Limitations of Electric Impedance Plethysmography

By J. van den Berg, D.Sc., and A. Jappe Alberts, B.Sc.

Electric impedance plethysmography has been offered as a substitute for mechanical plethysmography and would be particularly suitable for regions in which the mechanical method cannot be applied. A comparative investigation of mechanical and impedance plethysmograms, taken simultaneously from a finger or a forearm, revealed that, while the normal pulsations were reproduced reasonably well, electric impedance plethysmography cannot be employed to determine volume changes following venous occlusion. The reasons are discussed.

While it has been established that the electric impedance of a part of the body varies with the rhythmic changes in blood content, comparative data concerning the quantitativeness of the calculated changes in volume have not been published.

It was the aim of our investigations to record simultaneously the impedance and the mechanical plethysmograms of a finger or forearm and from these data deduce the quantitativeness of the impedance method. In both methods the measuring technic disturbed the normal conditions slightly, but this did not affect our results, because the two plethysmograms were recorded simultaneously from the same object.

Methods

Figure 1 shows a scheme of the arrangement as applied to the finger. For the finger we used the mechanical plethysmograph of Buytendijk which has a response time of 0.06 second. It was air-filled and stabilized for temperature changes. For the forearm an air-filled and stabilized mechanical plethysmograph with response time of 0.3 second was constructed. While the pulsations were recorded at about 50 per cent of their real values this presented no difficulties, since the arm was mainly used to study the effects of venous return occlusion.

Figure 2 shows a scheme of the impedance plethysmograph. A current was sent through the object with the aid of the four-electrodes technic. \( I_1 \) and \( I_2 \) are current electrodes, \( M_1 \) and \( M_2 \) measuring electrodes which took practically no current from the object, as the input impedance of the recording apparatus was great.

The advantages of the four-electrodes technic as compared with the two-electrodes technic may be stated briefly: A high frequency current tends to spread almost homogeneously through the conducting material. This enables one to limit sharply the part to be investigated and to calculate—under certain conditions—the volume changes from the records and the other data. When the two-electrodes technic is used, one does not know how the current is distributed in the neighborhood of the electrodes and what parts of the object must be included in the calculations. This is due to the fact that, with the four-electrodes technic the impedance of two adjoining sections in the sum of the impedances of each section, but this is not true for the two-electrodes technic. The four-electrodes technic, however, does have a disadvantage in investigations on a terminating object, such as a finger, the section at the end cannot be investigated.

It was necessary to wet the cleansed skin beneath the electrodes thoroughly with electrode paste in order to diminish the resistance between the electrodes and the object. The shape of the current electrodes was not critical. Narrow (1 mm.), thin (0.1 mm.) bands of rolled copper or thin copper wires were used as measuring electrodes. Needle electrodes were employed for subcutaneous investigations.

The current was provided by a 60 kc, 50 volts or a 185 kc, 250 volts generator. High series resistances of \( 5.7 \times 10^3 \) ohms (60 kc) or \( 85 \times 10^3 \) ohms (185 kc) were used in order to make the current practically independent of the object; thus the voltage over the measuring electrodes was a constant times the impedance between them.

A calibration resistance of 12 ohms (60 kc) or 200 ohms (185 kc) could be added to the chain by means of a switch. This procedure decreased the current and thus the measured voltage by 0.2 per cent. The variations due to changes in volume were compared with this calibration pulse.
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The voltage between the measuring electrodes was fed into an amplifier (A) (fig. 2), by means of a wire wound potentiometer, which drove one half of the push-pull stage (B) with a negative bias. The signal was rectified by anode detection and recorded by a spotlight galvanometer (G) between the anodes. The push-pull stage had a fixed bias, so that the signal delivered to B must have a fixed size. This was achieved with the aid of the potentiometer, which thus could be calibrated in ohms; 15 to 300 when using the 60 kc generator, 40 to 500 with the 155 kc generator. Variations up to about 10 per cent were recorded linearly, the response time of the galvanometer being 0.18 second.

The input impedance of amplifier (A) was $90 \times 10^6$ (60 kc) or $35 \times 10^6$ ohms (155 kc). Batteries and an electronically stabilized powerpack were used for feeding generators and recording apparatus. After 15 minutes the fluctuations were less than 0.1 per cent.

Several factors complicate the calculation of actual volume changes from corresponding impedance variations; (1) The distributions of the mean impedances in different parts of the test object and hence of the electric current are not known exactly; (2) The effects of vascular filling following venous occlusion on mean impedance cannot be determined; (3) At constant volume, the impedances may vary with temperature, blood velocity, internal shifts of fluid and varying degrees of moisture on the skin.

Actually, corresponding absolute changes in volume can only be calculated (a) when all mean impedances are equal to each other, the current being distributed homogeneously through the object, and (b) when the volume variations also have a homogeneous distribution, the relative expansion of all parts being equal to each other.

When the electric current has a sufficiently high frequency condition o is nearly satisfied. The following formula holds for a cylindrical object when all impedances are pure resistances.

$$\Delta V = -\rho \frac{\Delta R}{R_0} \frac{L^2}{R_0}$$

where $\rho$ = specific resistance of blood; $L$ = length of the object; $R_0$ = mean resistance of the object, to be read on the potentiometer in figure 2; $\frac{\Delta R}{R_0}$ = percentile change in resistance, to be determined by the calibration pulse; $\Delta V$ = absolute change in volume.

Formula 2 holds in this case for a frustum of a cone with radii of the bases $r_a$ and $r_b$.

$$\Delta V = -\rho \frac{\Delta R}{R_0} \frac{L^2}{R_0} \frac{1 + c + c^2}{3c}$$

(when $c = r_a: r_b = 2$, this means only a factor $7:6 = 1.17$).

When the impedances were not pure resistances a correction was necessary because the apparatus compared the moduli of the impedances. This correction factor was $1:\cos (\varphi - \psi)$ when the mean impedance...
of the object was $R_1 e^{i\phi}$ and the specific impedance of blood $\rho e^{i\phi}$, thus for a cylindric object,

$$\Delta V = -\rho \cdot \frac{\Delta R}{R_0} \cdot \frac{L^2}{R_0} \cdot \frac{1}{\cos(\phi - \psi)}$$  \hspace{1cm} (3)$$

in which again $\Delta R:R_0$ was determined by the calibration pulse.

Measurements of Lissajou's figures showed that $\phi$ approximated 30 degrees, 25 degrees and 5 degrees at 60 kc when the two-, three- and four-electrode technics were used on the finger and $\phi$ was less than 1 degree in all cases at 185 kc. For the forearm we found in the same way that $\phi$ approximated 15 degrees and 5 degrees at 60 kc and 10 degrees and 1 degree at 185 kc. For blood at 37 C, we found $\phi < 30$ at 60 kc and 185 kc. Thus the correction factor $\phi: \cos(\phi - \psi)$ was small.

In the experiments to be described we used formula 3 to calculate the corresponding variations in volume, or formula 2 with correction factor $\phi: \cos(\phi - \psi)$ when necessary. Differences between the calculated and true values, as recorded simultaneously by the mechanical plethysmograph, were caused by deviations from the idealized case. We have tried to analyze the complicating factors.

**Results**

**Pulse Volumes.** In considering finger pulsations the following details are important. The proximal measuring electrode lay on the distal side of the top ring (closed with ointment) of the mechanical plethysmograph (fig. 1). The mechanical plethysmograph measured the pulsations of the completely enclosed part of the finger. This was not the case with the impedance plethysmograph, for the four electrodes technic did not include the finger tip. In some instances the pulsations of this part were measured separately with the mechanical plethysmograph. They appeared to be relatively great, because the finger tip has a good blood supply.

Figure 3 shows that the shape of the pulsations as recorded by the two methods was practically identical. Pulsations of the mechanical plethysmogram were delayed approximately 0.07 second because the records were derived from different areas of the finger, as explained above. From such records we calculated the pulse volume variations as indicated by mechanical and electric impedance technics, correcting the latter for probable finger tip changes.

In 20 normal subjects it was found that the ratio of impedance to mechanical volumes had a mean value of 1.5 (S.D. = 0.6.) This ratio appeared to be fairly constant during an experiment (3-18 observations); the maximum deviation from the mean ranged from 2 to 35 per cent in the same object. These limits can perhaps be narrowed by taking the shape of the finger (e.g., thickness) into account.

**Occlusion Plethysmography.** The agreement between mechanical and impedance plethysmograms was, on the contrary, less satisfactory in the case of experiments in which the
outflow from a finger or forearm was abruptly stopped by the inflation of a cuff approximately to 60 mm Hg.

Several types of anomalies are illustrated in figures 4 and 5. (1) The impedance plethysmograph recorded the volume change immediately after occlusion insufficiently (fig. 4) and sometimes hardly at all. (2) During the occlusion the impedance plethysmogram showed, in nearly half of the cases, pulsations that were greater than before the occlusion (fig. 5). (3) Shortly after the start of the occlusion the impedance plethysmogram sometimes showed a negative pulse (fig. 5). (4) Directly after release of the pressure, especially in the case of the forearm, a sharp positive peak appeared (fig. 5).

Since these anomalies varied from case to case it was impossible to select experimental conditions under which the impedance plethysmogram would be a true copy of the mechanical record during and after venous occlusion.

**DISCUSSION**

Our investigations suggested that four factors are responsible for the errors in impedance plethysmograms after venous occlusion:

1. A great and variable change in resistance between the interior of a finger or arm and the measuring electrodes could counteract the effects of occlusion. Thus, a decrease in resistance during occlusion would direct a greater part of the voltage over the input resistance of the amplifier. Since venous occlusion causes a volume increase of approximately 1 per cent, in mechanical plethysmograms this should decrease the resistance by at least 500 ohms. It was found, however, that the total resistance was less than 10 ohms when the electrodes were applied properly. This was observed (a) by using the measuring electrodes as current electrodes, while leaving them in the same position, (b) by measuring the impedance from Lissajou's figures and, (c) by determining the voltage distribution, using the electrical equipment as a valve voltmeter.

In the deductions of formulas 1, 2 and 3 it was assumed that blood would be homogeneously distributed in the test object. If this is not the case, one would get smaller variations in resistance and too small a value from the calculations. In the finger the blood is certainly not homogeneously distributed; it circulates for the greater part through the skin. But, by determining the mean impedances of different sections of the forearm, it was found that regions with meager blood supply, such as bone and tendon, conduct electrical current poorly; their specific resistances were much higher than those of blood and blood-containing tissue. Hence, such parts represent a parallel circuit of practically infinite electrical resistance, leaving the important part as a nearly cylindric ring, for which formulas 1, 2 and 3 hold. Since the volumetric variations during normal pulsations and venous occlusion are relatively small, one might expect that the deviation from a homogeneous distribution could be corrected by a nearly constant factor, provided there were no effects of a particular nature associated with the occlusion.

It was impossible to study the homogeneity of current distribution directly. We tried to trace it indirectly in the finger by using subcutaneous needles as measuring electrodes in several places. The agreement between the curves did not improve.

It was also assumed in the formulation that the electric current is homogeneously distributed in the object, without preference
routes and without areas where the effect of the incoming blood might be obscured. This could also be studied only indirectly. In the case of the forearm we used our electronic apparatus as a valve voltmeter and measured the voltage distribution on the skin. While the current distribution was certainly not homogeneous, the differences were not great enough to explain the large deviation in the impedance plethysmogram. This was confirmed by results of earlier experiments on the forearm, by which the mean specific resistance of each segment of the forearm appeared to be practically the same, provided that bone and tendon did not take part in conduction of the current. The possibility that certain areas in the forearm were not tapped by our electrode was investigated by comparing the impedance plethysmograms of four- and two-electrode technics. In the latter case the current would be compelled to follow other routes. In some cases the two-electrodes technic yielded curves almost identical with the mechanical plethysmogram, while the four-electrodes technic showed a large deviation. In other cases the agreement hardly improved. In the finger, too, we often noted a considerable difference between the two-, three- and four-electrodes technics.

Agreement appeared to depend also on the external conditions of the object. It was relatively greatest when the person was kept warm and when the blood was circulating properly through the limb (the jacket of the mechanical plethysmograph was kept at 30°C). Wetting of the skin by sweat first counteracts the occluding effect, but as soon as a layer forms it helps. In our experiments we found no evidence that the duration of the experiment or the amount of moisture found on the skin after removal from the plethysmograph affected the reliability of impedance plethysmograms.

2. A temperature change in an appendage during the occlusion would have a great influence on the impedance plethysmogram. It was concluded from experiments on blood samples at different temperatures that the temperature coefficient of human blood is approximately identical with that of an electrolytic solution: about 2 per cent per degree centigrade. If this may be applied to the average specific resistance of the tissue, a temperature drop of 0.5°C. may compensate for the effect of the occlusion. The effect of temperature was investigated in the finger by recording simultaneously the subcutaneous temperature with a thermocouple. In some cases a drop in temperature of circa 1°C. per minute was recorded during the occlusion, and the effect on the impedance plethysmogram manifested itself accurately. In a series of experiments, it was discovered, however, that the temperature drop did not occur when the object was kept sufficiently warm. The same holds for the forearm.

3. The specific resistance may, however, change at a constant temperature and even with such rapidity that it may explain the lag in the impedance plethysmograph at the beginning of occlusion (see also point 4). Specific resistance may change through a shift of plasma to tissues (Edelman) or from movement of blood from the arterial to the venous side. A number of investigators have observed that the hematocrit value of venous blood is greater than that of arterial blood. The thermal gradient, normally present between the arterial and venous systems, may likewise disappear during an occlusion, so that $p$ in formulas 1, 2 and 3 does not remain constant.

It was not possible to estimate the magnitude of such effects from the tables given by Henderson. In six experiments carried out at 37°C., the specific resistance of venous blood of the arm was found to be 2 per cent greater than that of the arterial blood; the average specific resistances ranged between 134 and 210 ohms per centimeter. In three experiments on dogs, the specific resistance of venous blood of a leg increased 3 per cent 30 seconds after venous occlusion. In seven human experiments an increase of about 0.5 per cent was found in samples taken two seconds after occlusion. Skimming of blood near the pressure cuff can also not be dismissed.

4. Hemodynamic effects may account for (1) an imperfect registration by the impedance plethysmograph of the volume change during
occlusion, (2) the negative pulse often noticed at the start of cuff inflation, and (3) the positive peak sometimes associated with release of venous compression.

In the first place, according to Coulter and Pappenheimer\textsuperscript{12} the specific resistance of blood is affected by velocity of flow. From their data it appears that the specific resistance in a tube 1.26 mm. in diameter increased 15 per cent when the velocity decreased from 60 cm. per second to a very low value. This effect was observed when a pressure of 203 mm. Hg, which practically stops the flow, was put on the cuff. The change in specific resistance in our experiments was probably too small to explain (1) the inadequate recording of the occlusion effect, but sufficient to account for (2) the small negative pulse at the start of and (3) the positive peak at the release of the occlusion pressure.

Secondly, according to Burton and associates\textsuperscript{3-13} the diameter of small vessels depends on the inside pressure. This may explain the increasing level of the pulsations and the fact that the changes in volume calculated from the pulsations were too great.

In the third place several investigators\textsuperscript{14-19} found that the hematocrit value of blood flowing in vessels less than 0.3 mm. in diameter depends on the size. We believe that this alters specific resistance, for this depends indirectly on the diameter. When the pressure increases during occlusion, the vessels enlarge slightly. The hematocrit value increases, the specific resistance becomes greater, and thus the impedance plethysmograph does not register the full effect of the occlusion.

While the electrical impedance plethysmograph appears to be limited to quantitative studies of normal pulsations, this may give important data concerning the peripheral circulation.

Nyboer\textsuperscript{2} calculated from the average amplitude of pulsations a factor which, multiplied by 2, appears to be closely related to the blood flow. It might be assumed that this represents also the inflow during venous occlusion. However, it fails to take backflow into account and assumes that the occlusion pressure chosen does not alter arterial inflow. These variables may explain the great variations one obtains in the slopes of curves in successive tests and the necessity, emphasized by Abramson,\textsuperscript{20} of taking about 20 curves on each subject.

**SUMMARY**

The reliability of a four-electrode impedance plethysmograph for the study of pulsatile and volume flow was tested on normal subjects by comparing tracings obtained from a finger or forearm with those simultaneously recorded by a mechanical plethysmograph.

The impedance plethysmograph recorded the contour of finger pulsations satisfactorily. Changes in volume of the normal pulsations could be calculated with reasonable accuracy from the impedance plethysmogram by introducing a correction factor.

Changes in volume following venous occlusion were not properly recorded by the impedance plethysmograph. There were several anomalous effects and the increase in volume due to the venous occlusion was not recorded accurately.

The anomalous effects were caused by hemodynamic factors, changes of the specific resistance during the occlusion and under certain conditions, variation of the temperature.

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