are based on the power source output characteristic, to which maximum voltage and current are added, always with the aim of avoiding side effects. With the design of the review, also this claim is satisfied, as shown in Fig. 4. The topology of the converted is illustrated in Fig. 5.

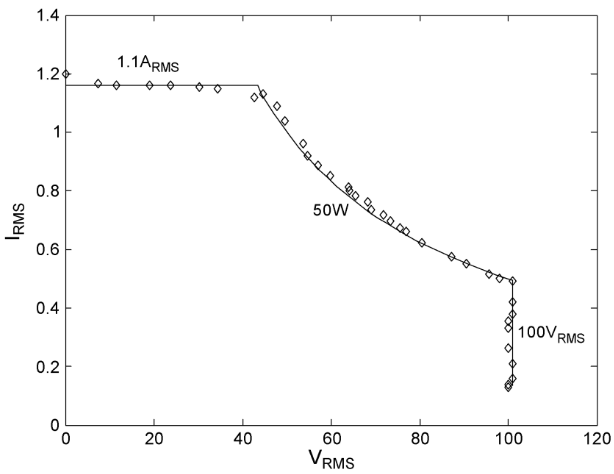

Figure 4: Measured data overlaid on a desired current (I) vs voltage (V) curve during electrosurgery, both expressed as RMS values. The image is adapted from [12].

The transitions are based on different values of duty cycle regulating DC-DC buck converted and DC-AC boost converter. Furthermore the duty cycle is determined for each cycle individually, not depending on previous values, resulting in a deadbeat control, i.e. within one or two duty cycle(s). The fast power regulation is also important for avoiding tissue damage. Furthermore, feedback control circuits decrease electromagnetic emissions, thus reducing interference with other systems and capacitive effects, reducing risk of alternating tissue burns as described in the Risks-section (2.3).

3.2 Thermal Control System

Another implementation for regulation of current and voltage output is the one based on thermal measurements, as described by Abdullah et al [11]. The first idea in the article is based on measuring temperature at the site of the cut through thermocoupling and a thermal camera, processing and storing the information, and then comparing it (Thermal Evaluator Process) with existing data from

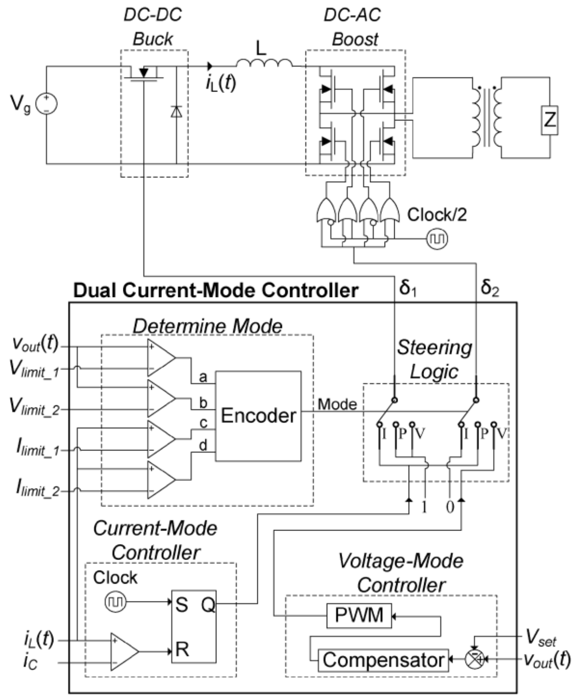

Figure 5: Topology of the DC-DC buck converter. The circuit is able to switch between desired output modes (see Fig. 4). The image is adapted from [12].

Thermal Default Data Storage, which is the set point. If the temperature is considered too high according to the difference between set point and measured data, then the Thermal Evaluator (comparator) will order the Voltage Evaluator (power supply) to reduce the voltage by a certain interval, and vice versa. The difference between set point and measured temperature is evaluated by a PID controller, which creates a pulse width modulation (PWM) signal applied to the power supply. In this way body temperature is consistently sensed and kept constant. The process is shown in Fig. 6.

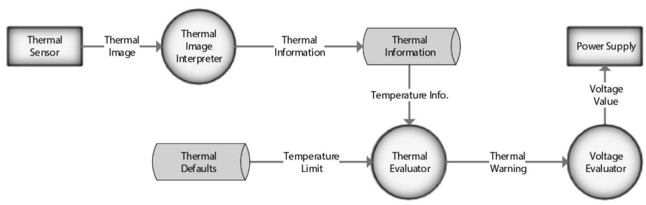

Figure 6: Data flow diagram for thermal image identification and image processing. The image is adapted from [11].

In order to validate the process, results were compared to outcomes obtained without controller on a chicken breast tissue. From Fig. 7 and Fig. 8 it is evident that there are reductions in collateral tissue damage using control surgical technologies. This could eliminate human error aspects, causing thermal damage, due to overexposure to the organic tissue.

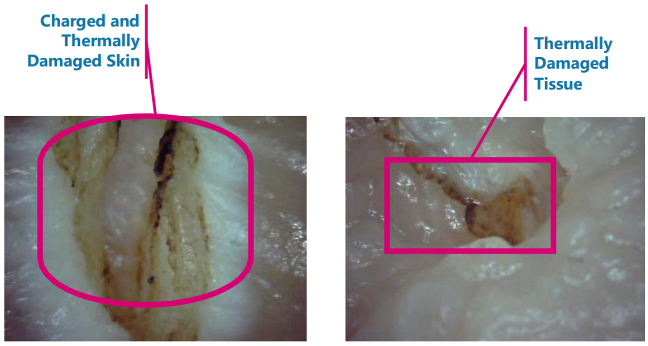

Figure 7: Thermal damage to tissue at 80°C without using the controller. This results in thermal damage to the tissue. The image is adapted from [11].

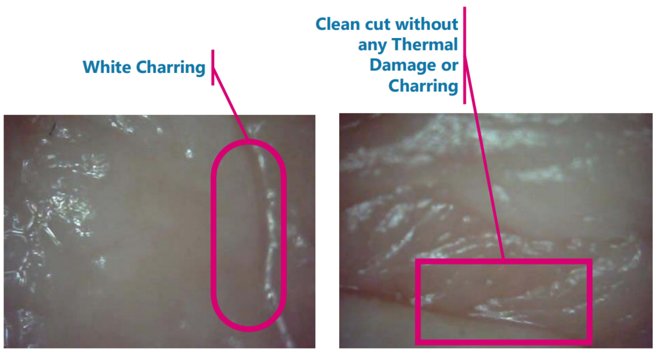

Figure 8: Tissue cutting using the thermal controller system. No thermal damage is observed. The image is adapted from [11].

To gain knowledge on the extent to which heat spreads in tissue, it is also useful to model temperature changes. This can be used to study thermal processes and consequently control these variations [14]. Moreover, these kind of simulations are interesting for supplenting experimental methods, which are complex and time consuming. Yakhutlov et al. proposed a mathematical model built on SolidWorks, using a Finite Element Method (FEM) and setting physical properties of the element, such as width, length and initial temperature. Subsequent optimisation was performed by comparing estimation of temperature with measured data. According to the author, the model can be used for different organs and applied for controlling surgeries thanks to the knowledge on the temperature field [14].

3.3 Optimisation of parameters to avoid Feedbacks

Feedback system control loops are expensive and not yet trivial. Nowadays, surgeons manually regulates parameters before the surgery, which is why many studies are focused on negative feedbacks to regulate power output in real time. However, it would be time-saving, easier, more user-friendly and cost effective if one could optimise settings of the generator, thus obtaining equally satisfying results. One study was carried by Kshirsagar et al. in 2021 for a specific case, i.e. Electrosurgery Turbinate Reduction [15]. The paper compares a temperature controlled system to a electrosurgery submucosal diathermy (SMD), which was able to remove heat through blood flow. The study is limited by using egg whites and chicken breasts, which are not affecting real vascularization. Nevertheless, results showed similar volumetric coagulum for almost all the combinations of power and time. Furthermore, time for the formation of the lesion was shorter using SMD. Accordingly, this study could be seen as the first of many to open the way in validation of parameters for clinical use [15].

3.4 Automatic regulation

It is also possible to optimise internal components of the generator to obtain the least voltage variation and thus reduce control efforts to keep the average power output constant [16]. The schematic of such a unit is illustrated in Fig. 9. When the transistor is in conduction the current flows through the inductor. When it is turned off, the current flows through the capacitor and start decreasing. The study was carried out using a PSPICE simulation to find the best values for inductor L, capacitor C and winding relation N of the transformer. A time domain transient analysis was performed, using ideal components, having as output the mean power (obtained by using a first order low pass filter). The authors also expressed the intention of enhancing the work made by applying system identification techniques to improve the effectiveness of the circuit analysis [16].

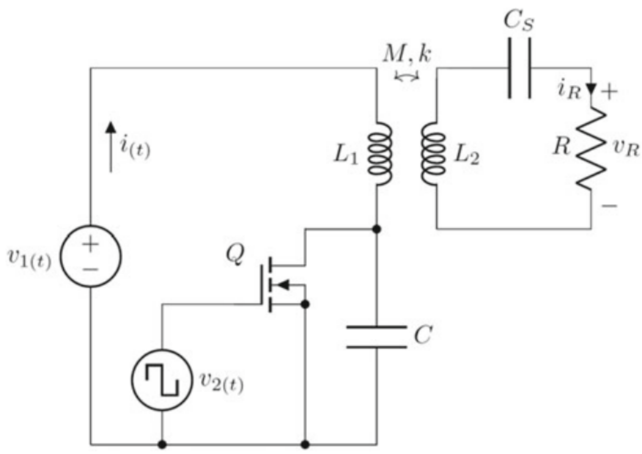

Figure 9: Schematic view of a constant average power output electrosurgery unit. The image is adapted from [16].

3.5 Stabilization of cutting

When vaporising tissues during electrosurgery, energy can be generated by ohmic heating. This is affected by electrode speed, since it influences the time spent heating the tissue. Together with power density, this is related to the energy necessary to vaporise. Known from the spread of power density, if the electrode moves too fast, there is no time to vaporise the tissue. Therefore, controlling the output corrected for speed of electrode can improve the outcome. This result has been proved qualitatively (Fig. 10), and look very promising [17].

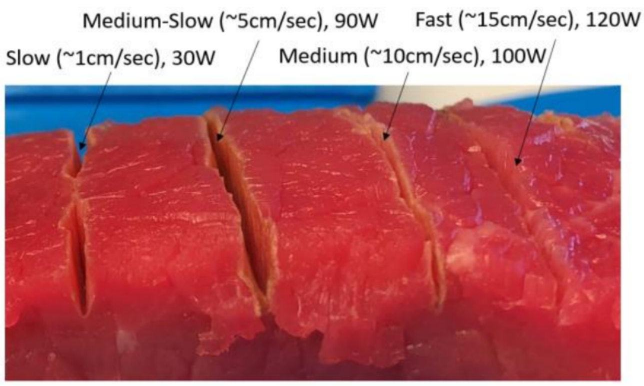

Figure 10: Thermal damage on for speed compensated power delivery. Arrows indicate the cutting speed. The image is adapted from [17].

In the same article, additional experiments were carried out. One of the most important result was that, although fast control loops reduce tissue damage, speed had a greater impact on performance than fast transient control loop. Moreover, it has been shown a dependence between higher output power and increasing electrode speed (Fig. 11). Thus, to avoid charring at slow speeds, output power needs to be reduced. The limit of the experiments is found in the qualitatively judgement of the cuts (visual scored from 0-4, where 1 indicates a good cut, 0 indicates sticking, 4 excessive thermal spread) very promising [17].

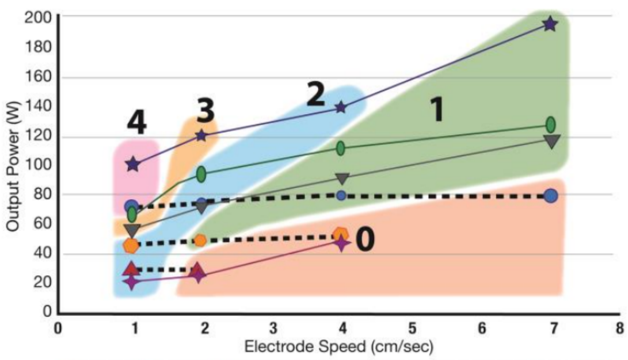

Figure 11: Power vs Electrode Speed for constant power at 80W (blue dot), 50W (orange hexagon), 30W (red triangle) and for constant voltage at 290V (green ellipse), 270V (dark green inverted triangle), 170V (purple). The image is adapted from [17].

4 Modelling tissue response

What does it mean to model electrosurgery, and why do we need it? Electrosurgery models are commonly used to predict tissue damage and evaluate the safety of the operation, as well as improving and developing new equipment design. Optimisation and adjustment of electrosurgical device parameters is essential to obtain desired result and prevent off-target tissue damage. However, developing predictive models for the outcome of electrosurgery treatment for different tissue types has proven to be challenging [7]. There is a lack of correspondence between existing models and observed experimental effects. There are multiple processes taking place at the interface between active electrode tip and tissue, including electrical, thermal, thermodynamic, mechanical and chemical effects [8]. Due to the complexness and lack of complete understanding of the interactions, theoretical models tend to fail to accurately capture experimental results [4]. Developing precise models will enhance understanding of surgical procedure, which may decrease the number of incidents occurring due to lack of knowledge on thermal spread. Moreover, generator settings can be optimised and predicted in advance, which could serve as an alternative or complement to generator mode controllers. A further option is to use proper models to develop accurate virtual reality (VR) simulations that can be implemented in surgical training, as described by Pan et al [18].

Excessively elevated temperatures is a major challenge for application, resulting in damage on tissue and surrounding structures, often in the form of burns, as discussed in section 2.3. Accidental burns may be superficial, but can also be lethal if severe and undiscovered. Clinical understanding of how and why electrosurgical burns occur is still not widespread, and there is a lack of predictive models for how energy distributes and dissipates in different tissue types. Dissipation of energy is strongly dependent on properties of the specific tissue, and these properties may also change as a function of temperature, heat loss and phase change [4]. In this section, models with different approaches and based on different physical principles will be introduced and discussed.

4.1 Equivalent electronic circuit models

The diverse electrical properties of body tissue can be simplified to electrical circuit components to simulate the response to electrosurgery. This model is convenient for assessing how tissue parameters changes as a function of electrical load. Dornhof and Belik performed a spectral analysis of porcine muscle tissue impedance, and simulated a fit close to the obtained results [7]. The authors constructed repeating RC elements in series to obtain a simple but yet accurate circuit model. The resulting seven-component RC series can be found in Fig. 12. The fitting parameters can be modified using a simulator to adapt the model for tissue types of other impedance values [7].

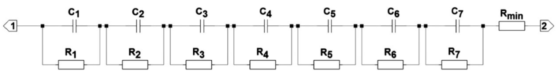

Figure 12: Equivalent electronic circuit models made of RC cell components. Resistance values are all equal, and varies for different tissue types. Capacitance values are found from simulations, and will decrease in magnitude from left to right. The image is adapted from [7].

The authors conclude their model to be adequate for simplified analyses, but not a perfect model of tissue response [7]. A circuit model may be too simple to capture all physical effects occurring at electrode-tissue interface. However, the model could prove very useful for simulating tissue behaviour when testing generator control technologies, and could hence be used in combination with the approaches presented in the previous section.

4.2 Multiphysics models

Recently, computational multiphysics models and simulations have been developed to complement experimental models. Yang et al investigated changes in thermal conductivity of tissues, and its correlation to the applied thermal dose [10]. For estimating thermal conductivity, an inverse heat transfer analysis was used. The authors proposed their findings to be included in a finite element model (FEM) to obtain a more complete model of tissue behaviour during electrosurgery, and to develop an improved algorithm for generator settings [10]. Pan et al used another approach, proposing a physics-centric meshfree model for electrocautery based on continuum mechanics [18]. From this they developed a virtual reality system to be implemented for surgeon training. Karaki et al developed a continuum thermodynamical model of in vivo electrosurgical heating of hydrated soft tissue, using a computational model with conserved mass, momentum and energy balance, as well as accounting for electric charge conformation for small deformation and matter phase changes [4]. Despite including numerous physical parameters, the model failed to precisely mimic the behaviour of soft tissue, especially for high power settings. The authors suggest to include more parameters in future studies, like a hyperelastic model for tissues and including friction effects between electrode and tissue [4].

Overall, the general trend for multiphysics modelling attempts is that more tissue parameters and effects should be included in future studies [7][10][4][18]. However, if all possible effects are to be accounted for, strong computational powers are required and computational times will be excessively long. In addition, data sets and amount of will be very large, which may complicate the process of connecting and analysing correlation between input and output parameters [19]. A possible solution to this issue could be to implement machine learning in the multiphysics models.

4.3 Implementing machine learning

A novel strategy is to use artificial intelligence to develop a reliable model, accounting for the heterogeneity of soft hydrated tissue [19]. Machine learning could be a useful approach to work with the large data sets required to achieve a sufficiently accurate model. Machine learning enables machines to learn and make predictions by recognising patterns in input parameters. With traditional programming, desired response of the program is explicitly stated. With machine learning, the implemented algorithm make the program capable of making a decision without specifically being told to react in that manner. The machine is "trained" in advance by providing input data for processing, and steering the response. The computer will thereafter make decisions based on the learning process [20].

Han et al proposes a hybrid approach, where they combine deep convolutional neural networks (CNN) with a finite element method (FEM) and iterative solvers to improve multiphysics computations [19]. The applied CNN approach is trained to map input micropore pressure distribution and topology of the tissue to output deformation field. The predicted deformation field is then used to solve the level set evolution equation, which is the topology input for the next iteration. Figure 13 shows a comparison between a conventional PGD iterative multiphysics simulation and the machine learning hybrid approach.

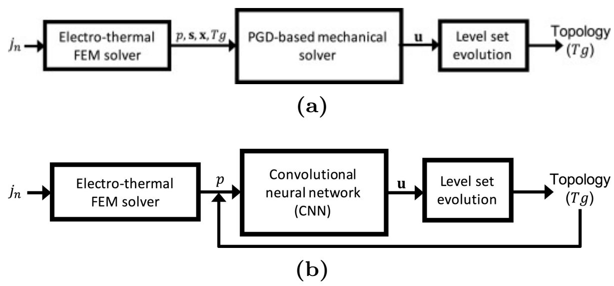

Figure 13: Figure compares the modelling of tissue electrosurgery approach when using conventional multiphysics equation solver (a) and a hybrid approach where machine learning is used to accelerate computation time and improve modelling accuracy (b). Figure is adapted from [19].

For this experiment, the authors proved that the deep learning approach could be used to accelerate computationally costful simulations, without affecting the precision of the FEM. The authors propose further improvements of their CNN model to more accurately mimic tissue behaviour. However, the authors do not report on the accuracy of their proposed model, but focus rather on the performance of their machine learning approach [19]. The use of machine learning and artificial intelligence in the general health care sector is developing fast, and general performance of models must be evaluated before implementation is feasible [20]. In this manner, machine learning may not yet be readily available for widespread use in modelling of electrosurgery, but is certainly an interesting option to handle the large data sets needed to account for the complexity of the interactions between tissue and active electrode.

5 Advice

Electrosurgical units are frequently used, regardless a lack complete understanding of their thermal spread in tissue and current leakage issues [8]. The research field for improving operation and enhancing understanding is large and versatile, as presented in above sections. In this paper, suggested approaches are to develop more intricate and smart generator control system or to develop more representative multiphysics models of tissue behaviour with the aim of anticipating tissue responses and enhance understanding of the physical processes. The approaches largely overlap, as also modelling of electrical circuits and tissue are needed in order to develop proper generator control systems. Hence, it is challenging to draw a definite line between the two approaches. They are based on the same fundamental principles, but differ somehow in implementation. Whereas generator control system could be controlled by a feedback loop extracting information from the tissue during surgery, the modelling could be used to predict tissue behaviour in advance and increase the surgeon's understanding of the processes taking place in the tissue at different generator modes [11][4].

Developing more advanced feedback mechanisms for controlling generator output appears to be the simplest and most easily achievable solution. There exist a lot of knowledge on generators and feedback mechanisms for automatic control systems, making the solution seemingly feasible. Knowledge on ESU behaviour is derived from basic laws of electrical circuits. For automatic management, tissue impedance can be calculated based on measurements of current and voltage. In order to test and develop new generators, computational models of tissue as a series of impedance elements (RC-circuit) can be used, hence combining the two above options closely [7]. Based on these models, control systems can be derived for adjusting voltage, current and/or power output of the ESU in a manner that is safer for the patient [5].

A drawback as well as an advantage for developing more automated generator control systems is increased ease of use for the surgeon. Equipment training can then be solely based on the operational technique, and less on tissue response to different control system settings. However, as of today, lack of knowledge among surgeons on the fundamental principles of instruments, biophysics and relevant anatomy is a main cause of complications [6]. Hence it seems counterintuitive to encourage a solution that further allows surgeons to lack knowledge on the physical processes occurring in the tissues during electrosurgery. In this manner, developing proper physical models for tissue behaviour could possibly close the current knowledge gap.

Accurate modelling of tissue behaviour during electrosurgery could be a useful strategy for increasing surgeon knowledge [10]. If correlation between input and output parameters can be accurately mapped and quantified, a better understanding of the physical processes between active electrode and tissue can be obtained. However, as presented in the modelling section, there is yet no model that precisely captures all observed experimental effects [19]. One could also raise questions on whether it is actually feasible to develop such models. Tissue behaviour and architecture is complex, and inter-patient variability can be large. Investing capital, time and resources into heavy research in the area could potentially result in a good model, but not necessarily. It might not be realistic to create accurate enough tissue models. With this in mind, developing better generator control systems appears to be a safer option.

Machine learning is an interesting aspect for processing the large data sets needed to develop an accurate tissue behaviour model [19]. Better systems for machine learning are developed fast, which makes it an interesting option for this purpose. The field of artificial intelligence in the medical field is up and coming, and disrupting technologies improving patient experience and medical insight has been uncovered. Machine learning could be used both to speed up the simulation processes, as well as to process larger data sets and discovering parameter correlations more efficiently than humans [20].

Overall, we think it would be wise to focus on developing generators with good feedback control mechanisms. Increasing patient safety in an efficient manner should be first hand priority. However, the knowledge gap on the physical processes occurring during electrosurgery is concerning, and increasing our basic understanding should also be of priority. In this manner, one should not write off the usefulness of having a good and representative multiphysics model of electrosurgery. If more accurate models can be developed, surgeon training could be performed more thoroughly, for instance by creating virtual reality simulations based on representative tissue behaviour models, as done by Pan et al [18].

6 Conclusion

Principles of electrosurgery must be thoroughly understood by all personnel present in the operating room. This forms the basis for patient safety and helps in early recognition of possible complications, such as burns [6], which is recognised as one of the most widespread and harmful risks of electrosurgery. In order to improve patient safety, a better understanding and prediction of thermal spread in tissue is essential. We proposed as solutions both multiphysics modelling and various approaches for generator control systems, using feedback control loops or not. In addition, the possible advantages of using machine learning to speed up and improve the modelling process was highlighted. As for generators, we referred to the importance of rapid switching between power and voltage control based on the change of temperature of the skin, either by measurements or implementing simulations to predict it [11][12]. Alternatively, there is a possibility to omit feedback systems all together through proper identification and optimisation of parameters in advance [16][15]. The latter would be a faster way of implementation, and, once the method is established and is sufficiently accurate, also easier to use.

Overall we believe that developing proper generator control systems would help reducing the occurrence of accidental burns. However, one must not neglect the importance of the operating personnel having proper knowledge on tissue response and the equipment used. Hence the significance of proper models should also be stressed. By developing models that accurately captures tissue behaviour, surgeons may gain a better understanding of the physical processes taking place between electrode and tissue during electrosurgery, which may also contribute to further reducing the number of burn incidences. To conclude, generator controllers provides a safety net by automatically adjusting to patient parameters, whereas multiphysics modelling has the potential to strongly improve surgeon training in advance. Especially implementing machine learning to speed up and improve simulations and developing representative VR systems for surgical training appears novel and promising technologies, and improvements of these technologies are expected in the near future.

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