Venous occlusion plethysmography

Part 1: Basic principles and applications

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A complete review of plethysmographic methods using the venous occlusion technique is given. All methods known to the author are covered, with comments on their applications. A comprehensive list of relevant literature concludes the review.

PLETHYSMOGRAPHY is the recording of variations in the volume of a liquid or an undissolved gas in biological tissues. In the latter sense, study of gas contents, it is used for investigations of the respiratory system (whole body plethysmography or impedance plethysmography of the chest). In the first sense, the study of liquid contents, it is a tool for studies of peripheral circulation through the recording of the varying blood content in a limb. Attempts have also been made to derive certain information on more central functions of the circulatory system as well as to study certain organs, either operatively exposed or studied via a natural cavity in the body. One specific method for peripheral circulation studies is venous occlusion plethysmography, which will be treated below. The scope is a comprehensive review of known techniques, based on a study of the literature as well as on the writer's own work and experience.

The basic principle of venous occlusion plethysmography

If a limb of the body is inserted, wholly or partially, into a device which can measure its volume and an occlusion cuff is mounted on the limb, proximally to the device (see the sketch in Figure 1), one has an arrangement which allows for a non-invasive measurement of perfusion and several other physiological parameters[1-5].

Before the veins are occluded through inflation of the cuff, the tissue volume, enclosed in the measuring device, remains constant at the resting value V_0, and the total arterial and venous blood flows through the limb cross-section at the entrance to the device are equal (in temporal mean values, i.e., apart from pulsations). Pressure and flow values may be represented by the notations defined in Figure 1.

As a reference point, we may define zero time as the moment when the cuff is suddenly inflated to a certain pressure (denoted by p_m) which should fall between the venous pressure p_v and the diastolic arterial pressure p_{aD}. Due to the gradient inside the tissue, a pressure somewhat lower than the cuff pressure is exerted on the veins, the true value of this pressure varying with the depth of the vein. One may call the smallest value (in the cross-section through the middle of the cuff, but outside the bones, which will be briefly discussed later) the occluding pressure p_{occ}. This is the relevant value for the occlusion and it must be larger than the venous pressure, so that no vein is left open. The venous drain from the limb is thus suddenly stopped and only the arterial inflow Φ remains, until the distal venous pressure p_{vd} reaches the occluding pressure. When this occurs, the veins under the cuff, one after the other (outwards), open up again. A schematic drawing of the corresponding volume variation with time is given in Figure 2, omitting the superimposed pulsations.

In the first part (after occlusion) of the course of this curve[6], the flow still amounts to the resting value Φ_0 (see Figure 1) and therefore the initial slope[7,8], or derivative with respect to time t, of the volume increase is a measure of the arterial inflow in the undisturbed state:

$$\Phi_0 = \left.\frac{dV}{dt}\right|_{t=0} \qquad (1)$$

In its initial part, the volume increase is thus linear, but as the distal venous pressure grows, the flow is gradually reduced[6] and the increase becomes curved. When the distal venous pressure reaches the occluding pressure, the curvature increases rapidly due to the starting drain, but the net flow soon stabilises again at another almost constant value, much smaller than the resting value. At this part of the volume increase, another linear slope is found, but with a much smaller rate. Here the total volume of the blood vessels remains constant. The increase is explained by the accumulation of extravascular liquid in the tissue due to an increased capillary pressure, which disturbs the equilibrium in the liquid-exchange through the capillary walls, assumed to have existed before the occlusion. This will be further discussed below.

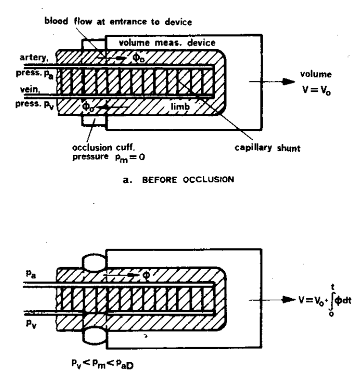

Fig. 1. Schematic representation of venous occlusion plethysmography, a) before and b) after the occlusion (the cuff is inflated at a pressure p_m when $t = O$).

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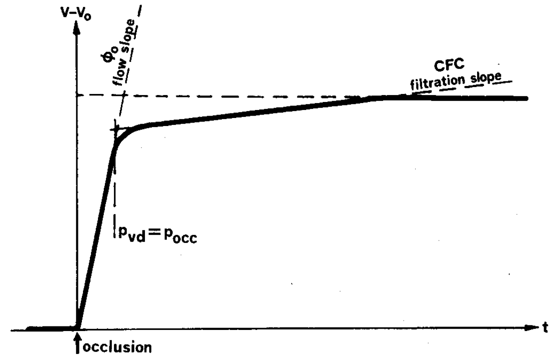

Fig. 2. Basic course of the volume increase after occlusion of the veins (superimposed pulsations are not drawn).

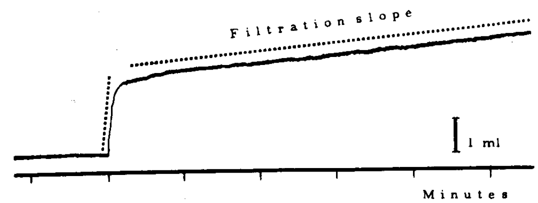

Fig. 3. Course of the volume increase, measured over the foot and calf of a small infant (cf. Fig. 2—the transition to a horizontal asymptote in real cases occurs much later than sketched there).

In this phase, in- and outflows at the entrance to the measuring device are almost equal. The small difference amounts to the net outflow through the capillary walls (φ_{CFC}, see below) and here one has

$$V = V_0 + \int_0^T \Phi\, dt + \int_T^t \varphi_{CFC}\, dt \quad (2)$$

where T is the moment when the veins under the cuff open (actually a midpoint of a small time interval in which they open). At times between the occlusion and this moment, only the first integral in Equation 2 remains, but with t instead of T as the upper limit (see Figure 1).

Eventually, the pressure of the extravascular liquid is so much increased (due to the elasticity of the tissue) that a new equilibrium is reached for the liquid exchange through the capillary walls. Here the volume course reaches a horizontal asymptote.

Figure 3 shows a recording of the volume curve, from the foot and calf of a small infant, on which the two linear slopes of the volume increase can be seen. The time scale is here so much compressed that the pulsations are no longer visible.

Perfusion

The blood flow Φ_0, measured according to Equation 1, is a function of the basic volume V_0 under study. Therefore the measurement is more properly presented as the mean perfusion P of the tissue involved

$$P = \frac{\Phi_0}{V_0} \quad (3)$$

a mean value of the local tissue perfusion, taken over the whole enclosed limb volume V_0. The perfusion is often given in ml/(min, 100 ml).† Normal values in this unit[9] at rest and measured over the foot and calf occur at about 4 for the adult, 7 for the newborn and roughly 15 for the premature infant. A typical perfusion measurement for the newborn infant is shown in Figure 4 and was recorded during exchange transfusion at infusion (A) and withdrawal (B) of blood.

Capillary filtration coefficient (CFC)

The fluid exchange through the capillary wall[10] is probably passive in both directions; active transport, should it occur, is not dominant. Passive exchanges occur through diffusion and filtration. The filtration portion, which causes the second linear slope in the plethysmogram, is of itself the less important. However, as a function of the capillary wall surface, it is an indirect indicator of the local capillary vascularity, and it is to be expected that physiological factors, for example changes in total wall surface, influence filtration and diffusion in similar manners. In addition, filtration studies can give hints on severe capillary lesions, and the correlation between filtration and perfusion can give an indication of the relation between "nutritive" blood flow, through capillaries, and "non-nutritive" blood flow, shunted past the capillaries. The information on capillary filtration, which is available through plethysmography, can therefore be of diagnostic value, even though the diffusion, which is much more difficult to measure, is not known.

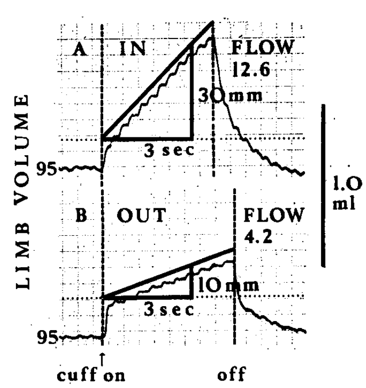

Fig. 4. Example of perfusion measurement on a newborn child at infusion ("IN") and withdrawal ("OUT") of blood during exchange transfusion.

Experimental investigations have shown that about 80% of the pressure increase in the distal veins after occlusion Δp_{vd} is transmitted to the capillaries[10]:

$$\Delta p_{cap} \approx 0.8\, \Delta p_{vd} \quad (4)$$

where Δp_{cap} is the corresponding pressure increase in the capillaries. The pressure increase in the distal veins is, furthermore, approximately given by

$$\Delta p_{vd} \approx p_m - p_v \quad (5)$$

where the difference between the cuff pressure and the true occluding pressure is neglected. With these formulae, one can calculate the capillary filtration coefficient, *CFC*, defined as

$$CFC = \frac{\varphi_{CFC}}{V_0\, \Delta p_{cap}} \quad (6)$$

where

$$\varphi_{CFC} = \frac{dV}{dt}, \quad (7)$$

taken at the second linear slope of the plethysmogram. The approximation through Equation 5 gives a systematic error. Experiments have shown that the *CFC* remains quite constant for different values of the distal venous pressure increase. A better approximation is therefore found[10] if two values φ_{CFC1} and φ_{CFC2} are taken at two different cuff pressures (p_{m1} and p_{m2}). The difference between the corresponding distal venous pressure values is nearly the same as the difference between the two cuff pressures. Therefore one finds, from Equations 4 and 6, as a better approximation:

$$CFC \approx \frac{\varphi_{CFC1} - \varphi_{CFC2}}{0.8\, V_0\, (p_{m1} - p_{m2})} \quad (8)$$

The *CFC* is often given in ml/(min, mm Hg, 100 ml). Normal values in this unit[9] fall at about 0.005 for the adult, 0.01 for the newborn and 0.025 for the premature infant. This demonstrates the higher vascularity ("capillaries per unit volume") of the newborn.

†*The notation ml/100 ml/min (sometimes seen) is unclear since it can mean either (ml/100 ml)/min = ml/(min, 100 ml) or ml/(100 ml/min) = (ml, min)/100 ml!*

Peripheral resistance

The peripheral resistance R is of diagnostic importance for certain purposes. From measurements of blood pressure and perfusion, this resistance can be calculated from the definition

$$R = \frac{\bar{p}_a}{P} \quad (9)$$

where $\bar{p}_a$ is the mean arterial pressure, which can be estimated from the diastolic and systolic values and is approximately the diastolic value plus $\frac{1}{3}$ of the difference[4], but is better measured invasively. Normal values[9] are roughly 23 for the adult, 10 for the newborn and 3 (mm Hg, min, 100 ml)/ml for the premature infant.

Maximal perfusion capacity

For diagnostic purposes the maximal perfusion capacity is of great value. This is the highest value of the perfusion that can be elicited. An approximation is arrived at if the patient is made to perform muscular work with the limb to be studied, if it is warmed up or—probably the best method for this purpose—through reactive hyperaemia as a result of an ischaemic period. If the last method is used, the cuff is inflated to a suprasystolic pressure for, usually, 5 to 10 minutes. The reaction to this interruption of the circulation is a greatly increased perfusion which comes close to the highest possible value. Normal values are about 5 to 10 times higher than at rest.

Volume pulsation

The "resting volume" with an empty cuff is, of course, not constant, but pulsates with the heart beat and at times, one may even find a peripheral variation with the respiration. The volume pulsation may also serve diagnostic purposes, the curve being influenced by the elastic properties of the arterial walls and possible proximal obstructions. The local peripheral resistance should also have some influence on the curve form, especially when a proximal obstruction does exist.

Because of the limited propagation velocity of the pulse wave, there is some loss of detail in the pulse curve if one measures over a longer distance of the limb. This can, for example, lead to the disappearance of the dicrotic notch.

Elasticity of the blood vessels

From studies of pressure-volume relations at varying pressures in the plethysmograph, elastic properties of veins and arteries can be assessed[11,12]. The final value of the distal venous pressure is determined by the occlusion cuff, and the volume in the veins, at the point where the *CFC*-slope begins, depends upon the pressure in the plethysmograph and the elasticity of the venous walls. The pulsations in the volume, measured by the plethysmograph, and in the intra-arterial pressure (measured invasively) are governed by the pressure in the plethysmograph and the elasticity of the arterial walls[11,12].

Through mathematical analysis of the pressure and volume pulsations, based upon a mathematical model of the vascular circuit in the limb, more detailed information on the elastic (compliance) and resistive properties of the arterial part can be obtained[13,14].

Blood pressure

The systolic pressure is easily measured during plethysmography. The cuff is inflated to a suprasystolic pressure and the air then slowly let out again, until the measured volume in the plethysmograph just starts to increase[15,16,17]. This increase is caused by the systolic peaks of the pressure pulsation in the arteries, which now can just pass the "cuff barrier". The diastolic pressure can be determined from a graph, showing perfusion as a function of cuff pressure as a result of a number of measurements. "Knees" on the curve (where it bends towards an upper or lower asymptote) show the diastolic and systolic pressure values, the latter somewhat more accurately than with the above method[16,18].

This procedure with a diagram is a little tedious, but of interest in cases where the Riva - Rocci - Korotkoff method fails, for example in the newborn, if a plethysmographic study is undertaken for other reasons.

Diagnostic applications

One important application is the diagnosis of arteriosclerotic changes in the arteries of the leg. A suitable procedure for this purpose is a study of the perfusion capacity at reactive hyperaemia[19,20,21]. Siggaard-Andersen has determined normal values of perfusion in this state[20], which can be derived from

$$P = 31\left[1 + 10\left(\frac{60}{60+t}\right)^3\right] \quad (10)$$

as a quite good description of the mean values, with a variation of about ±25% initially, increasing up to ±60% after 20 seconds.

This formula has been devised by the present author from the values given by Siggaard-Andersen. The time t is here measured in seconds from the end of an ischaemic period of 5 minutes and the perfusion P in ml/(min, 1). In arteriosclerosis without complete obliteration, the maximal value is significantly smaller, but still occurs at the moment when the flow is released. When an artery is occluded the maximal value is greatly reduced and is also delayed, so that it may occur even one or two minutes later. The starting value of the perfusion, after the ischaemia, may in that case be even lower than at rest. The effect of external pressure during reactive hyperaemia has also been studied[22].

As has already been mentioned, certain changes in the blood vessels and, under some circumstances, data contributing to cardiac diagnosis, can be inferred from studies of the volume pulsation[23-27]. Hitherto, the more usual procedure seems to have been a more or less qualitative judgement of the curve form. A Fourier analysis of the pulse curve, which would then have to be related to the pressure pulse curve, has not yet been tried, as far as the author knows (although the analysis for elastic properties, mentioned above, is related to it[14]). However, such an analysis could quite possibly give more quantitative results for diagnostic purposes.

Attempts are sometimes made to discriminate, by plethysmographic methods, between the perfusion of the muscles and the skin. The best method is probably the measurement of the clearance of a radioactive liquid, injected into muscle and cutaneous tissues[28]. More direct volume-plethysmographic procedures seem, for this purpose, more or less unreliable, or require, at least, the utmost care in the procedure and the choice of the site of measurement which may not always have been observed in the past[29].

Comparative blood pressure measurements by means of a segmental plethysmograph have been applied to the diagnosis of arterial insufficiency in the lower limb[17].

In order to broaden the range of linear increase of volume after occlusion, one may expel the blood from the vessels in the limb part under study, by means of a suprasystolic pressure applied to the part studied for a brief period before the occlusion[30], either in the plethysmographic chamber or with a second cuff. The plethysmographic record then starts with empty veins, in this case a maximal volume is observed after some 10 seconds, whereafter the volume drops to a plateau[30]. This effect is a moderate reactive hyperaemia.

In a few applications, plethysmography has been applied to certain organs, exposed through surgery. One example is the measurement of the perfusion of the testis (surgically exposed at ablation of the testis in cases of cancer of the prostate), with occlusion at the funicle[31]. Another example is the measurement of volume pulsations in a segment of an exposed artery[32].

Volume changes with posture (of the limb) and breathing, measured with a plethysmograph, can give diagnostic in formation on venous disorders[33,34,35]

A technique for ocular plethysmography can provide diagnostic data in carotid artery disease[36].

Part 2 of this paper will be published in the September issue.

Venous occlusion plethysmography

Part 2 : methods

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THE FIRST PART of this review covering the basic principles and applications of venous occlusion plethysmography appeared in the August issue of this journal (*Biomedical Engineering, 10*, 300-302).

Here a brief survey of quantitative and more direct methods will be given. There is also a number of more qualitative or more indirect methods for which the literature is referred to [2,37-40] (for example photoplethysmography[5,26], mechanical force or displacement sensors[23], thermal clearance or clearance of a radioactive liquid[28]). The general references above also give reviews of methods mentioned below.

Displacement methods

In this group of methods a chamber, which encloses the limb to be investigated, is used, together with a liquid or air. The displacement of the fluid is, of course, a direct measure of the limb volume. The technical problems involved mainly concern a suitable transducer for displacement variations and the seal at the entrance to the chamber. The calibration is simple and direct: injection or withdrawal of a known volume of the fluid. If a liquid is used, the most common choice is water.

Liquid plethysmographs

These are the more accurate, as far as the volume measurement itself is concerned, because of the direct connection between the limb volume and the displacement. The influence of temperature, provided the liquid is at body temperature, and of ambient pressure, is minimal. On the other hand, the moisture and the hydrostatic pressure may, under some circumstances, have physiological effects on the limb. But, again, the moisture is "standardised" to 100% (absolute value) and the hydrostatic pressure difference between two points on the limb amounts to only a few centimetres of water if the limb is held in a horizontal position. The mean pressure can easily be selected (zero, negative or positive) by means of the position of the free water surface. The pressure pulsations with volume can be made negligible by using a highly sensitive transducer, requiring only minimal shifts of the liquid level, for the displacement.

This type of plethysmograph is the first choice where the greatest possible accuracy is required, for example in research, the air plethysmograph being the second choice. For diagnostic purposes, however, both are often considered too complicated and other methods are chosen, which are easier to apply, but still sufficiently accurate for the purpose.

The seal is somewhat simpler with the liquid plethysmograph than with the air-filled one. Procedures are given in literature.

Methods for measuring the displacement are:

(1) Mechanical recording through the movement of a piston[4], which controls a pen.

(2) Pressure measurement. The hydrostatic pressure, measured at a fixed level in the water chamber, varies in proportion to the shift of the free water surface, i.e. in proportion to the volume variation if this surface lies in a vertical, cylindrical extension of the chamber. In a variation of this method, essentially a combination of water and air plethysmography, the pressure variations in an air volume, trapped above the water, are measured[41,42,43].

(3) Optical sensing of the position of the free surface in a funnel with a lamp and a photodetector[44] (cf.[39], preface). Earlier methods of this kind used the projection of a liquid column on a moving film.

(4) Conductance measurement[45,46]. If, for example, two vertical wires are mounted in a funnel with the free surface, connected to the chamber, one can measure an electrical conductance which varies in proportion to the volume variation.

(5) Capacitance measurement[32,39,47-50]. The electrical capacitance between two electrodes in a funnel varies linearly with the volume displacement. A useful configuration is a pair of concentric cylindrical electrodes, of which the outer one is grounded and hence functions as a shield as well. If the liquid is water, the inner electrode should have a uniform isolating layer, since otherwise the Q-value of the capacitor is too low. At a frequency of 100 kHz or less, the water in this capacitor then acts as a moving (grounded) electrode and the capacitance is measured over the isolating layer[39]. At a frequency of the order of 100 MHz, the water column can be regarded as a moving dielectric. In the frequency range between those values, a continuous transition from the one state to the other occurs.

At lower frequencies, where the water acts as a moving electrode, a hysteresis is found and therefore a non-linear characteristic[39], as is shown in Figure 5a. The reason is that the contact angle at the isolating layer, caused by the surface tension, is different for an upward and a downward motion. This effect, which disturbs at small shifts, can be reduced if a non-

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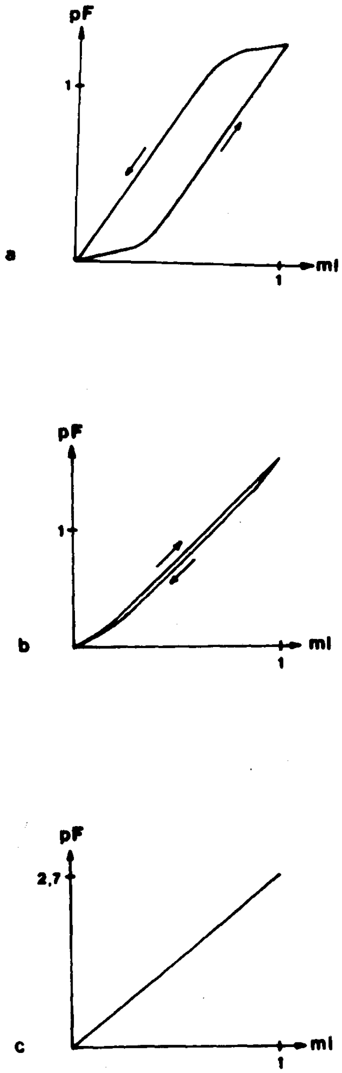

Fig. 5. Influence of surface tension (contact angle) with a capacitive displacement transducers, using (a) only water, (b) water with a "buffer-layer" of 2-octanol and (c) only iso-butanol between the electrodes (the inner electrode has an external diameter of 15 mm, the outer one an internal diameter of 30 mm; in (a) and (b) the inner electrode has an isolating layer of 0·5 mm Plexiglass).

conductive and non-miscible liquid is floating on the water surface as a thin layer, so that the interfacial tension causes a contact angle of the water which is zero or negative. Figure 5b shows the effect on the characteristic of a layer of 2-octanol. As shown in Figure 5c, the hysteresis disappears completely when the liquid is non-conductive throughout the capacitor. In this case an isolating layer on an electrode is no longer needed.

The author has built a plethysmograph of high accuracy for research purposes on this basis[39], in which the liquid in the capacitive transducer is iso-butanol (chosen for its relatively high dielectric constant, while still being quite harmless), separated from the water by means of a slack membrane. The transducer has two cylindrical electrodes of 30 mm inner diameter and 15 mm outer diameter, with an active length of about 40 mm. It was designed for research on the newborn and premature infant, and for this reason a very high sensitivity was needed. For calibration, a 1 ml syringe is mounted in the transducer. In order to exclude the volume pulsations during calibration, it was also fitted with a simple type of stopcock construction, so made that it does not cause a displacement when closing. Figure 6 shows plethysmograms from the feet and calf of a 2½-month-old child with oedematous feet[39], recorded with this transducer, together with the volume pulsations at higher amplification. Figure 7 shows a series of plethysmograms, made with the same equipment during blood exchange transfusions on a newborn baby[51]. The numbers from +45 to −45 show the actual deviation in ml from the initial value of the circulating blood volume (CBV). The measurement of the systolic blood pressure is also shown, as described in the first part of this paper. An amplified recording of the pulsations is also presented, made for heart rate determination.

For more details on this system (which is also equipped with an automatic reset) the literature is referred to[39].

(6) Transmission line arrangement. An interesting transducer for liquid level, based on a transmission line principle, has been developed[52]. It should be useful for plethysmography, although not yet used for this purpose as far as the author knows.

Air plethysmography

This method measures the displacement in air instead of a liquid. This stresses problems with the seal and increases the sensitivity to temperature changes, while making it much easier to apply. With some arrangements, the ambient pressure also has an influence. The displacement is usually measured via pressure [17,36,41-43,53], in which case the volume of the chamber should be constant (or have a constant compliance). A newer and interesting development[13] for air plethysmography uses a pneumotachograph for measuring the in- and outflow of air through a connection to the ambient atmosphere. This gives the derivative of the plethysmogram, a direct flow signal, which can easily be integrated for the volume signal by electronic means.

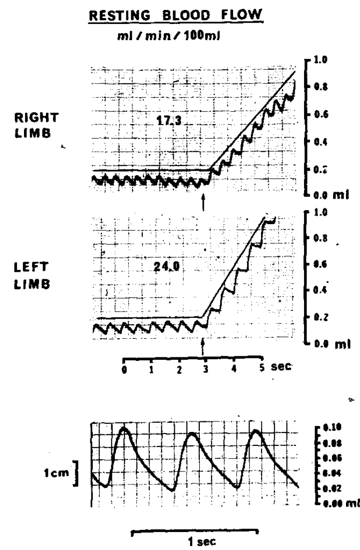

Fig. 6. Plethysmograms from the foot and calf of a 2½-month-old child with oedematous feet. Below: the volume pulsation without venous occlusion in the same child. The perfusion is considerably higher than normal.

Mercury strain gauge plethysmography (Whitney)

This method uses a thin and elastic tubing, filled with mercury, wound around the limb[15,29,54-56]. If a purely radial expansion is assumed, without change in the form of the cross-section area of the limb segment, the variation in the electrical resistance of the mercury channel reflects that of the volume of a (somewhat undefined!) segment of the limb, extending on both sides of the gauge winding. The method is handy and easy to use, but of limited accuracy[29,57]. Nevertheless, careful application can give very good results[58]. For some applications, a temperature compensation can be advantageous[59].

Impedance plethysmography

This method is also called rheography. The electrical impedance of a limb segment varies with its blood content[60,61] (cf. [34]), which has been made use of for venous occlusion plethysmography.[24,25,62]

In 1967-1969 there was an interesting discussion on the validity of this technique[63-65]. Hill, Jansen and Fling[63] argued on the basis of their own experiments and theoretical considerations, that the technique was spurious and the signal measured merely caused by electrode artifacts. Following this, the technique was defended by Kinnen[64,65]. Everybody working with impedance plethysmography would do well to study their publications. Certainly, Hill and his colleagues pointed out some serious defects with many

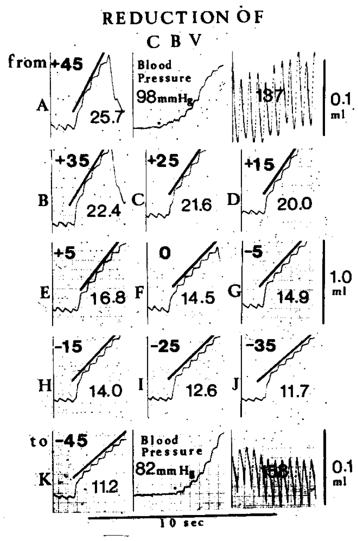

Fig. 7. Plethysmograms during blood exchange transfusion in a newborn child.

systems used, but it does not necessarily follow that impedance plethysmography is impossible. Their studies demonstrate the absolute necessity to use a four-electrode system with a real and active current source (and not an approximate current source made up of a voltage source with a high output impedance). The inner pair of electrodes is used for voltage measurement via an amplifier with a very high input impedance, while the outer electrode pair is connected to the current source. Two- and three-electrode systems do suffer from the faults pointed out by Hill and his colleagues—the voltage measurement must be "floating"!

The experiments of Hill, Jansen and Fling with a liquid-filled silastic ball[63] do not really prove that the signal is merely a strain-gauge effect at the electrode, although seemingly identical to such a signal. Elastic theory shows that the strain in the wall varies linearly with the enclosed volume for variations which are typical in plethysmography, and this is what makes the signals look the same. Furthermore, their experiment with a piece of rubber tubing, in which a liquid was injected without any change of impedance[63], looks very much like a situation where both length and diameter change in such a way that their counteracting effects on the impedance cancel, proving nothing. Even if the equipment is not only carefully designed, but also properly used, serious mistakes can be made with impedance plethysmography.

A point less often considered is that, if the surface of the voltage electrodes is too large, they "attract current lines" and distort the field[66], and that the resistive part of the impedance should be extracted through phase-sensitive detection[66]. In recent years some basic mathematical studies have been published[78-80] which may contribute to further developments of the technique. Several additional applications, besides venous occlusion plethysmography, are given in the literature[67-77].

Electrical field plethysmography

This technique is closely related to impedance plethysmography, but the electrodes are so located that the signal is a measure of the electrical field distortion (caused, for example, by movement or expansion of an internal organ) rather than of impedance change[81].

Capacitance plethysmography (Figar)

This method makes use of the fact that the electrical capacitance between the skin of a limb and a surrounding electrode varies with the volume of the limb[82-87]. Again, a purely radial expansion is assumed and the method is linear and independent of the circumferential distribution of the radial expansion only under certain circumstances[85]. An earlier analysis of the method[86], often referred to, is partly erroneous[85-87].

Photogrammetric plethysmography

A technique, which seems rather tedious, is stereophotogrammetry. This is performed by means of photographing the limb from different directions with a number of stereocameras[88]. The photographs are then evoluated through photogrammetry.

Gravimetric plethysmography

A recent development is a kind of weighing of the limb under study, in that it is suspended at a strain-gauge force transducer[89].

Conclusions

A brief survey of different technical methods for plethysmographic investigations has been given in the latter part of this review. Of the methods mentioned, the mercury strain-gauge and the capacitance techniques appear to be the more suitable ones for general clinical applications, being easier to handle and reasonably accurate when properly designed, whereas the water-filled plethysmograph is the most exact technique and should be the method of choice for research purposes. With the latter method, the capacitance displacement transducer has been proven to be the most reliable one[29], when the problem of the surface tension is solved, preferably by using a non-conductive liquid throughout the capacitor[29]. The transmission-line transducer[52] may, however, be the more promising of the alternatives. Other methods for making a displacement transducer suffer from uncertainties, such as the limited bandwidth of the piston technique and the dependence upon the ion content of the water (altered by transpiration) for the resistive technique, to mention two typical examples.

The impedance technique suffers mainly from the difficulty of a direct calibration and needs utmost care in the design of the instrumentation and caution in the placement of the electrodes and the interpretation of the signals. New light has been cast on the investigations of Hill and his coworkers[63], in favour of the technique.

With the water-filled system using a capacitive displacement transducer, designed by the author[29], it has been shown that a sensitivity of the order of 0.1 ml can be achieved, which allows for research-type investigations on the newborn and the premature infant. With this equipment, several studies have been performed by Dr. Olov Celander and the author. One such study was the investigation of the reactions of the peripheral circulation of the newborn during exchange transfusions[51], which showed it to be considerably more able to compensate for changes in the circulating blood volume than was previously assumed. This equipment proved to be well accepted by the infant, since it could generally be kept more or less asleep during the investigations, being undisturbed by the boot filled with water at body temperature. The inflation generally elicited no reaction from the child. Only occasionally would it move the leg, which, of course, resulted in a level-shift in the recording, easily compensated for by means of an automatic reset facility. Such level shifts occur due to small movements at the entrance to the plethysmographic boot and introduce no more than a negligible error (a very small change in the basic volume under study) in the perfusion measurement. It was observed that placement of occlusion cuff just above the knee was better than between the knee and the boot, resulting in smaller artifacts, due to the shift of tissue towards the boot as a result of its compression (this shows as an initial jump in the recording, which does not disturb the following plethysmogram if it does not jump off the paper). Typical examples of registrations are given in the illustrations.

As a general remark, it may be pointed out that the bone is a certain source of error in plethysmography, since the veins in it do not compress and therefore allow for a certain drain past the occluding cuff to an extent which seems not to have been investigated but should be negligible. Some investigators prefer segmental plethysmography. In this situation it is important to keep the limb horizontal; otherwise the lower, distal part fills earlier than the segment under study, because of gravity effects (this can be shown with two mercury strain-gauges at different heights). Some advocate the exclusion of the distal circulation by means of a second cuff, distal to the segment, which is inflated to a suprasystolic pressure. It is, however, to be expected that, with such an arrangement, the ischaemia in the distal part will cause reactions in the segment under study.

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A correction has been introduced in the formula (10) in Part 1
Addresses mentioned are no more valid