Electrical Impedance Plethysmography
A Physical and Physiologic Approach to Peripheral Vascular Study

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The quantity of blood measured by electrical impedance plethysmography is defined by its resistive effect in parallel to the resistance of other tissue of the segment. By substitution of this parallel resistive value, together with data relative to the resistivity of blood and the length of the segment in the formula for the volume of an electrical conductor, we are able to derive the volume of the pulse in cubic centimeters. It follows that the volume displaced from the venous reservoir and the rate of refilling of the venous reservoir of an extremity may also be determined quantitatively.

Numerous attempts and methods have been evolved to measure pathologic and functional vascular change in the extremities. Little attention, however, has been given to the quantitative changes recordable by various methods of electrical plethysmography,1-5 which until recently have been difficult to formulate. The current presentation deals principally with the calculation and interpretation of volemic changes in the extremities as they appear measurable by electrical conductivity.

The electrical conductivity method gives a physical measure of the ionic conduction of a given body segment in contrast with electronic conduction characteristic of metallic substances. An attempt will be made to restate and formulate the laws of electrical conduction as they appear applicable to changes within a body segment which is being studied by the passage of a radio frequency current. As has been shown elsewhere,6 transient and static values of electrical conductivity are associated, respectively, with dynamic and balanced conditions of arteriovenous blood volume differences within a given segment.

Method

A differential electrical impedance bridge operating at 150 to 200 kilocycles, as described elsewhere,4 is used as the basic instrument for measurement of small and large variations in volume of the extremities.

In this study, our measurements on human extremities are made with aluminum foil strips 1 cm. wide, mounted on a gummed tape 2 cm. wide. After wetting the foil with a concentrated salt paste (non-drying), the electrodes are applied firmly without preliminary massage or washing. This tends to avoid local circulatory reactions which may modify our measurements. The electrodes are usually applied circumferentially and held loosely by a clip lead to avoid constriction (fig. 1).

There appears to be an inherent advantage in a four electrode technic as shown later. The two outer electrodes (I1 and I2) are used for applying the current, and the two inner electrodes are used for delineating the segment under measurement. The inner edge of the E1, E2 pair is the effective edge of the segment for measurements of the limb. Most of the measurements reported here are based on a conventional two electrode method represented by the E1, E2 pair to which the current is also applied under such conditions.

The standard for comparison of the segmental pulse volume resistivity is usually .05 to 0.1 ohm resistance. One ohm is used for comparison of large changes in segmental blood volume. A small percentile change of the total substitution resistance for the segment is also adaptable as a standard.
THE PHYSICAL BASIS AND ELEMENTARY CONSIDERATIONS IN ELECTRICAL VOLUME RECORDING

The electrical impedance pulsation represents a changing number of ions brought to the segment by the arterial stream at a rate exceeding the venous outflow during the cycle. The over-all change in volume of a segment is the differential effect of expansion and emptying of the vascular components of the entire segment.

It may be possible to account segmentally for the volumetric shift of blood by considering its effect as a variable parallel electrical shunt. Equations for the effect of parallel resistance are well known.

![Fig. 1. A photograph of the forearm illustrates the manner of applying the aluminum foil electrodes. The arrangement is tetrapolar. The inner electrodes are designated E₁, E₂, and the outer electrodes I₁, I₂. The segment of 20 cm. in length between E₁ and E₂ is the effective resistance (Rₑ).](image)

The total electrical conductance of the extremity segment is probably equal to the sum of the paralleled conductances of the blood and segment proper. Each additional pulse of blood represents another path through which electrical current will flow.

The effective parallel resistive value of the added or displaced blood may be derived by substitution of measured values in the expression:

\[ R_b = \frac{R_N R_0}{R_0 - R_N} \]

(1)
in which \( R_0 \) represents the original resistance of the segment, \( R_N \), the new total resistance. \( R_0 - R_N \), which is equal to \( \Delta R \), represents the change in resistance incurred by the change in blood volume of the segment, by pulsation or otherwise. When small volume and resistive changes occur, then \( R_b^2 \) expresses essentially value of the product \( R_N R_0 \).

The volume of blood within the segment is a direct and linear function of electrical conductivity. This is true within wide limits of expansion of elastic cylinders such as arteries, veins, intestines, and rubber tubes, as shown elsewhere by one of us (J.N.). The inclusion of ground meat, long bone, or ground bone changes the slope of the relationship but does not destroy the lineal effect.

The change in volume of blood uniformly distributed within a segment may then be calculated from the derived expression of the volume of a cylindrical conductor:

\[ V_b = \rho \frac{\mu}{R_b} \]

(2)
in which \( \rho \) represents the specific resistivity of the segmental blood, \( l \) the length of the segment being measured, and \( R_b \) the calculated effective parallel resistance of the blood related to the change. Compare equation 1 in Medical Physics, Vol. II, p. 738.

Direct comparison of the impedance and sensitive mechanical plethysmographic records of the volume pulse of the finger published elsewhere shows no apparent discrepancy between the forms of the curves recorded at approximately the same amplitude. They appear identical, and this suggests the similarity of origin to the volume pulse of the segment.

THE MEASUREMENT OF THE VOLUME PULSE

The volume of blood pulsed into a peripheral segment is usually equal to the volume of blood leaving during the cycle. If one had an accurate measure of either the input or output, or of both volumes, it is probable that valuable data covering vascular responses could be scientifically expressed. If a measure closely proportional to the absolute pulse volume were obtained, it would not be necessary to know either phase of the volume change.

Segmental blood flow can be approximated at present by the venous occlusion plethysmograph. This method is objectionable since the pressure of occlusion may modify the vascular responses and other factors beyond reasonable control. If, under these conditions of
measurement, one also knows the pulse rate, the pulse volume may be deduced from such data.

Since there is usually a continuous venous run-off from the segment during the cycle, it is apparent that the recorded volume pulse is the net difference between a momentary excessive arterial input and the run-off of blood, whether it be venous or arterial, during the cycle in the absence of stasis.

If the above events are true, the recorded pulse volume is directly proportional, but not necessarily equal to the sum of the true arterial inflow and the venous outflow from a given segment. It follows that the mean height measurement of the pulse wave should be a valid index of this proportional volume. In our study, twice the mean height for the area under the curve is chosen to represent both input and output volume. In effect, this represents a sequestration of the total segmental input without occlusion or run-off of the venous return.

In practice, one obtains the mean height of the pulse volume by planimetric integration over the entire pulse distance. The measurement of several pulses serves to reduce the error. This value is multiplied by two, since the recorded volume increase served both as a measure of input and of output volumes during the entire pulse cycle.

This measured value is then interpreted in terms of ohmic resistance based on comparison with the 0.1 ohm standard recorded in the original trace or in the records with the equivalent substitution of resistance. This value in ohms represents $\Delta R$ of equation 1. As one has measured the approximate substitution resistance ($R_o$) for the extremity conductor before the pulse volume modified the conductor, one may then derive $R_x$ arithmetically.

The effective parallel shunt, $R_\theta$, is then calculated from the known values ($R_x, R_o$, and $R_\theta - R_x$) by equation 1.

The calculation of pulse volume is completed by equation 2. In addition to $R_\theta$, one must know the other measurable units defined in this equation. We will assume that the measured resistivity of nonflowing venous or arterial blood will supply the factor $\rho$. Theoretically, this may be different for each individual. Its value is in the order of $145 \pm 3.75$ S.E. ohm cm. at 37.5 C. measured at 175 kilocycle frequency. We assumed a value of 150 ohm cm. for many of our measurements. The derived pulse volume multiplied by the heart rate gives the proportional volume of expansion of the segment in cc. per minute. If one knows the volume of the segment, it is possible to express proportional expansion in terms of volume per minute per 100 cc. of segment.

The volume of the peripheral segment is never an ideal cylindrical conductor for which the equations were designed. Some corrections should probably be made for the shape of the conductor. Cole and Curtis have discussed this factor in relation to cell models.

Comparative measurements of similar segments on opposite limbs obviate many of the difficulties due to shape and enhance the value of our observations in a limited number of cases.

**RESULTS**

**Bipolar and Tetrapolar Resistive Measurements of a Body Segment Including the Skin.**

Horton and van Ravenswaay and Barnett have shown that the reactive component of electrical impedance is very high in skin compared to its value in deep tissues. If this is true, then it appears that the determined values for impedance of a segment in which the deep tissues predominate in volume are probably too high by bipolar measures. Since the total impedance of the segment enters into the calculation of the parallel resistance, the value of mean pulse volume would probably be in error.

In table 1, column $R_\theta$ shows that for equal segments, the four electrode method gives consistently lower values for total segmental resistance than the two electrode method. No attempt was made to measure at controlled conditions of rest, exercise, postprandial time, or room temperature. The subject was recumbent.

The four electrode method basically eliminates the highly reactive skin and leaves one with a better measure of the internal tissues, including the blood, which appear predominantly resistive to alternating current. The pulsatile volume should probably be calculated
ELECTRICAL IMPEDANCE PLETHYSMOGRAPHY

on the resistive values obtained by tetrapolar leads, if a closer approximation to the true proportional pulse volume is desired.

Column \( R_b - R_N \) or \( \Delta R \) represents twice the mean height of the pulse expressed in ohms. It appears that no consistent prediction can be made of this value under the conditions of measurement (but at no time do these exactly equal each other).

The value, however, for the parallel resistive effect (\( R_s \)) of the blood pulse volume is predictable and consistent. Each of the tetrapolar legs electrically shunted in parallel are shown (table 2). The value for the total resistance of both legs is predicted to be 38.1 ohms; however, by measurement, we obtained 37.2 ohms, which is reasonable. For mean change in pulse height, we predicted .0187 ohm and obtained .0191 ohm. For calculated volume changes, we predicted .773 cc. and obtained .828 cc. for pulse volume. We predicted 47.4 cc. and obtained 50.8 cc. for pulse volume per minute. Similar values are shown for predicted and measured parallel resistances and parallel pulse

| Table 1.—Comparative Resistive Values of Pulse Volume by Bipolar and Tetrapolar Measurement* |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Segment (Recumbent)             | Length (cm.)   | \( R_b \) (ohms) | \( R_{14} \) (ohms) | \( R_b - R_N \) (ohms) | \( R_b \times 10^3 \) (ohms) | Pulse Volume\( \uparrow \) (cc.) | Pulse Rate | Minute Volume (cc.) | Room Temp. (C.) | Time (min.) |
| Right forearm                   | 20             | 86.7           | 86.58          | .120            | 0.626          | .959              | 56.6         | 54.3           | 27.5           | 3            |
| Left forearm                    | 20             | 95.9           | 95.79          | .111            | 0.824          | .728              | 56.6         | 41.2           | 27.5           | 5            |
| Right forearm                   | 20             | 90.7           | 90.61          | .0894           | 0.898          | .688              | 54.1         | 36.1           | 27.3           | 14           |
| Left forearm                    | 20             | 96.1           | 96.024         | .076            | 1.214          | .494              | 54.1         | 26.7           | 27.1           | 18           |

Two Electrode Studies

| Segment (Recumbent)             | Length (cm.) | \( R_b \) (ohms) | \( R_{14} \) (ohms) | \( R_b - R_N \) (ohms) | \( R_b \times 10^3 \) (ohms) | Pulse Volume\( \uparrow \) (cc.) | Pulse Rate | Minute Volume (cc.) | Room Temp. (C.) | Time (min.) |
| Right forearm                   | 20             | 99.5           | 99.383         | .117            | 0.844          | .711              | 57.7         | 41.0           | 27.5           | 0            |
| Left forearm                    | 20             | 108.5          | 108.38         | .115            | 1.02           | .589              | 56.6         | 33.3           | 27.5           | 3            |
| Right forearm                   | 20             | 103.6          | 103.50         | .0986           | 1.09           | .552              | 56.6         | 31.2           | 27.3           | 11           |
| Left forearm                    | 20             | 110.2          | 110.12         | .0769           | 1.58           | .380              | 57.7         | 21.9           | 27.0           | 21           |

* In this experiment a progressive change in measurements is shown with time. This is probably physiologic rather than physical in origin. Premasurement period of rest may have been inadequate. The decreased minute volume with time is suggestive of peripheral vasoconstriction which occurs with the change to a recumbent posture.

† Probably no more than three or four figures at any time are significant in columns designated \( R_N \) in this and subsequent tables. They merely illustrate the influence of the shunt due to the pulse. For practical purposes in calculation of pulse volume, \( R_N \) equals \( R_b \).

‡ Resistivity of the blood assumed as 150 ohm cm.

measurements is lower than the corresponding bipolar measurement of a given arm.

The resultant effect on the calculation of pulse volume shows that tetrapolar measurements give higher values than bipolar measurements.

It follows that the values for pulse volumes per minute in our data are significantly higher for the tetrapolar method in spite of slightly higher pulse rate during the bipolar measurements in the reported experiment (table 1).

Parallel Impedance of Two Similar Segments as a Measure of Parallel Pulse Volume

The effect of electrically parallel circuits is defined by equation 1. The resistive values for study of the left leg, the right leg, and of both volume studies in the arm segment (table 2 and figure 2).

A bipolar technic was employed because the four electrode method was not available at the moment. Perhaps a better correlation may be obtained with more careful control. The experiment proves that we may study complex biologic electrical impedances, such as the blood pulses, in parallel, and predict the final impedances and the parallel segmental expansion due to blood with fair accuracy, under changing physiologic conditions.

External Parallel Shunts on the Skin between the Effective Electrodes

The summary of such an experiment is tabulated and shown (table 3 and fig. 3). It is noted
TABLE 2.—Parallel Impedance Study of Two Similar Segments
Study of Two Legs on Subject J. N.

<table>
<thead>
<tr>
<th>Segment (Reclined)</th>
<th>Length (cm.)</th>
<th>$R_0$ (ohms)</th>
<th>$R_0 - R_Y$ (ohms)</th>
<th>$R_H \times 10^4$ (ohms)</th>
<th>Pulse Volume* (cc.)</th>
<th>Pulse Rate</th>
<th>Minute Volume (cc.)</th>
<th>Room Temp. (°C)</th>
<th>Time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left leg</td>
<td>20</td>
<td>76.5</td>
<td>0.0352</td>
<td>1.53</td>
<td>0.392</td>
<td>61.3</td>
<td>24.0</td>
<td>21.0</td>
<td>0</td>
</tr>
<tr>
<td>Right leg</td>
<td>20</td>
<td>75.8</td>
<td>0.0367</td>
<td>1.57</td>
<td>0.392</td>
<td>61.3</td>
<td>24.0</td>
<td>20.8</td>
<td>48</td>
</tr>
<tr>
<td>Both legs in parallel—measured</td>
<td>20</td>
<td>37.2</td>
<td>0.0191</td>
<td>0.725</td>
<td>0.828</td>
<td>61.3</td>
<td>50.8</td>
<td>21.0</td>
<td>44</td>
</tr>
<tr>
<td>Both legs in parallel—predicted</td>
<td>20</td>
<td>38.1</td>
<td>0.0187</td>
<td>0.776</td>
<td>0.773</td>
<td>61.3</td>
<td>47.4</td>
<td>21.0</td>
<td>24</td>
</tr>
</tbody>
</table>

Study of Two Forearms on Subject M. K.

<table>
<thead>
<tr>
<th>Forearm</th>
<th>Length (cm.)</th>
<th>$R_0$ (ohms)</th>
<th>$R_0 - R_Y$ (ohms)</th>
<th>$R_H \times 10^4$ (ohms)</th>
<th>Pulse Volume* (cc.)</th>
<th>Pulse Rate</th>
<th>Minute Volume (cc.)</th>
<th>Room Temp. (°C)</th>
<th>Time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right forearm</td>
<td>20</td>
<td>144.5</td>
<td>1.060</td>
<td>1.95</td>
<td>0.307</td>
<td>75.0</td>
<td>23.0</td>
<td>23.0</td>
<td>0</td>
</tr>
<tr>
<td>Left forearm</td>
<td>20</td>
<td>157.9</td>
<td>1.161</td>
<td>1.54</td>
<td>0.390</td>
<td>65.2</td>
<td>25.4</td>
<td>23.0</td>
<td>3</td>
</tr>
<tr>
<td>Both forearms in parallel—measured</td>
<td>20</td>
<td>74.7</td>
<td>0.781</td>
<td>0.714</td>
<td>0.844</td>
<td>60.7</td>
<td>58.8</td>
<td>23.0</td>
<td>6</td>
</tr>
<tr>
<td>Both forearms in parallel—predicted</td>
<td>20</td>
<td>74.7</td>
<td>0.697</td>
<td>0.831</td>
<td>0.721</td>
<td>70.1</td>
<td>51.6</td>
<td>23.0</td>
<td>8</td>
</tr>
</tbody>
</table>

* Resistivity of blood assumed as 150 ohm cm.

![Graph](https://example.com/graph.png)

**Fig. 2.** The parallel effect on the pulse volume of combining resistive changes in the right arm (RA), and left arm (LA), is shown in the third and fourth curves. The calculations are outlined in the text and table 2, subject M.K. An A.C. coupled amplifier controls the terminal oscillograph. The drift shown in the standardization curve is characteristic of the end recording equipment.

that the total resistance ($R_0$) of the leg segment drops from 75.8 ohms to 71.7 ohms on applica-

tion of salt paste between the electrode region. A further drop to 52.9 ohms occurs on wrapping a sheet of aluminum foil around the midsection of the measured segments. Later, by calculation, it appeared that the effective parallel resistance of the salt and aluminum foil (surface shunt) was 175 ohms.

The influence of salt paste on the final pulse volume because of its coldness appears to have resulted in a slight reduction of 1.3 cc. per minute from a level of 24.0 cc. per minute for the segmental expansion.

The addition of aluminum foil over the salt paste was followed by measurement six minutes later. These values showed an increase in pulse volume and minute volume. The level exceeded the paste study by 6.1 cc. and the control level by 4.8 cc. The change was not due to room temperature, which was constant. The subject complained of a feeling of warmth under the aluminum foil. The change might have been due to local changes interfering with radiation of heat from the segment. It is improbable that the physical application of a shunt resistance of 175 ohms in parallel with the leg was the cause of physiologic changes. It is concluded that physiologic changes in pulse volume and minute volume are secondary to the peculiar method of producing the physical shunt.

By further experiment under controlled conditions, an external physical shunt of 200 ohms parallel to the blood circulation and the tissues of an extremity did not produce a physiologic change, but the anticipated physical effect of
Table 3.—The Effect of a Low-Resistive Parallel Shunt on the Skin Between the Electrodes on the Resistances and Volume Pulse

<table>
<thead>
<tr>
<th>Segment (Recumbent)</th>
<th>Length (cm.)</th>
<th>$R_a$ (ohms)</th>
<th>$R_a - R_N$ (ohms)</th>
<th>$R_a \times 10^6$ (ohms)</th>
<th>Pulse Volume (cc.)</th>
<th>Pulse Rate</th>
<th>Minute Volume (cc.)</th>
<th>Room Temp. (°C.)</th>
<th>Time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right leg (control)</td>
<td>20</td>
<td>75.8</td>
<td>.0367</td>
<td>1.57</td>
<td>.392</td>
<td>61.3</td>
<td>24.0</td>
<td>20.8</td>
<td>0</td>
</tr>
<tr>
<td>Right leg covered with paste</td>
<td>20</td>
<td>71.7</td>
<td>.0318</td>
<td>1.62</td>
<td>.370</td>
<td>61.3</td>
<td>22.7</td>
<td>21.0</td>
<td>8</td>
</tr>
<tr>
<td>Right leg covered with aluminum foil</td>
<td>20</td>
<td>52.9</td>
<td>.0223</td>
<td>1.25</td>
<td>.479</td>
<td>60.0</td>
<td>28.8</td>
<td>20.8</td>
<td>14</td>
</tr>
<tr>
<td>Right leg after aluminum foil and paste removed</td>
<td>20</td>
<td>77.8</td>
<td>.0373</td>
<td>1.62</td>
<td>.371</td>
<td>63.8</td>
<td>23.6</td>
<td>21.0</td>
<td>32</td>
</tr>
</tbody>
</table>

The calculated effective parallel resistance of the aluminum foil and the electrode salt paste is 175 ohms.

Subject J. N. stated that the paste felt cold while the aluminum foil covering the leg produced a warm feeling which may account for some shift in minute volume.

Mild Exercise and Pulse Volumes of the Forearm Segment

Subject E. T. was studied before and after one minute of flexion and extension exercise of the fingers, using the bipolar method on the forearm. The results are shown (table 4) and indicate a significant rise in the calculated pulse volume and minute volume by impedance methods on the same arm. There is an evident return to normal pulse volume and minute volume within six minutes. A change from 19.9 cc. to 26.0 cc. per minute is shown after one minute of exercise of the same type in one forearm of subject J. N.

It appears from limited data that the vascular expansion may be differentiated as to exercise in the extremities as shown in the forearm segment under controlled conditions by electrical impedance studies.

Table 4.—Physiologic Response in Pulse Volume to Exercise*

<table>
<thead>
<tr>
<th>Subject (Recumbent)</th>
<th>Length (cm.)</th>
<th>$R_a$ (ohms)</th>
<th>$R_a - R_N$ (ohms)</th>
<th>$R_a \times 10^6$ (ohms)</th>
<th>Pulse Volume† (cc.)</th>
<th>Pulse Rate</th>
<th>Minute Volume (cc.)</th>
<th>Room Temp. (°C.)</th>
<th>Time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm before exercise</td>
<td>20</td>
<td>132.0</td>
<td>.0713</td>
<td>2.44</td>
<td>.246</td>
<td>56.2</td>
<td>13.8</td>
<td>20.0</td>
<td>0</td>
</tr>
<tr>
<td>Forearm after exercise</td>
<td>20</td>
<td>128.0</td>
<td>.0874</td>
<td>1.82</td>
<td>.330</td>
<td>57.7</td>
<td>19.1</td>
<td>20.0</td>
<td>1</td>
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<tr>
<td></td>
<td>20</td>
<td>128.0</td>
<td>.0862</td>
<td>1.90</td>
<td>.316</td>
<td>57.7</td>
<td>18.2</td>
<td>20.3</td>
<td>2.5</td>
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<tr>
<td></td>
<td>20</td>
<td>128.5</td>
<td>.0736</td>
<td>2.24</td>
<td>.268</td>
<td>57.7</td>
<td>15.4</td>
<td>20.3</td>
<td>6</td>
</tr>
</tbody>
</table>

Subject J. N.

| Forearm before exercise | 20           | 91.8         | .0437              | 1.93                     | .311               | 63.8       | 19.9                | 20.8             | 0           |
| Forearm after exercise     | 20           | 94.1         | .0640              | 1.38                     | .433               | 60.0       | 26.0                | 21.2             | 1           |

* Exercise was moderate flexion and extension of the fingers for one minute.
† Resistivity of the blood assumed as 150 ohm cm.
**Electrical Measurement of Large Changes in Venous Blood Volume of the Forearm Segment**

Until recently, it has been difficult to approximate the volume of blood leaving or entering an extremity segment passively, such as may result from posture. On the basis of the foregoing changes in resistance produced by the pulse volume, we reanalyzed the type of experiment originally recorded at Wright Field.

A forearm segment was prepared as usual with two electrodes for resistive studies at a given posture. The arm was allowed to rest in a natural position and \( R_0 \) was measured by substitution. \( R_0 - R \) or \( \Delta R \) was recorded at low recording sensitivity, so that 1 ohm was equal to 5 mm. excursion of the galvanometer. This is shown in figure 4 at region 1, where there is no evidence of drift or other imbalance except the standard. The base of measurement was 165 ohms and the pulses were visible but not measurable. The arm was then raised gradually above the shoulder level as the subject was sitting. This was associated with a precipitous drop in electrical conductivity and presumably a passive decrease in the amount of venous blood stored in the veins of a given segment. This emptying of the veins is recorded opposite region 2. This was followed by a very slow rate of decrease in conductivity opposite regions 3 and 4 of the record.

When the arm was lowered moderately fast, the initial effect was to produce the wave in the conductivity record opposite region 5. This may have been associated with partial reflux or retrograde flow of venous blood which was not held back by the venous valves above the proximal electrode on the arm.

Thereafter, the return curve was more uniform at region 6 before rising asymptotically toward the baseline at regions 7 and 1. The volume of the arm and the venous reservoir had nearly refilled to the original level at regions 7 and 1, judging from the conductivity curve. Region 6 may be important as a measure of unobstructed filling of the venous reservoir.

<table>
<thead>
<tr>
<th>Subject (Recumbent)</th>
<th>Venous Outflow (cc)</th>
<th>Standard of 1 ohm (mm)</th>
<th>( R_0 ) (ohms)</th>
<th>( \Delta R ) (ohms)</th>
<th>( R_0 \times 10^3 ) (ohms)</th>
<th>Venous Outflow (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left forearm</td>
<td></td>
<td></td>
<td>118</td>
<td>1.8</td>
<td>119.8</td>
<td>7.81</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>5.5</td>
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<tr>
<td></td>
<td>8.5</td>
<td>4.0</td>
<td>118</td>
<td>2.1</td>
<td>120.1</td>
<td>6.75</td>
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<td></td>
<td>11.0</td>
<td>4.5</td>
<td>118</td>
<td>2.4</td>
<td>120.4</td>
<td>5.92</td>
</tr>
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<td></td>
<td>16.0</td>
<td>6.0</td>
<td>118</td>
<td>2.7</td>
<td>120.7</td>
<td>5.33</td>
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Room temperature 27 to 27.5 C.; arm volume approximately 650 cc.; resistivity of blood assumed to be 150 ohm cm.

Data arranged in the order of magnitude for \( \Delta R \) of the given segment.

The linear relation to the volume of venous outflow becomes self-evident.

It was estimated from the measurements that the drop in 7 ohms impedance was equivalent to 14.5 cc. of venous outflow from the segment by raising the arm under these given conditions. As the displacement of the segment was about 650 cc., the change in volume was calculated to be 2.23 cc. per 100 cc. of a given arm segment. Other typical results of partially controlled measurement during recumbency of a given subject, arranged according to degree of deviation in volume, are in table 5.

Record B demonstrates how repeated raising and lowering of the arm produces changes in conductivity similar to regions 1 to 7 on record A. No attempt to measure these has been made as more rigid controls of activity and posture...
must be defined in order to quantitate the events properly.

Electrical Measurement of Blood Flow Without Occlusion During Refilling of the Venous Reservoir

"Exact analysis" of physiologic change has been a difficult, tedious, and ungratifying task of measuring "blood flow" in various segments of the extremity by mechanical plethysmography following venous occlusion at the outflow region of a segment. At region 6 of the experimental curves (fig. 4), we assumed that the fairly uniform rate of change was an index of the rate of flow of blood, refilling the recently collapsed venous reservoir of the arm segment.

We derived the results in table 6 by measuring $\Delta R$ for a portion of slope 6 as representative of the portion of blood volume ($\Delta V$) which is filling the veins in a given time ($\Delta T$). It is also necessary to know the equivalent parallel resistance for value $\Delta R$, as well as the length of the segment and resistivity of the blood. Under these circumstances, substitution of values in equation 2 should permit the calculation for the change in volume ($\Delta V$). In the illustration (fig. 4), it appears that the volume is 1.75 cc. for a period of three seconds. This represents a flow of 35 cc. per minute. This figure is reasonable for the segment of about 650 cc. volume. Further results and calculations on the same subject under better controlled conditions are arranged in order of magnitude in table 6. It appears justified to conclude that with our

```
Table 6.—The Calculated Rate of Filling of the Venous Reservoir After Rapidly Lowering the Arm Without Occlusion

<table>
<thead>
<tr>
<th>Segment (Recumbent)</th>
<th>Venous Filling (mm./3 sec.)</th>
<th>Standard of 1 ohm (mm.)</th>
<th>$R_N$ (ohms)</th>
<th>$\Delta R$ (ohms)</th>
<th>$R_B \times 10^6$ (ohms)</th>
<th>Net Volume Flow (cc./min.)</th>
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</tbody>
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```

Room temperature 27 to 27.5 C.; arm volume approximately 650 cc.; resistivity of blood assumed to be 150 ohm cm.

The data as arranged shows the linear relationship between $\Delta R$, the resistance change per unit time and the calculated rate of return or filling of the venous reservoir with blood.

| Fig. 4. The effect of raising and lowering the arm on the recorded electrical impedance of a segment of the right forearm (curves A and B). The electrical conductivity decreases and the volume of the forearm decreases as the arm is raised. See the text for further details and interpretation. A bipolar arrangement of electrodes was used for these procedures. A string galvanometer is the end recorder. The paper film speed is 6.25 mm. per second. |

At region 6 of the experimental curves (fig. 4), we assumed that the fairly uniform rate of change was an index of the rate of flow of blood, refilling the recently collapsed venous reservoir of the arm segment.

We derived the results in table 6 by measuring $\Delta R$ for a portion of slope 6 as representative of the portion of blood volume ($\Delta V$) which is filling the veins in a given time ($\Delta T$). It is also necessary to know the equivalent parallel resistance for value $\Delta R$, as well as the length of the segment and resistivity of the blood. Under these circumstances, substitution of values in equation 2 should permit the calculation for the change in volume ($\Delta V$). In the illustration (fig. 4), it appears that the volume is 1.75 cc. for a period of three seconds. This represents a flow of 35 cc. per minute. This figure is reasonable for the segment of about 650 cc. volume. Further results and calculations on the same subject under better controlled conditions are arranged in order of magnitude in table 6. It appears justified to conclude that with our
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technic it is possible to measure the rate of venous filling after the venous reservoir of the extremity has been collapsed by postural means. Venous occlusion may be done while the extremity is raised, in order to prevent venous outflow. Under such conditions, blood accumulates, however, immediately, and the slope often approaches the slope described in region 6 (fig. 4).

It would appear that the new technic is more physiologic and potentially as valid a measure of peripheral flow as derived by venous occlusion methods [Brodie and Russell (1905),14 Hewlett and van Zwaluwenburg (1909),7 and the well known modifications of these]. A comparative analysis of simultaneous impedance methods of determining blood flow is being reported elsewhere.7, 10

Discussion

The electrical impedance method under consideration here is not basically different from that employed 10 years ago.1 Largely because of misunderstanding of the basic principles involved, progress of impedance measurement of the multicellular organism and its circulation has been slow and involved.

It is reasonable to assume that if there are series and parallel resistive circuits in the organism, then some of its functions may almost surely be defined in terms of resistive changes. The peripheral circulation is one of these functions. If the blood pools indefinitely or transiently within a limited segment, its resistivity will be added in some manner to the resistivity of the segment. Continuous records of electrical conductivity of a body segment trace the course of a blood volume pulse and measure its magnitude by virtue of the number and mobility of ions. If one is still in doubt on this fact, he should follow the blood conductivity of an artery in animal or man before, during, and after injection of electrolyte or nonelectrolytic substances. The dilution curve is clearly recorded elsewhere.8 The data derived from such an observation appears to be a function of partial or complete circulation time, cardiac stroke volume, total cardiac output, and blood volume, and diffusion from the vascular system.

The various functions of the peripheral circulation which may be defined also by impedance measures are pulse volume, minute pulse volume, pulse velocity, the rate of change of pulse volume, pulse form, blood pooling and emptying, particularly of the venous reservoirs, and secondarily, the backflow into the reservoir associated with postural changes in the extremity. The rate of filling of the venous reservoir from the arterial side may be a function of segmental blood flow, as observed electrically. This long list of possibilities sounds like a copy of the encyclopedia, but in all fairness, we should find out why and where we have failed or lost our patience to define a given vascular function by electrophysical measurement.

One basic clue to evaluation of the volume of blood at any given moment in a given segment is its parallel resistive measure. To find this, we must have other data as outlined.

The concept that volume of substance is a direct function of its electrical conductivity is taught in elementary physics of conductors in relation to electronic conduction. There is no justification in believing that it does not apply to ionic conductors, such as the blood. If the blood does not alter too rapidly in its electrolyte and nonelectrolyte ratio, its conductivity should justifiably enter into volume determination as it is directly proportional to the measure of segmental volume.6 It is not difficult to measure in vitro. If the body segment is measured at a given frequency, the blood in vitro relative to the segment should be measured at this frequency unless we have reached the infinite frequency impedance of this tissue with our signals. The physiologic conditions of flowing blood are more difficult to reproduce.

The vascular reactions to drugs, nerve block, arterial and venous occlusion, exercise, posture, anxiety, pleasure, physical agents, trauma, surgery, disease, and stimulation are but a few of the responses which may be carefully evaluated to advantage by electrical impedance methods. Burch's8 sensitive mechanical plethysmograph has already proved to be very useful in this regard, but Goodyer14 has recently pointed out some advantage to the electrical impedance method, although he did not show how to exact the volumetric data from his records in conventional terms.
Recently, Coulter and Pappenheimer\textsuperscript{13} have found that turbulence in flowing blood does not influence electrical impedance measurement of blood. Thus blood cells remain oriented in turbulent flow. At low flows, however, the blood viscosity decreases with increasing flow. This effect parallels the observation of Velick and Gorin\textsuperscript{18} who observed that the electrical resistance of flowing blood measured in the direction of flow was less than that of blood at rest. At present, we cannot supply a correction for the resistivity of blood, if a correction should be made for its flow or given velocity.

Some of the other major potential disadvantages concerned with conductivity methods are the unknown mean temperatures of the segment and its blood streams. Thermal gradients\textsuperscript{17} are present in the arteriovenous vascular system. This presupposes differences in the conductivity of arterial and venous blood of the peripheral segment. In addition to this, the relative velocities\textsuperscript{18} and proportion of plasma and red cells vary throughout the vascular system, and, therefore, are influential in distributing changes in resistance. Fluid shifts between the vascular and extravascular compartments also modify the electrolyte-nonelectrolyte ratio of each and incidentally the paralleled resistive effects pertaining to each. Pickering and Dow\textsuperscript{19} ascribe consistent findings of higher relative cell volumes and plasma protein levels in venous blood than in simultaneous arterial samples to the arteriovenous shift of water from plasma to cells. These factors must be evaluated ultimately in pulsatile and nonpulsatile impedance studies of body segments, if this approach is to become a useful tool in evaluation of vascular phenomena.

\textbf{Summary}

1. The quantitative measure of pulse volume and the venous blood pool is defined in terms of its parallel electrical resistance to the resistance of the whole segment or of the deep tissues of the segment.

2. The parallel resistivity of a transient change in blood volume is currently evaluated by bipolar or tetrapolar methods of conduction measurement.

3. The parallel resistive value of a given pulse or a shift in segmental blood volume, together with data of the linear dimensions of the segment and the resistive value of the blood are entered into the equation for the volume of an electrical conductor to calculate the quantitative volume of displaced or new blood.

4. The pulse volume is proportional, but not necessarily equal to the true arterial inflow or venous outflow from a segment. It follows that the minute pulse volume is proportional to the segmental blood flow.

5. The physical effect of parallel circuit arrangement of both legs by experiment proves unequivocally the quantitative nature of the segmental blood pulse volume as evaluated by its parallel resistive effect.

6. It appears that the rate of blood flow in a peripheral segment may also be approximated by evaluation of the rate of filling of a previously emptied venous reservoir produced by a change in posture of the segment.

7. The electrical impedance methods appear sufficiently accurate and sensitive to warrant further consideration for application to basic and clinical medical science.

\textbf{Addendum}

Since the original submission of our manuscript, F. H. Bonjer,\textsuperscript{20} in his thesis "Circulatieonderzoek door Impedantiemeting," has independently correlated the recently published equations\textsuperscript{6} and arrived at the quantitative solution for pulse volume from electrical impedance data on extremity segments, i.e.:

\[
\Delta V = -\frac{\Delta R}{R_0} \cdot \frac{p}{R_3}
\]

in which \(\Delta V\) represents the pulse volume related to its maximum excursion and the other values as defined above. In effect, this is equivalent to equation 2.

At present, his impedance unit employs a frequency of 60,000 cycles and a percentile change in resistance for a standard of comparison. A tetrapolar electrode system is also used to his advantage. Open ring flexible electrodes were made from braided fine copper wire.

He also refers to Russian, French, German and Austrian investigations on body impedance, some of which were unknown to us.
Our earliest pulsatile impedance investigations reported in 1940 were wholly independent of similar contributions published elsewhere.

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REFERENCES

6 ——: Impedance plethysmograph. In Medical Physics, ed. 2. Chicago, Yearbook Publishers, 1950. (Includes extensive bibliography on electrical impedance.)
Electrical Impedance Plethysmography: A Physical and Physiologic Approach to Peripheral Vascular Study
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