II. VOLTAGE-CURRENT CHARACTERISTICS OF AN AC ARC FOR DIFFERENT ELECTRODE SEPARATIONS WITH APPLICATION TO ELECTROSURGERY

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Abstract

The effect of linear electrode displacement in various irrigant solutions commonly used during transurethral electrosurgery was studied. Frequency and electrode type were held constant. A bipolar configuration was used. Results indicated that solutions such as glycine, tap water, distilled water and sterile water displayed a capacitive response to the AC applied signal. Electrodes immersed in glycine, distilled water, and sterile water showed no arcing. A complete understanding of the effects of electrode separation and other parameters such as irrigant solutions may help engineers to design hazard free electrosurgical apparatus.

INTRODUCTION

The focus of this work is an experimental investigation of the voltage-current characteristics of an AC arc in a simulated transurethral resection (TUR) environment. This electrosurgical environment consists of the electrosurgical electrodes, the irrigation solution (typically used in electrosurgery), and the tissue. The sensitivity of the voltage-current characteristics to electrode separation, the operating frequency (typical electrosurgical range), the medium in which the electrodes were immersed, and the electrode type was studied. In this paper the results of the electrode separation study will only be presented.

EXPERIMENTAL SETUP AND METHOD

The experimental setup is divided into three parts: the input waveform generator, the electric arc apparatus, and the IEEE-488 data acquisition system.

A sinusoidal signal produced by a JPC Sweep Function Generator was monitored by a Circuitmate Universal Counter UC10.

An ENI A-300, 0.3 to 35 MHz, power amplifier, with a gain of 55 dB (about 562), was used. The gain was further augmented by the addition of a step-up transformer providing a 1:6.85 ratio. Therefore, for an open circuit, the input signal of the frequency generator was increased by a factor of 3850 total. The transformer also isolated the power amplifier from the electric arc discharge. A triaxial cable (RG-8 A/U) two feet in length connected the power amplifier to the transformer. A resistance was required in parallel with the electric arc in order to avoid saturating and overloading the measurement system. To obtain the appropriate resistance that would support the operating wattage, ten 60 Watt light bulbs in series were positioned in parallel with the transformer and the arc apparatus. Not only did the parallel light bulb load act as a current shunt across the oscilloscope, but it also allowed sufficient voltage for the occurrence of an arc discharge. The total resistance of the light bulbs with no input signal was about 169.3 Ω. At high frequencies, the light bulbs acted as a resistive load with minimal inductive properties [1].

Coaxial cables (RG-174/U 50 ohms), approximately five feet in length, were used to connect both the light bulb load and arc apparatus in parallel with the transformer. The coaxial cables were laid out in a parallel line approximately 6 inches apart from the transformer to the light bulb load and from the light bulb load to the electric arc apparatus.

The electric arc apparatus is the main component of the experimental setup. Two rings stands were used to support the micromanipulator (Narishige No. 1000) and the wooden holders. Wooden holders were constructed and the appropriate sized holes were drilled vertically (0.1 inch in diameter) to support the electrodes. Putty was used to provide additional support and accurate positioning. The various solutions were poured into 400 ml glass (Pyrex) beakers filled to the 200 ml mark. A beaker holder was positioned 11.0 cm above the surface of the table.

The electrodes were placed 16.0 cm above the surface of the table. In this way, only the exposed metal portion of the electrodes were immersed in the solution. Also, since neither electrode was grounded, this denotes a bipolar configuration. With the right wooden holder stationary, the left holder was adjusted and calibrated using the micromanipulator. In this manner, various distances between the electrodes, d, were accurately obtained. Leads from the light bulb load that was in parallel with the arc apparatus were placed on the ends of the electrodes with alligator clips.

The current was measured through one electrode lead using a Tektronix A6302 current probe connected to the Tektronix AM503 current probe amplifier. The amplifier was then connected to channel one of the oscilloscope. Both the probe and amplifier have a bandwidth of DC to 50 MHz. Voltage across the electrodes was measured using a Tektronix P6009 high voltage probe which has an attenuation of 100X and a bandwidth of 120 MHz. This probe was connected to channel two of the oscilloscope.

A Tektronix 7D20 Programmable Digitizer, capable of extracting from each channel (voltage and current versus time) one thousand twenty-four points, was used to download the data into an IBM-PC compatible (8088) using the IEEE-488 (GPIB) interface. The current and voltage were displayed through channels one and two, respectively. The sampling rate of the Digitizer is 50 MHz and there are 8 bits/sample. By setting the trigger position and level, any desired waveform in time could be captured repeatedly and downloaded in less than two seconds.

RESULTS AND ANALYSIS

Repeatability Testing

In order to determine the accuracy of the experimental results, the error of the input signal was found by conducting a repeatability test. The current and voltage data for two loop electrodes (loop-loop configuration), 0.5 inches apart, immersed in commercial saline (0.52% NaCl), were examined at a frequency of 500 kHz. Using this set of parameters, the test was repeated three times. For each trial, the first five waveforms were averaged together point by point for first the current and then the voltage. Trial one was compared to trial two by taking the difference between each point and dividing by the average amplitude of the two trials. This was done for both the current and voltage data. The same technique was then repeated comparing trial one to trial three.

From the data, it is evident that the fractional difference in the repeatability is no greater than 10.5% (Figure 1). Therefore, the results obtained in this study cannot be more accurate than this value. It was decided that only one trial was required for each set of parameters and an average of the first five waveforms was calculated.

Sensitivity Analysis

The sensitivity of the V-I arc characteristics to electrode distances were tested and compared (0.05, 0.5, and 1.8 inches) for several different mediums.

The analysis of the results was conducted in the following manner. The average current and voltage data acquired from the method mentioned above, were used not only to obtain the voltage-current characteristics, but also to calculate the maximum current amplitude (peak to peak), the horizontal spread (the voltage spread where the current is zero), and the vertical spread (the current spread where the voltage is zero). All measurements are peak to peak.

The phase difference between the voltage and the current can be measured if one assumes the V-I characteristics resemble a Lissajous Figure.

Variability of Electrode Separation

In all tests, two loop electrodes (loop-loop configuration) were used with an operating frequency of 500 kHz. In addition, the electrodes were submerged in seven different solutions. In an effort to save space only a full length discussion for electrode separation in glycine is presented.

For example, the average V-I characteristics for an increase in separation distance in glycine is shown in Figure 2. It is apparent that the figure is oval in

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shape. In addition, time is in the clockwise direction denoted by the arrow in each figure; this indicates that glycine has dominant capacitive properties.

The maximum current amplitude was measured for each of the three tests; the results are plotted in Figure 3.

In the preliminary testing phase, three additional trials were performed at other distances and are also included in this study. It is evident that the current amplitude decreases about 30% which is above the 10.5% error of the input voltage. It can then be said that the current amplitude decreases slightly with an increase in electrode separation.

The horizontal spread was also calculated and these values are plotted in Figure 4. One can see that the horizontal spread is relatively independent (excluding the value at 0.5 inches) of the electrode separation. It should be noted that the horizontal spread is a measure of the inherent hysteresis of the V-I characteristics.

The values of the maximum current amplitude and the vertical spread were used to calculate the experimental phase. These values were then plotted versus the electrode separation distance and are depicted in Figure 5.

From this figure, it is clear that the phase shift decreases until 0.5 inches and then increases with respect to the separation distance of the electrodes.

<u>Summary of Electrode Separation: Group A.</u>

In summary, due to the sense of rotation, the V-I characteristics for the electrons immersed in Group A solutions (glycine, tap water, distilled water, and sterile water) all display a capacitive response to the applied AC signal. This implies that the current conducted between the electrodes through the medium is small in comparison to the displacement current. In a capacitor sense, the displacement current results from the time variation of the polarization in the medium. In this case, no physical transport of charge exists. On the other hand, for a resistive current, charge is transported from one plate to another though the medium.

In the cases where the electrodes are immersed in glycine, distilled water, and sterile water, no arc was visible. This implies that the time scale for an arc to develop in these mediums is longer than the period of the applied signal. On the other hand, for the results where tap water was the medium, an arc was seen in addition to condensation forming on the sides of the beaker.

It is seen that the V-I characteristics of the electric arc apparatus for the electrodes immersed in tap water stand out from the other three cases considered. Since tap water contains a higher mineral content than the other solutions, a higher conductivity (lower resistance) is expected which is consistent with the above observations.

<u>Summary of Electrode Separation: Group B.</u>

The key properties of the V-I characteristics for the electrodes immersed in various saline solutions are in an example in Figure 6. Higher currents are reached at lower voltages in comparison with Group A. In addition, while conducting these tests, an arc was visible within the medium. Both these factors are consistent with the expected higher conductivity for saline solutions. Also, the 0.9% NaCl solution is seen as more conductive than the 0.25% NaCl solution which is also consistent with this hypothesis. Again, note the 0.52% NaCl solution contains preservatives while the other two concentrations do not. Therefore, care must be exercised when including the 0.52% case.

Current saturation is another distinguishing feature of the V-I characteristics for the electrodes immersed in saline. A combination of the following factors may contribute to this trait. Current is created by electron emission at the cathode and subsequent ionization in the medium. A current limitation exists that is due to electron-ion recombination and from electrons losing energy by colliding with the NaCl molecules. This colliding acts as a frictional drag and the electrons attain a steady velocity under the applied electric field. A steady velocity implies a steady current. In addition, once the valance electrons have been ionized, it is more difficult to ionize the inner electrons. Due to these effects, there is a restriction to the number of electrons supplied by ionization, and this causes the current to be unresponsive to a further increase in the applied voltage.

Current amplitude is plotted as a function of electrode separation for the electrodes immersed in three saline solutions in Figure 7. Note since the variation are less than the input error of 10.5%, one can say that current amplitude is independent of electrode separation. It is not surprising that current saturation is independent of electrode separation as long as the separation is larger than the minimum necessary for saturation to be achieved. In this light, the tap water results can be reinterpreted. Tap water has a higher resistance than saline and, therefore, is not current saturated. When the electrodes are further separated in tap water, there can only be a decrease in current amplitude (current loss). On the other hand, for saline, the higher conductivity means that the maximum current is flowing for all separations distances considered.

The V-I characteristics for all saline solutions show some variation of horizontal spread with distance as shown in Figure 8, but a physical explanation is not obvious.

References

1. J. R. LaCourse, M.C. Voght, M.T. Miller, III, and S.M. Selikowitz, Spectral Analysis Interpretation of Electrosurgical Generator Nerve and Muscle Stimulation", IEEE Transactions in Biomedical Engineering, vol. 35, no. 7, pp. 505-509, 1988.

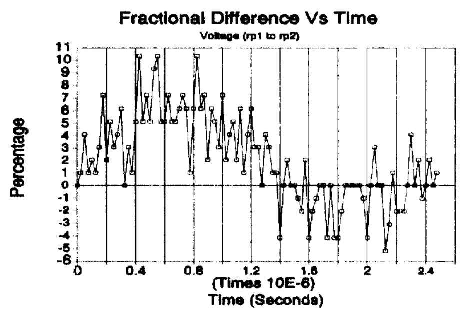

Figure 1 : Repeatability Test for Voltage, Comparing Trial 1 with Trial 2.

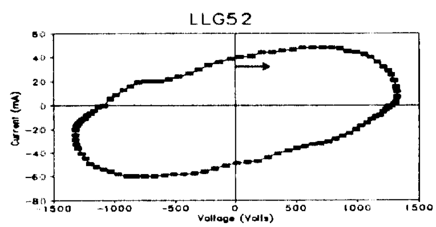

Figure 2: The V-I Characteristics of Glycine

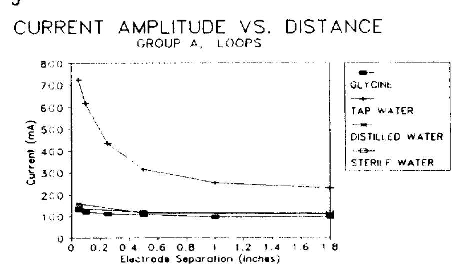

Figure 3 : Maximum Current Amplitude Versus Electrode Separation for Group A Solutions and Loop Electrodes.

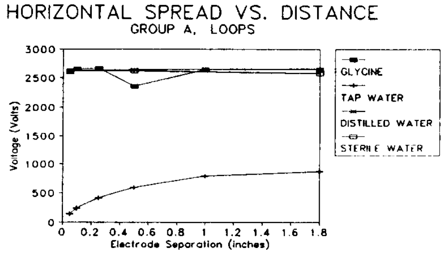

Figure 4 : Horizontal Spread Versus Electrode Separation for Group A Solutions and Loop Electrodes.

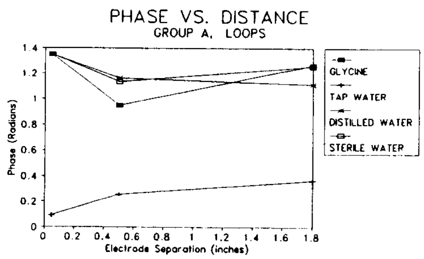

Figure 5 : Phase Difference Versus Electrode Separation for Group A Solutions and Loop Electrodes.

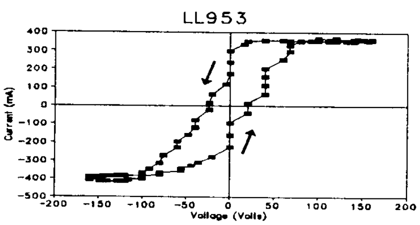

Figure 6 : The V-I Characteristics of 0.9% NaCl Saline Solution with Increasing Electrode Separation.

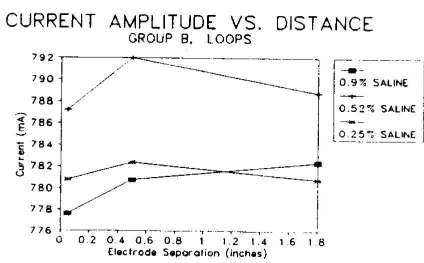

Figure 7 : Maximum Current Amplitude Versus Electrode Separation for Group B Solutions and Loop Electrodes.

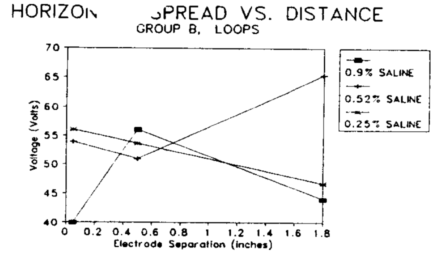

Figure 8 : Horizontal Spread Versus Electrode Separation for Group B Solutions and Loop Electrodes.