

Lymph Stasis: Pathophysiology, Diagnosis and Treatment

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VOLUMETRY OF LIMBS

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I. INTRODUCTION

The two most important and conspicuous signs of lymphedema are the increase in volume and the tense consistency of subcutaneous tissue.

The amount of interstitial fluid may increase 50 to 100% before edema is evident. Studies by Göltner et al.¹ using precise equipment state that an edema exists when the arm has increased by 150 ml. This is hardly detectable clinically but means that the volume of the interstitial fluid (mainly in the subcutis) has increased by 40 to 50%. The increase of size, which can be measured by volumetry, reflects to some degree the patients complaints such as the feeling of heaviness, impaired function because of the weight, difficulties with shoes and clothing, and ill-looking appearance.

The increased density of the soft tissue is felt by the patient like tightness of the skin and stiffness. This sign is easily detected by palpation and by the sign of Stemmer: the skin on the dorsum of the first phalanx of the fingers and toes does not fold when pinched. The positive sign is due to increased interstitial fluid and later fibrosis. It is detectable before any apparent increase in volume.

The clinical experience that the feeling of increased interstitial pressure precedes the increase in size and that the course of a successful treatment starts with a loosening of the tissue rather than reduction of volume, suggests that the properties of the interstitium enable some "storing" of fluid before clinically detectable changes of size. Various tissues or parts of a limb have different compliances. An increase of the interstitial fluid in a compartment of relatively small compliance changes the interstitial pressure rapidly and might thus easily give rise to this early feeling of density. The interstitial pressure can be measured by invasive methods, i.e., "wick-in-needle".^{2,3} This can be used for scientific purposes but is not suitable for routine examinations. Later (see Section III) a tonometer is described which might be of some value in quantifying the compliance or tonicity of the skin and subcutaneous tissue.

The result of treatment for lymphedema is always best when started at an early stage. The group of patients especially at risk have gone through axillar or inguinal lymph node excision and radiation. An exact and easy method of measuring the volume in these patient groups could thus be useful in picking out the patients who are at the beginning of a lymphedema formation. Moreover, quick and easy volumetric measures would give a good objective recording of the course of the disease, result of treatment, and the degree of disability.

Volumetric measurements have been done for more than 150 years and have been called plethysmography. The purpose has been to measure the change of volume, which is related to blood flow; these measurements are used for studies of circulation. The measurement of the absolute volume is of interest in the present context. The term volumetry will be used for this type of measurement.

Plethysmography is still an important method in studying circulation, particularly the venous return (obstructional venous plethysmography). The method has gone through extensive development regarding techniques (such as impedance plethysmography and "mercury in rubber" method) and target organ (finger, hand, foot, and skin). Even if this technique could be used for measuring the absolute volume of a limb, it has seldom been in the focus of interest.

Lymph stasis means a disturbance of fluid circulation and information on blood flow; in particular the venous return is important in lymphedema. A precise volumetric measurement which can be done and repeated quickly can express the change of volume per unit of time and thus serve as a plethysmographic recording.

The volume of normal extremities shows diurnal variations within certain limits, as well as side differences. Eccles⁴ shows a variation of 17 ml in a hand of a mean size of 340 ml over 5 d (water displacement method). The hand increases with heat and exercise, and

shrinks in an elevated position. The right hand is 10 to 20 ml larger than the left in right-handed persons. Likewise the dominant arm seems to be 50 to 60 ml larger than the nondominant one.⁵

Swedborg⁶ demonstrates a biological fluctuation over a fortnight of 100.5 ml in ten normal women with a mean arm volume of 2058 ml (water displacement). The maximal fluctuation of 195 ml occurred in an arm with a mean size of 1500 ml. Using an optoelectronic device, Göltner et al.⁷ could not demonstrate more than an average fluctuation of 4 ml in 100 arms and 6 ml in 100 legs of 50 women measured regularly at the same time of the day throughout 10 d. Nilsson⁸ measured the feet and ankles of 100 persons (water displacement). He found a mean volume of 1297 ml and showed a daily and hourly change of 18.2 ml (SD \pm 4.6 ml) over a 5-d period. He also found a larger right leg of 21.5 ml (SD \pm 26.1 ml). Even the left-handed patient showed a larger right leg, but to a lesser degree.

These normal variations should be taken into account when measuring lymphedematous extremities. As the daily variation seems to be bilateral, it is always judicious to compare the volumetric findings of the edematous limb to the sound side when possible at the same time of the day and to consider the dominant side slightly larger than the nondominant.

An ideal volumetric measure in lymphedema should comprise a quick, noninvasive, hygienic, accurate, easy, and bedside method which includes any portion of a limb. As the lymphedema often shows an uneven distribution throughout the limb, a desirable aim is information on the shape of the extremity.

II. VOLUMETRY

Various methods are available for measuring the volume of the extremities.

A. DISPLACEMENT OF WATER

The device consists of a vessel of suitable size. Water of ambient temperature is filled to overflow through a faucet. The extremity is submerged in the water to a defined point, and the displaced water is measured or weighed (see Figure 1). To ensure that a proper part of the arm is submerged, the fingers have to be stopped at the proper distance from the bottom of the vessel. This is done either by use of plates of known thickness put at the bottom of the vessel or by an adjustable plate that can be moved to a known distance from the bottom. The middle finger stops at the plate.⁶ Interdigital stops are also used.⁵ The arm and hand should be kept in the same position at each measure, preferably stretched.

No apparatus of this kind is found for the whole leg. Using the apparatus for the leg below the knee, the patient sits with the sole in contact with the bottom of the vessel, or a plate for the correct distance. To ensure the same position the heel and the calf are held in contact with the rear wall of the vessel.⁸ The method has been extensively used for arm and foot/calf. A standard deviation of approximately 25 ml for repeated measures of the arms has been documented by Swedborg.⁶

The method is cumbersome, especially for measurements of the total leg. It can not be performed in patients with skin lesions, and there are hygienic problems. Slopping of water is usual. It might be difficult to define the submersion mark and for the patient to find the same position each time. The method is usually applied to a certain part of the limb, and will not give information of the shape of the extremity and localization of the edema. It is possible to immerse the extremity gradually, thus stepwise measuring the volume, for example, of the hand, then of the forearm, and finally the overarm.⁵ Problems with submersion marks with this procedure are obvious.

A horizontal adjustment of the apparatus at each observation is necessary. Sufficient time for the overflow to drain is equally important, and it might be difficult for the patient to be still long enough.

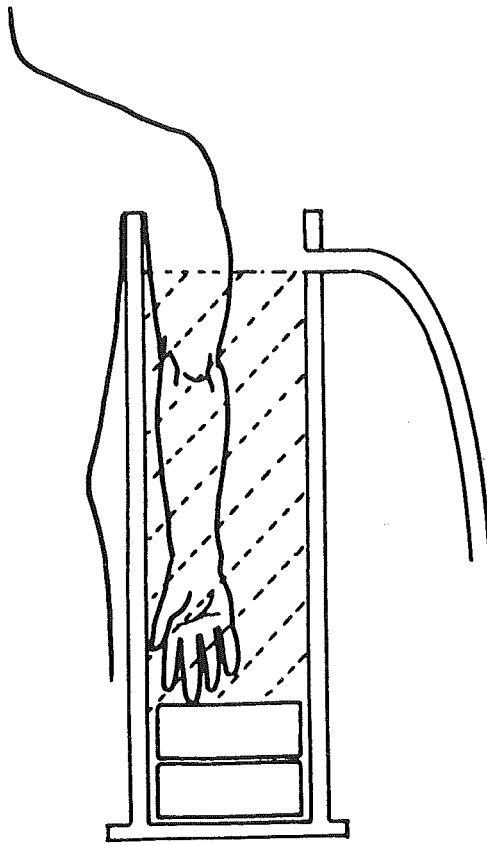


FIGURE 1. Apparatus for water displacement in volumetry. Plates or blocks are put in the bottom of the vessel to ensure the degree of submersion. The vessel is filled with water of ambient temperature until overflow occurs. When dropping from the faucet stops, the extremity is submerged until the fingertip of the third finger or foot reaches blocks or plates. The displaced water is measured or weighed. (From Swedborg, I., *Scand. J. Rehab. Med.*, 9, 131, 1977. With permission.)

B. CALCULATIONS FROM CIRCUMFERENCE MEASUREMENTS

Kuhnke⁹ has described a method to compute the volume by means of sequential measurements of circumference. He makes an assumption of circular circumference, taking a measurement every 4 cm. He has worked out three models, regarding the 4-cm measurements as slices of cylinders, of cones, and of spheres. The formula for the cylindrical slices is

$$V = \frac{1}{\pi} \left[\sum_{i=1}^n (U_i)^2 - \frac{1}{2} (U_1^2 + U_n^2) \right] \quad (1)$$

V is the volume, $\sum_{i=1}^n (U_i)^2$ is the sum of the squares of all observations at 4-cm distance. $\frac{1}{2}(U_1^2 + U_n^2)$ is a correction for the first and last measurement (slice) (see Figure 2). The three models give a fairly accurate volume and shape of the limb. For the sake of simplicity the slice model is most used.

The calculations assume a circular circumference, which seldom is true. Thus, there

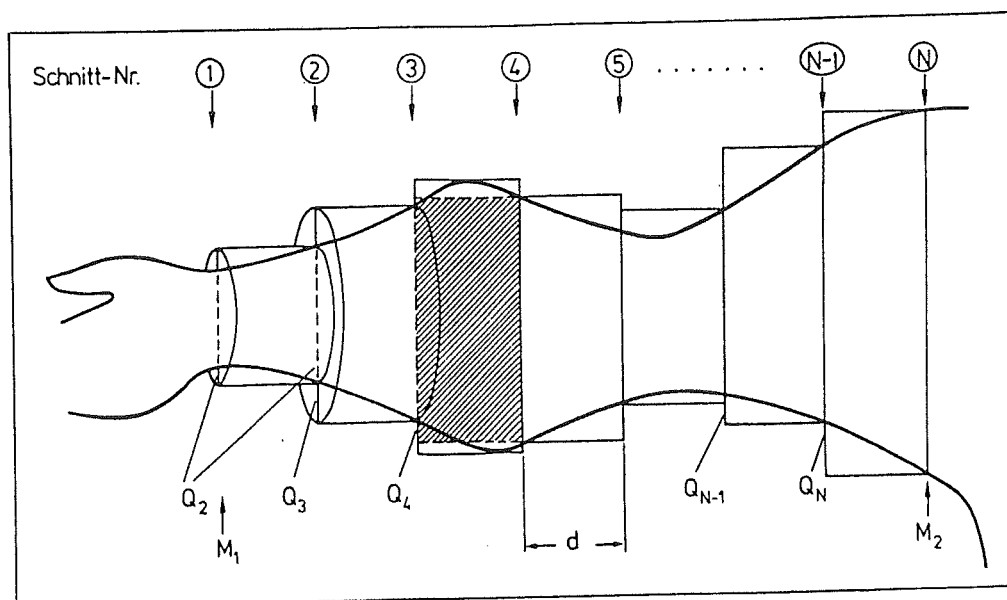


FIGURE 2. Model for calculation of volume by circumferential measurements. $N - 1$ denotes measurement of cross sections of slices (Q) with a thickness of $d = 4$ cm. The hatched section indicates the discrepancy with the true volume. (From Fischbach, J. U. et al., *Phlebot. Proctol.*, 15, 184, 1986. With permission.)

exists a methodological error giving a slightly larger volume (4%) than the true value.¹⁰ This is in accordance with other works.^{4,11} Strandén¹¹ found a high correlation ($r = 0.98$) between the water displacement method and girth measurement. The main source of error lies probably in taking the 30 to 40 measurements, not in the model itself.

The method is time-consuming and requires experience. It can hardly be performed when skin damage is present. The handling of the extremity and close contact to the equipment might raise hygienic problems.

The method is designed for the arm or leg without hand or foot. For the foot Katch et al.¹² give a calculation based on an ideal wedge shape:

$$V_{\text{foot}} = \frac{1}{2} \left(l \cdot \frac{c}{\pi} \cdot h \right) \quad (2)$$

Where l is the length of the foot, c is the ankle circumference (c/π is then the foot breadth), and h is the foot height from the sole to c . In this way the total leg can be calculated.

C. COMPUTER-ASSISTED TOMOGRAPHY

The computer calculates and sums up the volume of consecutive sections of the limb. The slice interval and entire distance to be measured can be preset. The accuracy of the calculations depends on slice thickness, delineating ability (the contrast between the skin and the air), and resolution properties of the equipment (size and number of pixels). The method gives an impression of the shape of the extremity and size and form of different tissues in the limb, such as subcutis, muscle, and bone, which might be of interest. The method is too resource consuming for routine determination of the volume, and exposes the patients to radiation. The method should not be used for routine measurement of volume, but can be valuable for diagnostic purposes. Nuclear magnetic resonance (NMR) also can be used without any hazard of radiation but is even more expensive.

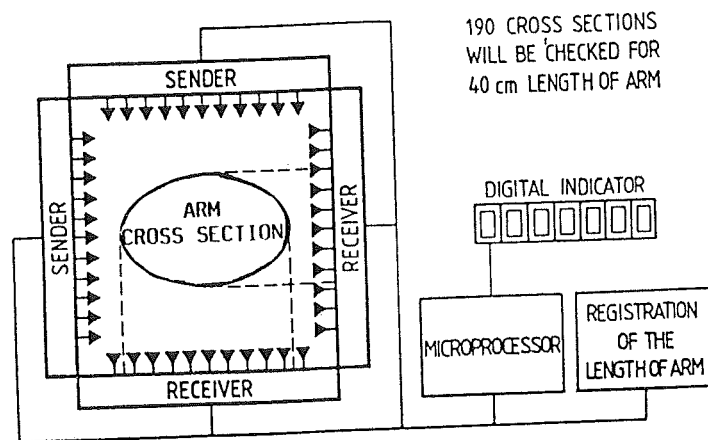


FIGURE 3. The principle of the optoelectronic volumetry. The frame with 360 light sources and sensors can be moved along the axis of the limb. The computer records the distance from a preset starting point and calculates the transections every 3 mm and finally the volume up to the point where the frame stops. (From Fischbach, J. U. et al., *Phlebol. Proctol.*, 15, 184, 1986. With permission.)

D. OPTOELECTRONIC METHODS

In recent years an optoelectronic device has been developed to meet the requirements of a quick, hygienic, and accurate method for volumetric calculation. This equipment works similar to computer-assisted tomography, but makes use of light instead of X-ray. A frame of 46×46 cm with light sources on two sides and corresponding sensors on the opposite side can be moved along the extremity. Numerous rectilinear light beams are thrown perpendicular to the axis and sequentially along the limb. The sensors that lie in the shadow of the extremity are not lit and make the calculation of the transection possible. This is done every 3 mm and is eventually summed up to the volume by the computer¹⁰ (see Figures 3 and 4). A similar device using videotape has also been made.¹³

The optoelectronic method is very accurate with a standard deviation of 8.9 ml (arm) and 16.8 ml (leg), less than 0.5% of the volume of the limb with repeated placing of the extremity in the apparatus. The equipment meets all requirements for a practical volumeter. The volume and transection of any part of the extremity can be calculated, and the shape can be displayed. The accuracy is adequate for calculation of change in volume within seconds; thus, the equipment is useful for circulatory studies such as venous obstruction plethysmography.¹³

The frame carrying the light sources and sensors is large and can hardly give any limitation for volumetry of the limbs. There are some difficulties at the end of the extremity (especially the foot). The form of the foot or hand is not ideal for this measurement. If the entire extension of the limb is wanted, the support is included in the calculation, but can be adjusted for. Compared to the first two methods mentioned in this section, the price is high, but it is expected to fall as the technology develops.

III. TONOMETRY

The tension of the skin and subcutis can be estimated by palpation and compared to normal parts of the body, preferably the symmetrical counterpart. In an attempt to objectively measure this tension, Clodius and Antoniazzi¹⁴ have constructed a tonometer. It consists of a metal plate which is placed horizontally on the skin (volar aspect of forearm or calf). The plate is provided with a central hole through which plunges a circular ball with a diameter of 10 mm (see Figure 5). The plunger can be charged with weights of 70, 140, and 210 g.

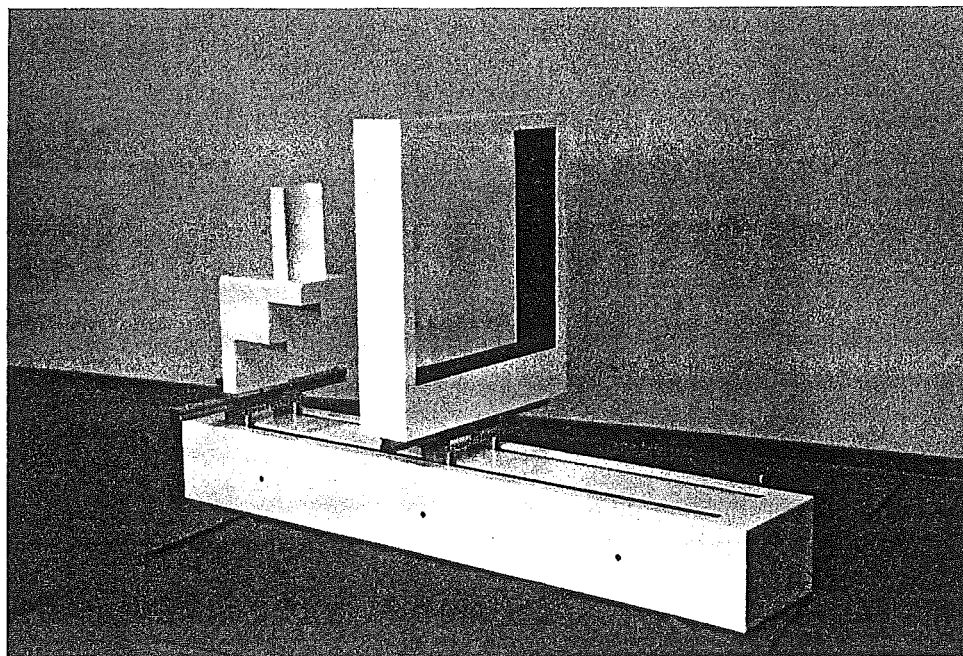


FIGURE 4. Optoelectronic volumeter, "Perometer", of professor Fischbach. (Courtesy of Professor J. U. Fischbach, Wuppertal).

The depth that the plunger sinks into the skin and subcutis can be recorded in centesimal fractions of a millimeter.

The apparatus measures the compressibility of the superficial tissue. This consists of several properties such as the amount of fibrous tissue, thickness of the fat layer, and hardness of muscles and also reflects to some degree the interstitial pressure. Any comparison between tonometry and measurement of interstitial fluid pressure (e.g., wick-in-needle method) has not been performed. Measurements compared to the normal side correlate well with palpation. It can hardly give much more than palpation does, but turns a subjective examination into an objective recording. Thus, it is most useful in repeated examinations for describing the course of the disease or effect of treatment. The method gives a fairly good impression of the laxity of subcutaneous tissue that regularly takes place early in the treatment, justifying its use in the follow-up of lymphedemic patients.

The disadvantage is that you do not exactly know what you measure. The compressibility of the tissue does not necessarily correlate with the interstitial pressure, neither interpersonally nor from time to time in the same patient. The device has to be placed on a horizontal surface of the body; it takes some time for the plunger to find the point of equilibrium; and being a bit top heavy it has a tendency to tilt when left alone. A brief support is necessary when charged with 210 g, and this might disturb the recording. Because of the size of the device, only plane body surfaces of some extension and without bony prominences can be measured, which limits the use.

As far the author knows, nobody has ever tried to quantify the sign of Stemmer: the displacement ability of the skin. Similar to the tonometer this gives an impression of the compliance of the skin, and thus the interstitial pressure. There should be a relatively easy task to determine, for a fixed point, the distance another point of the skin can be moved and the force needed. Until further methods are found, palpation and tonometry may suffice.

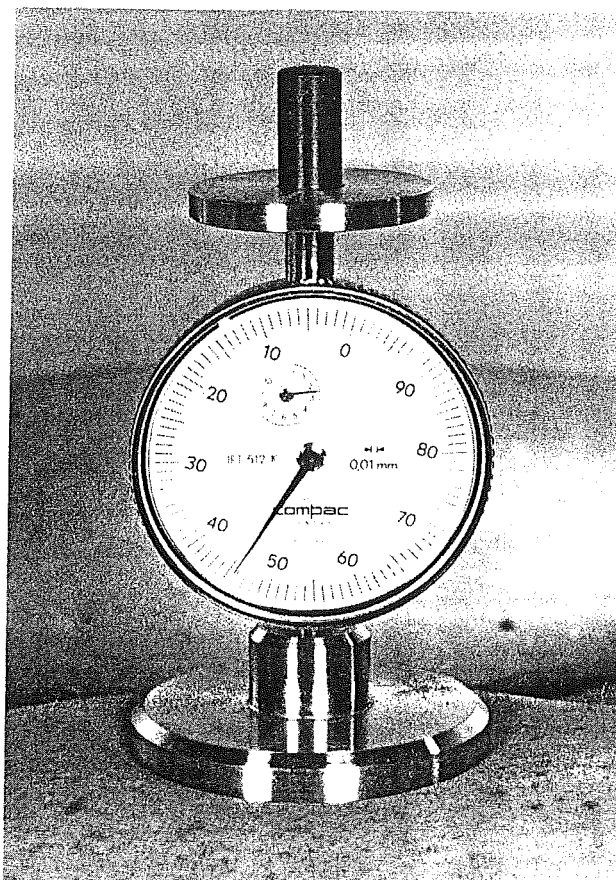


FIGURE 5. Tonometer after Clodius and Antoniazzi. The tonometer is placed on the calf of a healthy woman and charged with 70 g. The plunger is sunk 3.45 mm in the soft tissue. Two additional weights, each of 70 g, can be applied.

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