<u>How Electrosurgery Really Cuts Tissue</u>

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In the 1990s I started detailed investigations of the interactions of electrical energy with tissues during electrosurgery. For many years I had heard various conjectures about how the high voltage electrical energy delivered to tissue caused cutting and coagulation. Many of those conjectures were stated with great assurance, but without any substantive backing or support from withstanding challenges by either testing or theoretical calculations.

This short paper briefly summarizes the results of my investigations and analyses with regard to how electrosurgical energy cuts tissue. The related subject of why coagulation occurs during electrosurgery is a topic to be covered in a separate paper.

During electrosurgery a metal blade is powered by high voltage (at least 300 volts, generally much more) current that rapidly alternates between positive and negative voltage. The rapid oscillations between positive and negative voltage reduce the amount of neuromuscular stimulation. The oscillations occur at over 100,000 times per second (100,000 cycles per second is often called 100 kilo hertz or 100 kHz) and frequently are over 250 kHz and can be as high as 1,000 kHz. These frequencies are the same as commercial broadcast radio, which explains why electrosurgical equipment is sometimes referred to as RF (radio frequency) equipment. For reference, the electricity that enters our homes and businesses is only 60 Hz, over 1,000 times slower changing than the power used during electrosurgery. The rapid oscillations between positive and negative voltage do not give enough time for dissolved ions to move across cell membranes, thus preventing neuromuscular stimulation and complications such as cardiac arrest from occurring.

Briefly, none of the common conjectures about how electrosurgery cuts tissue withstand scrutiny. Each of the common conjectures is listed below along with the reasons why each conjecture is not correct. The list starts with the most common conjecture about how electrosurgery cuts tissue, the exploding cell theory. According to this conjecture the onslaught of electrical energy at the edge of the electrosurgical electrode (such as a blade) heats the water inside cells, causing the water to boil, leading to a rapid increase in volume resulting in cells exploding. This concept was first proposed by Valleylab (e.g., United States Patent 3987795, <u>Electrosurgical devices having sesquipolar electrode structures incorporated therein</u>, 1976) and has been subsequently repeated by others (e.g., Pearce JA: Electrosurgery. New York, John Wiley and Sons, 1986).

Among the theories why electrosurgical effects occur are the following.

1. The “exploding cell” theory (Valleylab): as cell contents heat, steam forms which expands the cells’ contents until cell membranes rupture, possibly augmented by sparks poking holes in membranes. Fails to explain why can cut cartilage, ligaments, paper, and other materials that do not have cell structure. For example, an electrosurgical blade easily cuts a paper towel wetted with saline and ligaments, neither of these materials have cellular structure.

2. “Vibrating ions” or “ionic resonance” theory: Frictional heating as ions oscillate as they attempt to follow rapidly changing electrical fields directions. Fails to explain why can cut with direct current and why get very effective results with materials like ligaments that are generally nonpolar. Although direct current cannot be used safely to on living organisms, *in vitro* tests on tissues such as beef liver reveal that direct current (no changing in polarity with time) cuts tissue very well.

3. “Volumetric Joule heating” theory: get electrical resistance heating (electronic engineers refer to this has I^2R heating as the electrical current (I) is opposed by the resistance ® as electricity passes through tissue). May be correct for bulk heating, such as when use multiple electrodes to kill tissue to reduce size of prostate. Incomplete in that it does not provide a mechanism for tissue bonds to be broken because only presents a mechanism for heating tissue, particularly when consider rapid cutting of tissue with the edge of an electrosurgical blade.

4. “Shock Wave” theory: shock waves form from sudden volume expansion caused by sparks heating many small volumes, leading to sudden changes in volumes, and these shock waves somehow cause tissue separation. Fails when consider that many tissues that cut easily are remarkably tough and elastic and little energy exists for mechanical breaking. Shock waves most effectively break brittle tissue, yet bone is particularly refractory to electrosurgical effects.

As an alternative to the preceding conjectures, I propose the following theory regarding how electrosurgical energy cuts tissue. The Team Medical “Spark impingement for pyrolysis and hydrolysis” theory uses chemistry and thermodynamics and recognizes that tissues are fundamentally hydrocarbons, albeit high nitrogen hydrocarbons with high water content.

The Team Medical “Spark impingement for pyrolysis and hydrolysis” theory of electrosurgical cutting:

1) Local rapid heating of very small tissue masses occurs because small tissue volumes hit by sparks do not have enough time for energy to leak out, such as by conduction (in thermodynamic terms, for the short time that a spark impinges on a small piece of tissue the tissue behaves adiabatically).

2) The region near the edge of the blade tends to restrict outflow of steam produced by heating the water in tissue. That restricted flow leads to pressures above atmospheric, which leads to higher temperature steam. Also, the amount of energy above that required to boil the water

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will cause the steam to superheat (get hotter than the boiling point of water at whatever pressure occurs in the small dynamic region where the blade is close to or contacting tissue).

3) Local rapid heating causes chemical bonds holding tissues together (such as those that hold proteins together) to cleave by pyrolysis (bonds break because they are hot, just like chemical bonds break in wood break when heated) and also by hydrolysis (bonds breaking by interacting with steam) which is known to occur with amino acids, the building blocks of proteins that make up tissues.

4) Experimental evidence supports this theory. Among the experiments done at Team Medical was measuring the voltage bias that naturally occurs between the blade and the tissue during electrosurgery. Unknown to almost everyone is that electrosurgical blades become positively charged compared to the patient and that this positive bias can be substantial, on the order of +60 volts. I expected that the bias would occur based on theoretical grounds (it is easier for electrons to jump from the blade to the tissue than it is for electrons to jump from tissue to the blade, a result confirmed during tests that observed the frequency with which sparks jumped during the negative going compared to the positive going parts of the power cycle). Reducing the number of electrons on the blade leads to the blade becoming positively charged and electronic components (the blocking capacitors) in the electrosurgical generator (ESU or Bovie) prevent the shortage of electrons on the blade from being immediately offset. Experiments were done that measured the offset voltage and special tests were done that allowed changing the offset voltage, including making it negative (such as -10 volts) rather than positive. The results when doing *in vitro* tests with negative rather than positive bias voltage differ dramatically. For example, it appears that the smoke produced has different chemical species when use negative bias cutting. As the cutting process breaks bonds the chemistry points to getting both NH_4^+ and acetyl ($R\text{-}COCH_3$) groups emanating from the surgical site, leading to acrid odor, particularly when have positive bias, and less so when have negative bias. That result occurred during tests.

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