The Electrosurgery: - A Story of Controversies and Discrepancies

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Abstract*—Though it has been known for decades, there are still controversies on how Electro-surgery physically really works.The known electro- and thermodynamical models of RF-electrsurgery are summarized and discussed. Especially their discrepancies and thermodynamical inadequacy (regarding pressure, temperature and power / energy) are emphasized.Thermodynamically the assumptions in the literature assume atmospheric pressure and range between two extremes:a) all the water of the cut volume has to evaporate to achieve cutting；b) less than 1% of this water ought to evaporate to achieve cutting；which leads to an energy density discrepancy of nearly one to ten.It is improbable, that cutting of the tissue in electrotomy would succeed due to a pressure equal to atmospheric pressure, since conventional "mechanical" cutting success is due to exercising a mechanical pressure on tissue much greater than atmospheric pressure.Electrodynamically, the points of view can be summarized in essentially two different models. 1) "the conventional field model" and 2) "the arcs-model". In the first one a solid (mechanical) contact between tissue and electrode is assumed, so that conventional field theory calculations can be applied to estimate power density configurations. In the second model, instead of solid contact, a "riding" of the electrode on a vapor film during cutting is assumed; with the result of formation of arcs. Arcs are considered in this model as essential, making the cutting electrode more effective. By some authors it is even mentioned that cutting in electrosurgery is only possible when the voltage between cutting electrode and tissue is high enough to produce arcs, or in other words: no arcs no cutting.Based on a qualitative proof of an "overpressure hypothesis" using "schlieren" photography, and depending on the thermodynamical similarity between electrosurgery and laser surgery , and using a biphasic system a new, more realistic model of electrotomy is introduced to overcome those discrepancies Controversies. The major features of this model are: 1- Cutting is due to partial evaporation under overpressure followed by pressure waves after tissue rupture.2- Coagulating effect during cutting is due to coagulating arcs over the vapor layer, their frequency probability correlates positively with crest factor. 3- The specific resistance of tissue is no longer invariant. It is temporal and spatial variant；It seems, according to our model, that maximum power of electrosurgical units are oversized which could affect, if true, patient's safety negatively.

Keywords— ***Electrosurgery; Electrotomy; Electro- / Thermodynamical Modeling; Partial evaporation; Overpressure /-Temperature; Arc Probability, Crest Factor; Tissue Resistivity.***

I. SOME PHYSICAL VALUES

As tissue consists to 85% of water, one can assume values for the thermal parameters of the tissue, which are about 85% that of water. Accordingly, and due to the physical quantities as they are tabled for water in reference [2]:

- Tissue specific heat = 3.5 J/K cm^3.
- Specific evaporation heat (at 100 ^{0}C, 1bar) = 1920 J/K cm^3.
- Specific heating energy from 35 ^{0}C to 65 ^{0}C (coagulation) = 105 J/ cm^3.
- Specific energy necessary for heating up to 100 ^{0}C plus total evaporation under atmospheric pressure = 2150 J/ cm^3.

II. CONTROVERSIES AND DISCREPANCIES

Knowing that electrosurgery is an "old" technique, one would expect everything is clear about how it works (i.e., how it functions electro- and thermo-dynamically). Reading the references, one is surprised to see the discrepancies, especially regarding electrotomy.

Electrodynamically, the points of view can be summarized in essentially two different models. Let us call them:

1) "the conventional field model" and
2) "the arcs-model".

In the first one, a solid (mechanical) contact between tissue and electrode is assumed, so that conventional field theory calculations can be applied to estimate power density configurations. In the second model, instead of solid contact, a "riding" of the electrode on a vapor film during cutting is assumed; with the result of formation of arcs. Arcs are considered in this model as essential, making the cutting electrode more effective.

Authors preferring the first model implicitly or explicitly are referenced for example in [3] and [4]. The introduction of the second model is mainly due to Pearce [5]. A substantially similar model can be found in a book [1] published in 1932, as was noticed by Pearce. Pearce also distinguished mainly between coagulating and cutting arcs. Khandpur [10] even mentioned that cutting in electrosurgery is only possible when the voltage between cutting electrode and tissue is high enough to produce arcs (200 Volt and above), or in other words: no cutting without arcs.

The first model has the advantage, that analysis and description of the surgical electrodynamical processes are quite easy and have deterministic character. Considering the arcs model leads to the following consequences;

1. The interaction between electrode and tissue always takes place at a point independent of the form of the electrode, and, to some extent, its size. Thus the maximum achievable power densities are higher, when arcs are considered.
2. Due to arcs, all electrosurgical systems (i.e., whole system: generator –electrodes-tissue) somehow posses spark-gap system properties.
3. Arcs are stochastic phenomena. Deterministic analysis and description of electrosurgical processes is no longer possible. Problem solving in this manner is a form of simplification by semi-deterministic modeling.
4. Additionally, arcs mean a wide band frequency spectrum, with high and low frequency components, producing interference problems with other equipment. Interference filtering problems are thereby more complicated. Pearce makes, in his interesting book [5], sophisticated studies regarding this problem.

The possibility of formation of arcs during electrosurgical processes can not be denied; in some electrosurgical processes arcs are intentionally provoked. The question is whether or not they are necessary for pure cutting. On the other hand, for cutting with simultaneous coagulation, arcs can become necessary as will be shown later.

The discrepancies with respect to thermodynamics of electrosurgery are more evident. Once again, we can divide the points of view into two models; let us call them the high and the low energy model.

High energy model: It is based on the assumption that all water of the cut volume has to evaporate to achieve cutting. Such a model can be implicit or explicit found for example in reference [3] and [4].

Low energy model: It is based on the assumption that less than 1% of this water ought to evaporate to achieve cutting. This model has been introduced by Pearce [5]. His argument for his model is based on the fact that water has a density (mass/volume) which is more than 1600 times greater than that of vapor. Pearce repeated in the section about electrosurgery in Webster's Encyclopedia [9] the water/vapor density ratio, but now he mentioned it to be 1300 to 1. He did not repeat the 1% assumption).

The first (high energy) model leads to a necessary cutting energy density of about 2150 J/cm3, the second (low energy) model leads to a necessary density of about 245 J/cm3. This yields a discrepancy of nearly one decade.

Regarding these discrepancies the provocative question can be posed:

"How does electrosurgery really work?"

III. TOWARDS A NEW MODEL

Both the low and the high energy model represent unlikely extremes and are thermodynamically improbable. The high energy model does not consider the volume-pressure-relationship. The low energy model is based on an assumption, that is only valid under atmospheric pressure. But, it is improbable, that cutting of the tissue would succeed under atmospheric pressure, because conventional cutting success is due to exercising a mechanical pressure (pressure = force / area) on tissue which is much greater than atmospheric pressure. Notice that a 1N force on a scalpel-tissue contact area of 1mm2 leads to a pressure of about 1Mpa (or 10 bar). Therefore, one could expect to some extent an “overpressure” to be necessary in electrotomy. This "overpressure hypothesis” was first introduced in [8].

Using "schlieren" photography could give, at the present time, a kind of qualitative proof to accept on reject this “overpressure hypothesis”. With schlieren photography it is possible to make density differences visible. Density difference can be caused by temperature differences, but also by pressure differences.

If a piece of tissue (meat) is mounted vertically, and if one cuts in the direction from bottom to top, then lateral or even downward escaping schlieren must be implied as “pressure schlieren”. Such an experiment has been carried out; the result can be seen in Fig.1. Fig. 1 therefore, is a qualitative proof for the existence of an overpressure in electrotomy.

Thermodynamically, the mechanism of electrosurgical or laser cutting are similar. Pearce [5] expressed this as presumption but he did not draw the appropriate conclusion accordingly. Due to the properties of laser, it is possible to achieve very high power intensities, which are not possible in electrosurgery. Fig. 2 shows temperature and pressure as a function of power intensity in laser cutting processes according to a model from Zweig and Weber [6]. In table 1 the maximal power intensities in electrosurgery depending on the applied RF-power and the radius of a semispherical active electrode are point out. Notice that if the arcs model according to Pearce [5] is considered, higher power intensities are achievable. According to Table 1 and Fig. 2 one can conclude that electrotomy occurs under “overpressure and overtemperature”

Depending on the applied power and the dimensions of the active electrode and the interaction modality (i.e. arcing, not arcing) maximal local pressures and temperatures such as 2 bar and 120 0C or 10 bar and 180 0C, but also 29 bar and 2300C are achievable.

A new model for electrotomy, which is mainly supported by the above mentioned “overpressure hypothesis” and a two-phase-model can be simplified and summarized in the following points:

1. The high volumetric electric power density in the direct neighborhood of the active electrode and the impossibility of a thermal equilibrium (because of the shortness of time) leads to cutting.

Fig. 1: Schlieren Photography during electrotomy.

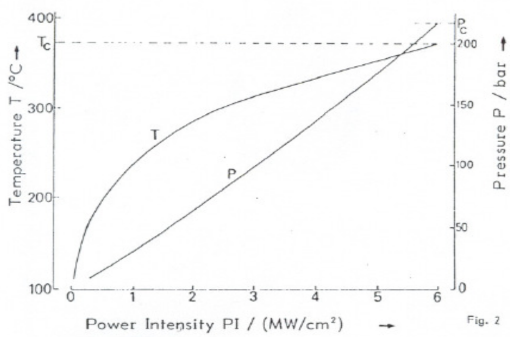

Fig.2.: Temperature T and Pressure P as function of applied power intensity in laser cutting (adopted from [6]).

TABLE 1: ACHIEVABLE MAXIMAL POWER INTENSITIES (IN MW/CM2) IN ELECTROSURGERY AS A FUNCTION OF APPLIED POWER P0 (IN W) AND THE RADIUS OF A SEMISPHERICAL ACTIVE ELECTRODE R0 (IN MM).

r_0	**P_0**			
	50	**100**	**200**	**400**
0.05	**0.32**	**0.64**	**1.28**	**2.56**
0.1	**0.08**	**0.16**	**0.32**	**0.64**
0.25	**0.013**	**0.026**	**0.05**	**0.1**
0.5	**0.003**	**0.006**	**0.013**	**0.026**

2. There is a minimum of volumetric power density needed for cutting, which depends on tissue properties (i.e., solidity, elasticity, viscosity, etc.), and that is the power density which leads to the minimum overpressure and volume enlargement (through evaporation) sufficient, in enough short time, to rupture the tissue. Higher power densities mean higher overpressures and hence deeper and faster cutting.

3. Overpressure means higher evaporation temperatures. Pressure and evaporation temperature are considered as a pair, for example (2 bar, 120 0C), (10 bar, 180 0C) and so on. Volume enlargement due to evaporation happens under such pressure-temperature-pair-constellations.

4. The electrical energy density needed for cutting is the summation of :

a) Warming energy density needed to warm tissue from body temperature (< 350C) to evaporation temperature (Td) under the considered overpressure (Pd) (i.e., for example 120 0C at 2 bar, 180 0C at 10 bar and so on).

b) Pressures/temperatures between 2 bar/1200C and 10 bar/1800C. Considering the mechanical pressure exercised in conventional cutting, as mentioned in the example above, it is more likely10 bar/1800C.

c)Volume enlargement between 2 and 5 times through evaporation, for which the necessary energy density can be neglected.

The above presumptions mean energy densities between 305 and 547 J/cm3 (notice that first Pd = 200 bar and Td = 23600C would lead to a necessary energy density of 1.9 kJ/cm3).

5.The rupture of the tissue under overpressure leads to:

- Pressure gradients and pressure waves leading on their side to:
  - Supporting further tissue rupture,
  - lateral pressing (pushing) of "rest-tissue".
- The rapid fall of pressure after tissue rupture leads to evaporation of the "rest-water" with the effect of cooling the tissue around.

6. A biphasic system can be used to explain cutting processes and the correlation between coagulation (hemostasis) and crest factor during electrotomy:

As above mentioned, cutting is due to evaporation under overpressure. One can model the tissue during cutting as a biphasic system consisting of a vapor layer with a specific resistance ρv and a tissue layer with a specific resistance ρt (ρv >> ρt). Fig. 3 shows the model simplifyingly considering a semispherical electrode form. Since ρv is much greater than ρt, a concentration of the power or energy in the vapor layer occurs, and the coagulation depth goes to zero if r2 - r1→ 0. Notice that if successively higher power is applied, or if cutting arcs are considered (as in Pearce model [5]), the result is the same, i.e. higher power density and hence higher overpressure, which leads consequently to deeper and faster cutting, which means reduced or no coagulating arcs, especially in the deeper cut regions.

On the other hand, wave forms with higher crest factors are used in cutting with considerable homeostasis. This means that higher maximum voltage amplitudes are necessary with the same energy or average power. This leads to a higher maximum field strength, and hence, to higher probability of arc formation (also in the deeper cut regions).

Presumed that such arcs occur just before tissue ruptures, then they are a kind of electric bridging the vapor layer in Fig. 3. We can substitute this idea by reciprocating the ratio of the specific resistances (i.e., considering now the case of ρt > ρv). This "reciprocal" ratio can now be considered as a function of how often arcs are established over time.

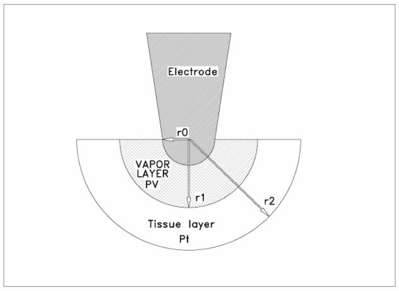

Fig.3.: A biphasic system for modeling electrotomy using a semispherical electrode

As the ratio of cutting power density to coagulation power density is about 4:1, it can be shown that coagulation occur if, and only if, $\rho v < 4\,\rho t$.

7. A consequence of this model is that the specific resistance of the tissue is no longer invariant. It is temporal and spatial variant (i.e., $\rho = f(t,r)$). This is in accordance with measurements of the load resistance in electrosurgery done by Lohr and Fastenmeier [7].

8. Another consequence of this model is that it seems to be that maximum power of electrosurgical units is oversized. This could affect, if true, patient's safety negatively.

IV SUMMARY

The known elctro- and thermo-dynamical models of electrotomy are summarized and discussed. Especially their thermodynamical inadequacy is emphasized. A trial to develop an adequate model is undertaken; this includes mainly the following points:

- Cutting is due to partial evaporation under overpressure followed by pressure waves after tissue rupture.
- Coagulating effect during cutting is due to coagulating arcs over the vapor layer, their frequency probability correlates positively with crest factor.
- The specific resistance of tissue is no longer invariant. It is temporal and spatial variant.
- It seems, according to the study here, that maximum power of electrosurgical units are oversized which could affect, if true, patient's safety negatively.

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