ANALYSIS OF FACTORS INFLUENCING THE
ELECTRICAL PROPERTIES OF BLOOD CELL SUSPENSIONS

by

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ABSTRACT

Analysis of Factors Influencing the Electrical Properties of Blood Cell Suspensions (May 1978)

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The resistivity of canine blood was measured at 37°C over a hematocrit range of 0 to 81 percent, with a variable-length conductivity cell similar to one developed by Dr. L. A. Geddes of Purdue University and his associates. Two different electrode materials were used. A vector impedance meter generating a 25 kHz signal was utilized in the measurement process. The data obtained with each electrode material was expressed by a least-squares exponential fit relating resistivity and hematocrit. Additional testing obtained data illustrating the temperature dependence of blood resistivity. The measurement system and technique were analyzed, and recommendations for future investigations were proposed.
ACKNOWLEDGEMENTS

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INTRODUCTION

The composition of blood is of considerable interest to those in the medical and life science fields. As a transport medium, blood is necessary to supply body cells with nutrients, oxygen, and hormones and to remove waste products from the sites of formation. Plasma, the liquid matrix of blood, is about ninety percent water. The solutes within this liquid include proteins, glucose, fats and inorganic ions, and suspended in the plasma are erythrocytes, leukocytes and platelets. These cellular components of the blood have specialized functions; erythrocytes serve as oxygen carriers, leukocytes defend the body against disease and infection, and platelets function in blood clotting.

In medical diagnoses, several variables in blood composition can be important health indicators. The plasma content can be drastically altered by dehydration, severe burns, hemorrhaging, or shock. The number and relative distribution of erythrocytes and leukocytes, the concentrations of plasma proteins and ions, and the presence of abnormally-shaped cells are factors significant enough to warrant development of more accurate measurement techniques. Consequently, the physical and chemical properties of blood components are of interest to investigators.

This senior honors thesis follows the style of Medical and Biological Engineering.
A. History and Development of Blood Conductivity Research

As early as 1897, researchers found that blood has characteristic electrical properties (Stewart, 1897), and this finding stimulated additional research in blood conductivity. Blood plasma, containing proteins and ions, was found to be an electrical conductor while erythrocytes acted as insulators (Stewart, 1897). With the discovery of this electrical difference between plasma and the cells suspended within it, further studies attempted to relate blood conductivity to the concentration of erythrocytes (Bugarszky and Tangl, 1898). Resistivity, the reciprocal of conductivity, was later correlated with hematocrit (the ratio of the volume of packed erythrocytes to the volume of whole blood) and mean cell volume (Stewart, 1899; Wilson, 1905).

B. Applications of Blood's Electrical Properties

As a result of blood conductivity studies, this electrical property has served as the basis for the development of clinical blood analysis equipment, specifically electronic hematocrit readers and aperture-counter devices. The hematocrit reader, as developed by Yellow Springs Instrument Company, operates using an established relationship between conductivity and erythrocyte concentration (Okada and Schwan, 1960). Aperture-counter devices (e.g. Coulter counters) detect changes in electrical resistance across a small bore orifice as cells flow through, and relate this change to the erythrocyte count and mean cell volume (Waterman et al., 1975).
The conductivity of blood, often related to erythrocyte concentration, is also dependent on temperature, plasma electrolyte concentrations, hemolysis, and pathological conditions of the blood (Hirsch et al., 1950). Variations of these factors could affect the operation of instruments utilizing this property of conductivity as the basis for measurements. It has not been determined if certain diseases or illnesses might change the electrical properties of the blood, such as the insulating character of the erythrocyte membranes, to the extent that the clinical instruments would give false or inaccurate readings. Determination and analysis of the most significant factors should identify the possible sources of error encountered with usage of this equipment.

C. Objectives

When developing and utilizing a measurement system, two qualities must be considered. The first is the reliability of the system, the degree to which an investigator can obtain consistent results using a single method of measurement. Also important is the objectivity, the degree to which consistent results can be obtained from the use of the same method of measurement by different persons. The overall purpose of this research was to evaluate previous studies on blood conductivity and determine the objectivity of data obtained by other investigators. Specific objectives included:

1. Analysis of measurement systems used previously in conductivity research, and evaluation of data obtained from such
systems, specifically that of L. A. Geddes (Geddes and da Costa, 1973).

2. Comparison of conductivity data obtained by varying the temperature and hematocrit of canine blood samples with data recorded by previous researchers.

REVIEW OF THE LITERATURE

Three areas involving blood electrical properties have been of particular interest to researchers. Several investigators, concerned with blood clot retraction and detection of clotting time, have studied the change in electrical resistance which takes place during coagulation (Graff et al., 1947; Wilson, 1906; Henstell, 1949; Rosenthal and Tobias, 1948). Others have attempted to analyze the effects of movement and sedimentation on the conductivity (Sigman et al., 1937; Thygesen, 1942). The research in the third area is concerned with relating conductivity to blood cell volume and hematocrit. Many investigators have studied the basic relationships between these two variables and blood electrical properties (Wilson, 1905; Okada and Schwan, 1960; Slawinsky, 1933; Geddes and Kidder, 1976). Others have shown that conductivity is affected by several factors, including temperature and pathological conditions (Hirsch et al., 1950; Rosenthal and Tobias, 1948).

Much of the recent research in the field of blood conductivity has been done by Dr. L. A. Geddes and his associates. Dr. Geddes' work has included the design and analysis of a variable-length conductivity cell (Geddes et al., 1971), the study of specific resistances of approximately ten different body tissues (Geddes and Baker, 1967), and the tabulation of specific resistances for human and selected animal bloods (Geddes and Kidder, 1976; Geddes and da Costa, 1973; Geddes and Baker, 1967). Whenever possible, Geddes' publications contain thorough descriptions of the conditions of measure-
ments, enabling other researchers to duplicate, to a certain extent, his experimental methods.
METHODS

A. Description of Previous Devices

Previous research on blood conductivity has produced a variety of devices for measurement of this electrical property. In a fairly extensive study of factors affecting conductivity, F. G. Hirsch and his associates utilized an assortment of equipment and a glass measurement cell (Hirsch et al., 1950). Their apparatus included a variable frequency oscillator which operated on frequencies up to 19,000 cycles per second, an alternating current resistance bridge with a null detector, and a constant temperature bath. The conductivity cell was basically a small glass cylinder with a coiled platinum wire electrode in either end. The electrodes were approximately five centimeters apart, but the tube was small enough that a single milliliter of blood could fill the cell (Hirsch et al., 1950). The device was designed as a horizontal cylinder to eliminate sedimentation effects (Hirsch et al., 1950).

R. L. Rosenthal and C. W. Tobias used a Pyrex tube, similar to a test tube, and a stopper which contained electrodes for measurements in their blood coagulation studies (Rosenthal and Tobias, 1948). The electrodes were small platinum plates with areas of 1/4 square centimeter, attached to the stopper with a separation distance of 1/2 centimeter. Rosenthal and Tobias also used a frequency oscillator and an impedance bridge, but an oscilloscope was used to detect the bridge balance. Their measurements were made at 1,000 cycles per second (Rosenthal and Tobias, 1948).
T. M. Wilson produced a conductivity cell in his research which had a capacity of only 0.1322 milliliters (Wilson, 1905). It was made of a glass tube with an outer diameter of six millimeters, and a glass piece which could be inserted into the tube. Platinum wire electrodes were fixed into the glass piece (Wilson, 1905). This cell was designed for use in clinical measurements or other situations when only small quantities of blood would be available (Wilson, 1905).

In their research of the specific resistance of canine blood (Geddes and da Costa, 1973), L. A. Geddes and C. P. da Costa utilized a conductivity cell which had been developed in some of their earlier research (Geddes et al., 1971). The cell consisted of a five-milliliter syringe with a stainless steel electrode permanently mounted in the end of the barrel. The other electrode was attached to the plunger and could be moved to different positions within the barrel. A small hole in the syringe allowed expulsion of blood when the electrode was pushed inward, and a plastic sleeve was used to cover this hole during measurements. The equipment used with the cell included an impedance bridge, a sine wave power oscillator, a bridge-isolation transformer, an oscilloscope, a thermostatically-controlled water jacket, and an Eberbach agitator (Geddes et al., 1971; Geddes and da Costa, 1973). All measurements were made at either 24,000 or 25,000 cycles per second (Geddes and Kidder, 1976; Geddes and da Costa, 1973).
B. Design of Measurement Device and Technique

In order to evaluate other conductivity studies, it was important that at least one of the previously used methods could be duplicated. Although several techniques have been described and documented, the descriptions found in the literature of L. A. Geddes' methods and apparatus are the most detailed and complete. His published results indicate that very thorough work has been done, with considerable data recorded to ensure reproducibility of the values. For these two reasons, Geddes' measurement system was chosen to be duplicated in this research.

Electrodes having very small surface areas are known to create problems when measuring small biopotentials, since the electrode-tissue interface exhibits a high impedance. This characteristic was effectively reduced with the method used by Geddes in his studies of stainless steel electrodes (Geddes et al., 1971). He also established a technique which would allow the impedance of the electrode-electrolyte interface to be distinguished from the resistivity of the electrolyte (Geddes et al., 1971).

The electrode-electrolyte interface has been shown to be equivalent to a resistance (R) and capacitance (C) in series (Geddes et al., 1971). Therefore, for the measurement cell having two electrodes separated by an electrolyte with an impedance (Z), the equivalent circuit shown in Figure 1a would represent the impedance properties. The capacitance $C_d$ can be neglected if the distance between the electrodes is large compared with the electrode diameter. Since the resis-
Figure 1a. Conductivity cell and equivalent circuit.

Conductivity

\[ \rho = \frac{(R \times A)}{L} \]

\[ Z_{12} = Z_1 + \frac{(\rho \times L_1)}{A} + Z_2 \]

\[ Z'_{12} = Z_1 + \frac{(\rho \times L_2)}{A} + Z_2 \]

\[ Z_{12} - Z'_{12} = \frac{\rho(L_1 - L_2)}{A} \]

\[ \rho = \frac{A(Z_{12} - Z'_{12})}{(L_1 - L_2)} \]

\[ \rho = \frac{(A \times Z)}{L} \]

Figure 1b. Derivation of resistivity equation.
tance and capacitance of each electrode-electrolyte interface is not a function of the distance between the electrodes, and the electrolyte resistivity, $\rho$, varies with the separation distance ($\rho = (R \times A)/L$ where $R$ is the measured resistance, $A$ is the electrode cross-sectional area, and $L$ is the distance between the electrodes), the resistance of just the electrolyte in the cell can be determined by taking measurements with two different column lengths (Geddes et al., 1971). In this research, as well as Geddes' studies, one of the column lengths used was half of the other length. Therefore, the resistivity equation (developed in Figure 1b) used in the measurement process was

$$\rho = (A \Delta Z)/\Delta L$$

where $\Delta Z$ was the change in the resistance and $\Delta L$ was the change in column length (Geddes and da Costa, 1973).

C. Equipment

The fabricated conductivity cell was made of plexiglass tubing with an inside diameter of 0.9525 centimeter. Each electrode was machined from a stainless steel rod to have an exposed surface 0.8727 centimeters in diameter; one electrode had a collar of a larger diameter to provide a constant insertion distance within the tube. Two electrode materials were used. The preliminary testing was performed using 304 stainless steel electrodes, while the second phase utilized surgical grade stainless steel (316 stainless steel). Small O-rings were fitted into grooves close to the highly-polished electrode surfaces to create a tight seal and also allow movements of the electrodes.
necessary for cleaning and conductivity measurements. One end of each electrode was threaded and two nuts were positioned to secure the lead wire spade terminal. The nuts on the movable electrode aided in the measurement process; they could be adjusted to allow only the desired amount of insertion into the tube. The two electrolyte column lengths, 2.90 centimeters and 5.80 centimeters, were indicated by lines etched on the outside of the tube. Two small holes, used when filling the cell and when expelling air or blood, were drilled on one side of the plexiglass cylinder close to the end in which the stationary electrode was placed. The beveled points were cut off two large-bore syringe needles, and the needles were epoxied into the filling holes. The cut ends were flush with the inside wall of the tube. Luer-lock caps were kept on the needle hubs except when adding or expelling blood. The conductivity cell used in this research is shown in Figure 2, and Geddes' syringe cell is shown in Figure 3 for comparison of the two.

In order to eliminate conductivity changes due to temperature variations, all but the preliminary tests were done utilizing a constant temperature water bath and a plexiglass chamber. This equipment was not available during the first testing period, and at that time the desired blood temperature was maintained by manually mixing hot and cold water in a large beaker containing the cell. The Brookfield constant temperature bath provided a much more convenient and accurate means of regulating the blood temperature. It was connected to the plexiglass box containing the measurement cell, as shown in Figure 4.
Figure 2. Variable-length conductivity cell.
Figure 3. Syringe Conductivity cell developed by L.A. Geddes and da Costa, 1973.
To constant temperature bath

From constant temperature bath

Figure 4. Plexiglass chamber for temperature control.
A thermistor was inserted into the box near the intake nozzle, and the temperature of the incoming water could be monitored with the telethermometer (YSI Model 42SF) attached to the probe.

In their research, Geddes and his associates used a constant-current comparison impedance bridge to measure the series resistance and capacitance of the electrolyte in the conductivity cell (Geddes et al., 1971). To balance the bridge, an oscilloscope was used with a bridge-isolation transformer to detect the bridge voltage. A sine wave power oscillator provided the bridge excitation. As an alternative to using an impedance bridge and the other equipment shown by Geddes to be necessary for blood conductivity measurements, a vector impedance meter (Hewlett-Packard 4800A) was utilized in this research. The meter indicated both impedance magnitude and phase angle, thereby providing capacitance and inductance measurements in addition to resistance readings. The measurement frequency could be adjusted from five to 500,000 cycles per second, and the meter held the voltage and signal current at constant levels by means of feedback loops (HP 4800A Manual). The published accuracy values for the device were + 6% of the impedance magnitude and + 6° on the phase angle (HP 4800A Manual).

D. Measurement Techniques

The blood used for the conductivity measurements was obtained from large, healthy dogs. The samples were drawn from the jugular vein, mixed with 0.025 milliliter of heparin for every ten milliliters of blood collected, and refrigerated until use (approximately eighteen
hours). Heparin was chosen as the anticoagulant to minimize conductivity changes which occur with chelating agents (Geddes and da Costa, 1973).

In order to achieve a wide range of blood hematocrit values, the entire sample, usually 40 milliliters, was centrifuged to separate the cellular components from the plasma. Separation of the blood was achieved with a Precision Scientific variable high-speed centricone. After centrifugation, the plasma and cellular components were mixed in different proportions. Hematocrit values were obtained with an IEC microhematocrit MB Centifuge, and generally were taken after each set of conductivity measurements.

During the preliminary phase, each blood sample was tested at 27°C, 32°C, 37°C and 42°C. The blood was warmed to the desired temperature in a manually-controlled water bath. This was done by immersing the electrodes and blood-filled cell in warm water. The apparatus was left in the water, controlled to within 1°C of the desired value, for twenty minutes to establish a constant temperature throughout.

In the second measurement phase, that utilizing the surgical stainless steel electrodes and the constant temperature bath, the cell was filled with blood and suspended in the plexiglass chamber. This testing was performed with a constant temperature of 37°C (body temperature). Since warm water was circulating around the electrodes and the cell, an equilibrium temperature was more readily achieved than with the earlier method. Therefore, only a five-minute warming period was required before removal of the cell.
All conductivity measurements were quickly made after the desired temperature was attained. The plexiglass cell was removed from the bath and gently shaken to eliminate possible sedimentation. Excess water was wiped off, the lead wires were slipped on the threaded electrode ends and the nuts were tightened down on the terminals. The impedance magnitude and phase angle were then recorded at a frequency of 25,000 cycles per second. One Luer-lock cap was removed to allow expulsion of fluid as the movable electrode was pushed into the second position, and the impedance and angle were recorded again after the cap was replaced. Shaking was contained throughout this procedure except when conductivity values were being read and recorded.

The collection of conductivity data included computations to determine the blood resistivity and hematocrit. The resistivity measured with the variable-length cell was calculated from the difference between the two resistance readings, and this value or its reciprocal, conductivity, could then be compared with published data. The hematocrit was also determined for each sample. A capillary tube was partially filled with sample blood after the impedance measurements, sealed with clay, and centrifuged for five minutes in a microhematocrit centrifuge. Using a precision ruler, the erythrocyte column height and total fluid height were measured. The hematocrit was calculated from the ratio of the two heights.
RESULTS

A. Phase One Testing

The conductivity testing was performed in two phases. The objectives of the preliminary testing, using 304 stainless steel electrodes, were directed at developing a basic measurement technique and obtaining some data for a tentative comparison with published results. Two sets of data were recorded, one group obtained by varying the hematocrit of the blood and the other by changing the temperature. All measurements were taken at a frequency of 25,000 cycles per second, since it has been shown that the capacitance of the electrode-electrolyte interface is almost eliminated with the use of frequencies in the 20,000 to 30,000 cycles per second range (Geddes et al., 1971).

The values found by varying the temperature of the blood were recorded for samples having a hematocrit of 49%. The temperatures ranged from 27°C to 42°C. The data obtained in this study are plotted in Figure 5, along with those found by Geddes and Baker in their investigations with human blood (Geddes and Baker, 1967). Since this published curve shows the temperature dependence of human blood, rather than canine blood, specific values on the two curves cannot be compared. However, the general forms of the two lines are in agreement.

The preliminary phase of testing also included measurement of the resistivities of various canine blood hematocrits. The values were recorded at a temperature of 37°C and a frequency of 25,000 cycles per second. The hematocrits ranged from 34% to 55%. (A hema-
Figure 5. Resistivity vs. temperature for canine and human bloods.
tocrit of 45% is considered to be average). In Figure 6, these resistivities are compared graphically with those obtained by Geddes and da Costa (Geddes and da Costa, 1973). The values obtained in this research were consistently lower than the published data, but the extrapolated graph displayed the expected exponential curve. The unusually close fit of the data to the line can be explained upon examination of the situation; relatively few samples were tested in this preliminary phase, and all of the blood was obtained from only two dogs. Therefore, the variations in resistivity due to differences in plasma proteins and ion concentrations would be negligible.

B. Phase Two Testing

The second phase of testing involved a more extensive collection of data for resistivity as a function of hematocrit. Since one of the purposes was to establish a reliable measurement system and technique, care was taken to allow little change in all variables other than those being studied. Therefore, the plexiglass chamber shown previously in Figure 4 was designed and built to minimize temperature variations from the desired 37°C. New electrodes were machined from 316 stainless steel, as this surgical grade of stainless steel exhibits very little corrosion in body fluids. The cell was rinsed and dried after the testing of each sample, and the electrodes were carefully cleaned to prevent formation of a layer of coagulated blood.
Figure 6. Resistivity vs. hematocrit using 304 stainless steel electrodes.
During the resistivity measurements, both the impedance magnitude and the phase angle were recorded. For hematocrits from 0% to 55%, the phase angle ranged from 0° to -5°, indicating that the electrolyte impedance was almost pure resistance with very little capacitance appearing between the electrodes. However, at hematocrits above 55%, positive phase angles between 20° and 90° were recorded. There was no obvious trend to this development of inductance. With some measurements, both electrolyte column lengths would produce positive phase angles. At other times, the longer column of blood would exhibit inductance while the reduced column would appear to be purely resistive. A literature search revealed no prior discovery of inductance produced by body fluids or tissues.

Although a malfunction of the vector impedance meter is suspected, all data values for impedance magnitudes are plotted on the graph of the results (Figure 7). However, two lines, representing equations calculated using the least-squares method, are graphed. One line is the best-fit line of all the data, the other represents the recorded values for hematocrits of 0% to 55%. The line obtained by Geddes and da Costa (Geddes and da Costa, 1973) is also shown in Figure 7.

C. Mathematical Relationship Between Resistivity and Hematocrit

Previous research has shown that the relationship between resistivity and hematocrit is exponential in nature (Geddes and da Costa, 1973; Geddes and Kidder, 1976). It is expressed in the
Canine blood at 37°C and 25 kHz

This investigation
All data

This investigation
0 - 55% Ht

Geddes and da Costa (1973)

Figure 7. Resistivity vs. hematocrit using 316 stainless steel electrodes.
form $\rho = \alpha e^{\beta H}$, where $\rho$ is the resistivity in ohm-centimeters, $\alpha$ and $\beta$ are constants, and $H$ is the hematocrit. By applying the method of least squares to the data obtained in both measurements phases, equations of this form were computed. Figure 8 compares published equations (Geddes and da Costa, 1973; Kinnen, et al., 1964) with the expressions calculated in this investigation.

<table>
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<th>Mathematical Expression</th>
<th>Correlation Coefficient</th>
<th>Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho = 56.8 e^{0.025H}$</td>
<td>0.989</td>
<td>Geddes and da Costa, 1973</td>
</tr>
<tr>
<td>$\rho = 56.6 e^{0.022H}$</td>
<td>0.862</td>
<td>Kinnen et al., 1964</td>
</tr>
<tr>
<td>$\rho = 50.2 e^{0.021H}$</td>
<td>0.978</td>
<td>This investigation, 304 Stainless steel</td>
</tr>
<tr>
<td>$\rho = 55.5 e^{0.031H}$</td>
<td>0.934</td>
<td>This investigation, 316 Stainless steel Hematocrits of 0% - 81%</td>
</tr>
<tr>
<td>$\rho = 66.3 e^{0.023H}$</td>
<td>0.905</td>
<td>This investigation 316 Stainless steel Hematocrits of 0% - 55%</td>
</tr>
</tbody>
</table>

Figure 8. Comparison of Resistivity Expressions for Canine Blood
DISCUSSION AND CONCLUSIONS

The issue which originally stimulated this research concerned the accuracy of electronic hematocrit readers or other devices that make measurements based on the electrical properties of blood. However, before a parameter analysis could be performed to determine possible causes of error in these devices, a system of measurement had to be devised. This portion of the experimentation was satisfactorily completed, but time limitations prevented an in-depth study of the many variables which might affect resistivity. As a result, this investigation dealt more with the properties of the measurement equipment than the properties of blood.

During the design and use of the conductivity cell, several questions arose concerning the details of the apparatus. The influences on conductivity of factors such as the electrode surface preparation, the diameter-to-length ratio of the cell, the current density at the electrode-electrolyte interface, and the electrode composition were unknown. Therefore, assumptions had to be made regarding some of the design criteria. Many of the assumptions were based on the realization that the resistivity equation of the variable-length cell does not include the characteristic impedances of the electrodes. This implies that the electrode characteristics may have little influence on measurements obtained with this technique.

An analysis of the data obtained in this research revealed that the previously established relationship between hematocrit
and resistivity could be observed, but specific values could not be duplicated. For the purpose of analyzing the influences of variables, only general relationships need to be determined. However, in some devices, specifically electronic hematocrit readers, measurements are based on a direct correspondence between resistivity and hematocrit values. The hematocrit reader developed by Yellow Springs Instrument Company does not use a variable-length cell for its resistivity measurements (Okada and Schwann, 1960). Consequently, the electrode-electrolyte interface impedance, which can be disregarded when utilizing the variable-length method of resistivity calculation, would be included in the impedance measurement of the blood. Since the interface impedance is affected by current density and electrode composition, it appears that instruments of this type must be individually calibrated or constructed in such a way that errors are not caused by differences between the devices themselves. It is possible that the method utilizing the variable-length cell could be modified for very small blood samples and used in a micro-hematocrit reader. This would eliminate another variable, the electrodes and their effects, from the resistivity measurements.

An unexpected occurrence during this research was the observation of inductance in the impedance measurements for high hematocrit values. Previous researchers had not reported this property, and the vector impedance meter was suspected to be the cause of the unusual readings. Repeated inspections of the meter throughout the year did not reveal a definite malfunction until shortly before
the planned termination date for the data collection phase. Therefore, it is not possible to make a statement as to the validity of the values measured with this instrument.

This research with the variable-length conductivity cell has yielded some conclusions regarding the measurement system and technique.

1. The measurement system appears to be reliable. This investigator was successful in obtaining similar resistivity measurements when testing samples with equal hematocrit values.

2. The measurement technique seems to be objective. The results of this research corresponded reasonably well with those reported by L. A. Geddes and his associates. This is shown by comparison of the mathematical expressions which represent the relationships found by both investigations.

3. Using the variable-length technique for calculating resistivity, electrode characteristics seem to have a negligible influence on the results. The use of both 304 and 316 stainless steel yielded two mathematical equations of exponential form with slightly different constants.

Using the results of this research, future investigations could determine and analyze the factors influencing blood resistivity. The measurement technique has been shown to be suitable for parametric studies. Recommendations for future research include:
1. Determination of the relationship between blood pH and resistivity.
2. Investigation of the relationship between temperature and resistivity at different hematocrits.
3. Analysis of resistivity changes due to current density variation.
4. Determination of an optimum diameter-to-length ratio for the conductivity cell. This would include both current density and capacitance considerations.

This research was beneficial in that it resulted in a measurement system which can be used in the future for additional investigations, and it demonstrated the effectiveness of a previously-developed technique. Since the system itself has been analyzed, it can be used with assurance in additional studies.
REFERENCES


