PROCEEDINGS OF THE SOCIETY FOR EXPERIMENTAL BIOLOGY AND MEDICINE **154**, 164-167 (1977)

Transmission of Applied Pressure Through Tissues: Interstitial Fluid Pressure, Solid Tissue Pressure, and Total Tissue Pressure (39628)

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When pressure is applied to an area of the skin, the pressure is transmitted through the skin and underlying tissue to structures such as the walls of blood vessels, bone, etc. The effects of applied pressure have been experimentally and theoretically examined as evidenced by the extensive literature discussing the effects of applied pressure on pressure distribution, blood volume shifts, and blood flow rate (cf. 1). However, the effects of external pressure on interstitial fluid pressure and solid tissue pressure in relation to total tissue pressure have not been experimentally examined and only preliminary theoretical effects have been considered (2, 3). In fact, there has been a good deal of confusion because of the failure to distinguish between interstitial fluid pressure and total tissue pressure as evidenced by the fact that the term "tissue pressure" has been used as if only one component of pressure existed in the tissues (cf. 1). The present report uses plethysmography to study the effects of changes in ambient pressure on interstitial fluid pressure, solid tissue pressure, and total tissue pressure in the subcutaneous tissue of the dog hindleg.

Materials and methods. Interstitial fluid pressure (P_{if}) of the dog was measured from capsules implanted in subcutaneous tissue of the upper and lower hindleg 4 to 8 weeks prior to use. (The capsules were a disk-shaped hollow (6 mm x 9 mm i.d.) porous polyethylene matrix (Bolab, Inc.) with an average pore size of 65 μm.) Total tissue pressure (P_{tot}) was measured either with small flaccid balloons inserted subcutaneously or, more frequently, by the needle method for measuring total tissue pressure (see (3) for a discussion of these methods).

Pressure transmission was examined in two different preparations. With the first, the intact hindleg of the pentobarbital anesthetized dog was placed up to the hip in a water filled plethysmograph and P_{if} and P_{tot} measured while applying positive or negative pressure to the leg. With the second preparation, the hindlimb was totally isolated from the dog and artificially perfused with whole blood as described elsewhere (4). The isolated hindlimb was then placed entirely inside the plethysmograph with only the arterial, venous, and pressure measurement catheters extending out of the plethysmograph.

Using the intact hindlimb preparation, the response of interstitial fluid pressure to alterations in ambient pressures was determined as P_{if} was increased above its normal value in the intact hindleg. In order to increase P_{if}, warmed Tyrode's solution was infused intravenously. When P_{if} approached or exceeded atmospheric pressure and the infusion was terminated, P_{if} at first decreased with time as if the tissues were undergoing stress-relaxation. Therefore, measurements were made about 0.5 hr after the infusion of Tyrode's solution when P_{if} appeared to have reached a steady value.

With changes in applied pressure, a small amount of fluid (less than 1 μl) is displaced into or out of the pressure transducer. This fluid shift affected the measured value of P_{if} only during the first several seconds after a pressure change since injection or withdrawal of 1 μl from the capsule was followed by reequilibration in approximately one minute. Therefore, values of P_{if} were taken when P_{if} had appeared to reach a plateau, or about 0.5 to 1.5 min after the pressure change.

Results. *Pressure transmission in intact hindleg with normal hydration.* When pressure in the plethysmograph was varied, total tissue pressure in the subcutaneous spaces of the intact hindleg as measured with both the needle and balloon methods changed by exactly the amount of the change in applied pressure, as expected from a simple mechanical point of view and as would be predicted from the relative accuracy of the auscultatory method for determining blood pressure. However, in the intact leg, interstitial fluid pressure, as measured by the capsule, changed by an average of 71% of the applied pressure when P_{if} was in its normal negative pressure range, irrespective of whether the applied pressure was positive or negative. As illustrated in Fig. 1, with zero pressure in the plethysmograph, total tissue pressure (i.e., the plateau in needle pressure) was +1 mm Hg while P_{if} was −6 mm Hg. Decreasing external pressure on the leg by 10 mm Hg caused total tissue pressure to fall 10 mm Hg while P_{if} fell only 7 mm Hg. These changes were reversed by returning external pressure to zero. When positive pressure was applied to the leg, opposite pressure changes occurred.

Pressure transmission as a function of hydration in the intact hindleg. The effect of varying the state of hydration of the tissue on pressure transmission was examined in the subcutaneous tissues of 9 dogs. Following control measurements, warm Tyrode's solution was infused intravenously. As P_{if} (with zero external pressure) increased, the percentage change in interstitial fluid pressure (in relation to applied pressure) increased in every animal. When P_{if} exceeded +2 mm Hg, P_{if} changed by 100% of the applied pressure as seen in Fig. 2. At these elevated P_{if} levels, P_{if} was equal to P_{tot}.

Effect of blood volume shifts on P_{if} changes during pressure transmission in the isolated leg. In another series of experiments, the totally isolated hindlimb was placed entirely inside a water-filled plethysmograph, with only catheters from the artery, the vein, the capsule, and the needle extending from the plethysmograph. With the arterial and venous catheters occluded so that no change in vascular volume could occur, P_{if} always changed by 100% of the applied pressure, irrespective of whether P_{if} was positive or negative. With the femoral catheters open so that blood could shift into or out of the leg, P_{if} changed by an average (n = 4) of 92% of the applied pressure when P_{if} (with no external pressure) averaged −2.6 mm Hg.

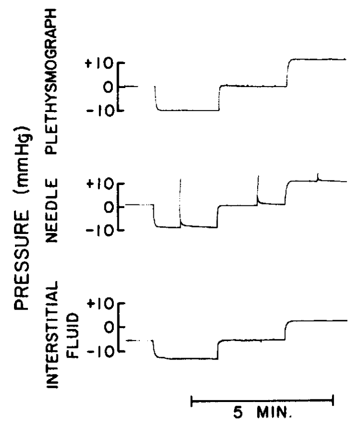

FIG. 1. Examples of the effects of altered external pressure on total tissue pressure (needle pressure) and interstitial fluid pressure.

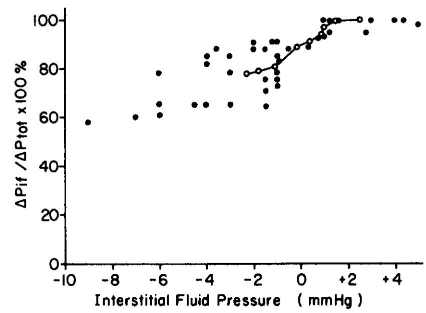

FIG. 2. Summary of pressure transmission to the interstitial fluid (ΔP_{if}) when pressure was applied to the limb surface (ΔP_{tot}) as a function of state of tissue hydration as indicated by interstitial fluid pressure (P_{if}). The solid line connects data from one animal showing the changes in interstitial fluid pressure response (ΔP_{if}) to applied pressure (ΔP_{tot}).

Discussion. This study shows that the interstitial fluid pressure in normally hydrated subcutaneous changes by only 70% of the pressure applied to the skin while total tissue pressure changes by 100% of the applied pressure. In order to interpret these results, it is necessary to familiarize the reader with the current concepts of interstitial structure and to discuss the interrelationships between fluid pressure, solid, pressure, and total pressure in the interstitial spaces.

The interstitium is the extravascular space in tissues that lies between the cells. Its structure is heterogeneous, being composed of fluid elements and nonfluid elements (collagen, elastin, cell membranes, etc.) (5). Both the fluid and nonfluid elements are independently capable of generating and transmitting pressure. These pressures, i.e., interstitial fluid pressure and solid tissue pressure (P_s) sum to produce total tissue pressure (2, 3):

$$P_{tot} = A_{if}\, P_{if} + A_s\, P_s,$$

where A is the fraction of the cross-sectional area of the interstitium occupied by fluid (A_{if}) and nonfluid elements (A_s). The value of total tissue pressure in subcutaneous tissue is determined by the sum of (i) the pressure due to radial tension of the skin and (ii) any external pressure. Total tissue pressure is exactly balanced by the sum of fluid and solid pressures in the interstitium. Obviously, total tissue pressure is responsible for such phenomena as blood vessel compression, while the interstitial fluid pressure participates in regulation of trnascapillary fluid movements.

It may be assumed that the fractional areas, A_{if} and A_s, do not change with an applied pressure. The change in pressure is then given as:

$$\Delta P_{tot} = A_{if}\, \Delta P_{if} + A_s\, \Delta A_s.$$

Since (i) A_{if} and A_s must sum to unity, (ii) both the fluid and nonfluid elements are relatively incompressible, and (iii) neither ΔP_{if} nor ΔP_s can be greater than ΔP_{tot} if A_s and A_{if} do no change, the solution to the above equation is $\Delta P_{tot} = \Delta P_s = \Delta P_{if}$ if the areas do not change. Thus, interstitial fluid pressure as well as solid tissue pressure should change by an amount equivalent to the applied pressure, regardless of the state of hydration. This was found to be true when blood volume shifts were prevented. In the leg where blood volume shifts occurred, P_{if} changed by less than 100% of the variation in ambient pressure in normally hydrated limbs. It appears that this reduced response may be due to a local tissue distortion which allows A_s and A_{if} to change so that the amount of pressure carried by the solid elements was increased. For example, consider the effects of applying a pressure of 10 mm Hg to the skin—that is, $\Delta P_{tot} = 10$ mm Hg. If A_{if} had a constant value of 0.9, then 9 mm Hg of the applied pressure would be carried by the fluid element and 1 mm Hg pressure would be carried by the solid elements. However, the change in fluid pressure would be equal to the change in solid pressure, or $\Delta P_{if} = \Delta P_s = 10$ mm Hg. On the other hand, in normal tissues (in which blood volume shifts could occur), the data of this study show that ΔP_{if} would normally be about 7 mm Hg when ΔP_{tot} is 10 mm Hg. Therefore, ΔP_s must be greater than 10 mm Hg and A_s must also have increased.

In overhydrated tissues where P_{if} was equal to P_{tot}, ΔP_{if} was found always to equal ΔP_{tot}, presumably because of separation of the solid elements with fluid to such an extent that they no longer make continuous contact so that A_s equaled zero (3).

As yet, there is no way to determine the functional values of A_s and A_{if}. Because of the lack of experimental determination of these fractional areas, it has been convenient to "surface average" the values of interstitial fluid pressure and solid tissue pressure (3) so that total tissue pressure is expressed as

$$P_{tot} = \bar{P}_s + \bar{P}_{if},$$

with the bar meaning surface averaged. Also, since A_{if} is thought to be close to unity (3), the surface averaged interstitial fluid pressure may be approximately equal to the real value of interstitial fluid pressure so that

$$\bar{P}_s = P_{tot} - P_{if}.$$

This surface averaging and the assumption that A_{if} is close to unity is necessary in order to allow the functional values to $\bar{P}$s to be determined. The mean values of $\bar{P}_s$ of this

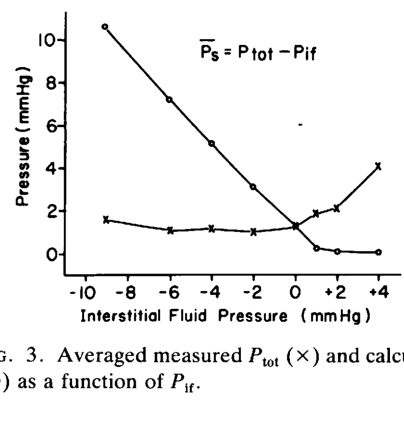

FIG. 3. Averaged measured P_{tot} (×) and calculated $\bar{P}_s$ (○) as a function of P_{if}.

study are shown in Fig. 3 as a function of P_{if}. Note that P_{tot} changed very little when P_{if} was increased until P_{if} was almost equal to total tissue pressure.

We appreciate the support of NIH Grant HL 11678, the comments and suggestions of Dr. Aubrey Taylor, Dr. Roger Norman, and Dr. Neil Granger, and the excellent secretarial assistance of Mrs. Billie Howard.

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Received May 27, 1976. P.S.E.B.M. 1977, Vol. 154.