TRANSCAPILLARY FLUID MOVEMENT IN HUMAN CALF AFTER WATER DRINKING

Ichiro Matsubara and Kojiro Matsuda

Department of Physiology, Faculty of Medicine, University of Tokyo, Hongo, Bunkyo-ku, Tokyo

The transcapillary fluid movement, induced by drinking a large amount of water, is known to lead to an increase in the extravascular fluid volume of tissues such as the muscle and the skin. The mechanism underlying this phenomenon, however, is poorly understood. The purpose of the present study was to know the nature and strength of the driving force which operates in such a fluid movement. The rate of capillary filtration was measured in the human calf by means of a pressure plethysmograph and the capillary filtration coefficient (CFC) and the effective filtration pressure were estimated.

METHODS

The experiments were performed on two young healthy men (age of 21 and 22) in the postabsorptive state. The subject laid himself in semireclining position and the right calf was placed in a water-filled plethysmograph, the upper edge of which was held at the heart level of the subject throughout the experiments. The room temperature was kept at 22±2°C and care was taken to keep the subject comfortable.

Fig. 1 illustrates diagrammatically the pressure plethysmograph employed in the present experiments. The lucite glass cylinder (16 cm inside diameter×15 cm) of plethysmograph had a double wall in order to maintain the water temperature around the calf at 35±1°C by perfusing warm water through the space between the walls. The calf was enveloped by a loose sleeve of rubber, 0.2 mm thick. After setting the plethysmograph onto the right calf, both ends of the rubber sleeve were everted and fixed to the ends of the cylinder. Each end of the cylinder was then closed by a rubber diaphragm (8 mm thick) and a "duralmin" plate (2 mm thick), both of which had openings fitted to the subject's calf in order to prevent the rubber sleeve from escaping out of the cylinder when the inside pressure was raised.

A level meter was connected with the plethysmograph to read volume changes of the enclosed part of the calf. The level meter was moved vertically to keep the meniscus always at the level of the upper edge of the plethysmograph. Otherwise, the hydrostatic pressure, developed by the vertical displacement of the meniscus due to the change in calf volume, would have affected the pressure in the plethysmograph. The level meter measured changes in the calf volume up to 200 ml with the sensitivity of 0.5 ml. A platinum wire was placed in parallel with the mercury column of the
Fig. 1. Schematic diagram of a pressure plethysmograph applied to the human calf. Arrows indicate inlet and outlet of warm water circulating around the inner cylinder of plethysmograph. For details see text.

level meter at a distance of 1 cm (Fig. 2). As the water volume in the level meter increased from 0 to 200 ml, electric capacitance between the mercury column and the platinum wire increased linearly from 30 to 150 pF. The change in electric capacitance was recorded with a pen writing oscillograph utilizing the frequency modulation. This method made it possible to record changes in the calf volume continuously under the pressure applied. In parallel with the electrical recording, the meniscus level was directly read on the scale every 30 sec.

The pressure of 160 mmHg (30–40 mmHg higher than the maximum arterial pressure of the two subjects) was applied to the plethysmograph from the pressure reservoir 1 (Fig. 1) to collapse the blood vessels and to squeeze out blood from the enclosed part of the calf. At the end of 2-min period of compression, the calf volume was read directly on the scale of the level meter. In the present report, this volume is referred to as “reduced calf volume” in the same sense as the “reduced arm volume” proposed by Krogh, Landis, and Turner. Immediately after determination of the reduced calf volume, the pressure was released.
Prior to the drinking of water or 0.9% saline, successive measurements of the reduced calf volume were carried out at 4-min intervals. The reduced calf volume gradually decreased. After three to four measurements, however, the decrease in each measurement became less than 1.5 ml. Then the subject was made to drink quickly warm (38°C) water or saline amounting 1% of the body weight. Thirteen minutes after the drinking, the pressure of 160 mmHg was applied for 2 min onto the calf and the reduced calf volume was determined with an accuracy of ±0.25 ml. Exactly same procedure was repeated 15 min later and the increase in the reduced calf volume in the 15-min period was recorded. In control experiments with the same procedure as above except drinking, the reduced calf volume was found to decrease less than 1.5 ml. This decrease, which was due merely to the compression applied for determining the reduced calf volume, was added to the above increase in reduced calf volume in order to obtain the actual amount of filtration during the test period of 15 min, 15–30 min after drinking. This kind of correction was first adopted by Brown, Wise, and Wheeler.

The capillary filtration coefficient (CFC) was also determined by the pressure plethysmograph. During the test period of 15 min, venous congestion was produced by inflating a pneumatic cuff (Fig. 1) applied around the thigh just above the knee. By means of the pressure reservoir 2 (Fig. 1), the cuff was inflated and the pressure in

---

**Fig. 2.** Level-meter designed for pressure plethysmography. Changes in calf volume can be recorded continuously under various applied pressures. For details see text.
The cuff was kept constant. The reduced calf volume was measured before and immediately after the venous congestion. The increase in reduced calf volume gave the amount of capillary filtration, which was facilitated by the increase in capillary hydrostatic pressure due to the venous congestion. The rate of filtration was thus calculated in ml per min per 100 ml of calf tissue. Such determinations of the rate of filtration were carried out with congestion pressures of 30, 40, and 50 mmHg. The rate of filtration increased linearly with the increase in congestion pressure, giving a regression line as shown in Fig. 4. The capillary filtration coefficient (CFC) was calculated from the slope of the regression line in terms of ml per min per 100 ml of calf tissue per mmHg increase in capillary pressure, on the assumption that the elevation of capillary hydrostatic pressure is 80% of the elevation of venous congestion pressure. CFC was determined before and after drinking of water amounting 1% of the subject's body weight. The venous congestion after water drinking was produced for the 15-min period between 15 and 30 min after the drinking.

Blood flow in the enclosed part of the calf was measured before and after water drinking by the venous occlusion method, inflating the pneumatic cuff (Fig. 1) around the thigh with a pressure of 50 mmHg. During the flow measurements, another cuff which was placed around the ankle was inflated to a pressure of 200 mmHg to occlude blood flow in the more distal portion of the extremity.

Blood samples were taken from the antecubital vein before and after water drinking in order to measure plasma osmotic pressure. Within 15 sec after 5-sec period of venous congestion, 8 ml of blood was collected in a polyethylene syringe wetted with heparin. Plasma osmotic pressure was measured by the Fiske osmometer based on the freezing point depression and was given in milliosmols per kg water (mOsm/kg H₂O). The accuracy was ± 1 mOsm/kg H₂O.

The total plasma protein concentration was also measured with a refractometer to estimate the change in the plasma colloidal osmotic pressure.

RESULTS

Effect of water drinking on extravascular fluid volume of calf. In order to measure the amount of increase in extravascular fluid volume after water drinking, changes in reduced calf volume during 13- or 15-min period were determined successively in Subject 1 (T.U.). No change was observed during the 13-min period immediately after the drinking as shown in Fig. 3. A distinct increase in extravascular fluid volume occurred for the 15-min period between 15 and 30 min after water drinking. In the next 15-min period the extravascular volume still increased, reaching to a cumulative amount of 7.2 ml to the calf volume of 1340 ml. However, a slight decrease was observed in the succeeding 15-min period. The mean rate of capillary filtration was found to be maximum during the 15-min period between 15 and 30 min after water drinking.

In contrast to the results after water drinking, no appreciable increase in extravascular fluid volume was observed within 47 min after drinking 0.9% saline. This fact indicates that ingestion of saline did not induce any measurable transcapillary movement of fluid.
Mean rate of filtration. The mean rate of filtration was estimated in two subjects during the 15-min period between 15 and 30 min after water drinking, i.e. in the phase when its maximum value was to be obtained. The actual amount of filtration with its SD was 5.3±1.1 ml in Subject 1 (T. U.) and 5.0±1.5 in Subject 2 (T. Y.). The mean volume of the calf sealed in the plethysmograph was 1340±27 ml in Subject 1 and 1410±30 in Subject 2, based on 12 measurements in each subject. The mean rate of filtration per min was calculated by dividing the amount of filtration measured in 15 min by calf volume and 15 (Table 1).

The amount of filtration after ingestion of 0.9% saline was -0.2±0.4 ml in Subject 1 and -0.8±1.0 in Subject 2, from 6 measurements in each subject. The rate of filtration was found to be almost nil.
Mean rate of filtration for 15-30 min after water and saline drinking.

<table>
<thead>
<tr>
<th></th>
<th>Rate of Filtration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ml/(min × 100 ml calf)</td>
<td></td>
</tr>
<tr>
<td>After Water Drinking</td>
<td></td>
<td>After 0.9% Saline Drinking</td>
</tr>
<tr>
<td>Subject 1 (T.U.)</td>
<td>0.026 ± 0.006 (6)</td>
<td>-0.001 ± 0.002 (6)</td>
</tr>
<tr>
<td>Subject 2 (T.Y.)</td>
<td>0.024 ± 0.004 (6)</td>
<td>-0.004 ± 0.005 (3)</td>
</tr>
</tbody>
</table>

The values shown are means ± SD. Numbers in parentheses indicate the number of measurements.

Capillary filtration coefficient (CFC). In Fig. 4 the rate of filtration is plotted against the venous congestion pressure in the two subjects before (open squares) and after (filled squares) water drinking. The values in Fig. 4 are not corrected for the decrease in reduced calf volume due to compression since

**Fig. 4.** Rate of filtration as a function of venous occlusion pressure in the calves of two subjects before (□) and after (■) water drinking. Each point represents mean (±SD) of 6 measurements.
the correction does not affect the calculation of CFC. Water drinking resulted in a distinct increase in the rate of filtration at each congestion pressure.

From the slope of the lines in Fig. 4, CFC was calculated on the assumption that the increase in capillary pressure was 80% of the increase in venous congestion pressure. In Subject 1 (T. U.), CFC was 0.0030 ml per min per 100 ml of calf per mmHg before water drinking and 0.0029 after drinking. In Subject 2 (T. Y.), CFC was 0.0033 before as well as after water drinking. CFC appeared not to be modified by water ingestion. These values obtained for CFC of the human calf are nearly the same as those in the forearm: 0.0037\textsuperscript{21}, 0.0038\textsuperscript{20}, and 0.0045\textsuperscript{20} ml per min per 100 ml of forearm per mmHg increase in capillary pressure.

The increase in effective filtration pressure after water drinking was calculated by dividing the observed rate of filtration (TABLE 1) by CFC. It was 8.7 mmHg in Subject 1 and 7.3 in Subject 2 during the 15-min period between 15 and 30 min after the drinking.

**Effect of water drinking on calf blood flow.** The calf blood flow before water drinking was 2.0±0.2 ml per min per 100 ml of calf in Subject 1 (T. U.) and 2.4±0.3 in Subject 2 (T. Y.), obtained from 12 measurements in each subject. The same number of flow measurements were made during the 15-min period between 15 and 30 min after water ingestion, giving values of 2.2±0.3 and 2.3±0.3 in Subject 1 and Subject 2 respectively. Calf blood flow appeared to be unaffected by water drinking.

**Plasma osmotic pressure and plasma protein concentration.** After drinking water of 1% of body weight, there was a fall in total osmotic pressure of plasma as shown in Fig. 5. This fall lasted until 20–40 min after the drinking. The falling phase of the total osmotic pressure coincided with the increasing phase of reduced calf volume. The maximum fall was 4–6 mOsm/Kg\textsubscript{H\textsubscript{2}O}. If we assume that the total body fluid, which initially composes 62% of body weight and has an osmotic pressure of 300 mOsm/Kg\textsubscript{H\textsubscript{2}O}, is diluted by water of 1% of body weight, the osmotic pressure will be decreased by 5 mOsm/Kg\textsubscript{H\textsubscript{2}O}. This is in agreement with the present experimental results.

Similar results were obtained by BALDES and SMIRK\textsuperscript{1} who observed a decrease in plasma osmotic pressure amounting to 10 milliosmols per liter after ingesting 1 liter of water in subjects weighing 64–75 kg. Allowing that the maximum fall is proportional to the amount of ingested water, the present value (4–6 mOsm/Kg\textsubscript{H\textsubscript{2}O} after drinking 600–650 ml of water) agrees well with their result.

Ingestion of isotonic saline did not induce any significant change in the total osmotic pressure of plasma (Fig. 5).

The plasma protein concentration was decreased by 0.4 g/100 ml in each
of 4 measurements in the two subjects after water drinking. The same degree of decrease was observed in 4 measurements in the two subjects after saline drinking. The corresponding decrease in the plasma colloid osmotic pressure was calculated as 2.2 mmHg, based upon the empirical equation described by Landis and Pappenheimer:

$$\pi = 2.1C + 0.16C^2 + 0.009C^3$$

where $$\pi$$ = colloid osmotic pressure in mmHg; $$C$$ = plasma protein concentration in g/100 ml.

**DISCUSSION**

The amount of transcapillary filtration, which occurred in the human calf after water drinking, was measured directly in the present study. Based upon the results obtained, it is possible to estimate the amount of fluid which accumulated transiently in the extravascular space of the whole body. Fig. 3 shows the accumulation of 7.2 ml of water in 1340 ml of the calf of Subject 1 (T.U.) after drinking 650 ml of water. If a uniform distribution of extravascular fluid throughout the body mass (specific gravity: 1.07, body weight: 65 kg) is assumed, the amount of extravascular fluid accumulated in the whole body is calculated as 330 ml.

The experiments most relevant to the present work are those reported by Smirk. He observed, in human subjects, an increase in leg weight after water drinking. In spite of the complication of the possible changes in the vasomotor tone in the leg weight measurement, he could detect an increase in
leg weight which was ascribable to fluid accumulation. According to his results, after drinking water of 1.3% of body weight, the leg weight increased by a maximum of 1.15%. He also showed that the increase in the leg weight persisted for 22-55 min after drinking water, but after this period there was no further increase. The present data on the time course of the increase in the reduced calf volume (Fig. 3) agree well with his result.

The effective filtration pressure rose about 8 mmHg after water drinking. As the underlying mechanisms of this phenomenon, the following three possibilities should be considered: (i) increase in capillary hydrostatic pressure, (ii) decrease in plasma colloid osmotic pressure, and (iii) decrease in plasma crystalloid osmotic pressure.

With respect to the first possibility, an increase in capillary hydrostatic pressure would be expected to involve dilation of arterioles or precapillary sphincter. Arteriolar dilation would increase the regional blood flow, while the opening of precapillary sphincters would increase CFC (filtration constant \(\times\) capillary surface area). Almost no change in the calf blood flow and CFC suggested that the capillary hydrostatic pressure was not affected by water drinking.

Concerning the possible implication of ADH in the capillary pressure, SMIRK\(^7\) showed that an injection of pituitary hormone did not diminish the increase in leg weight after water drinking.

As to the second possibility, the estimated degree of fall in the plasma colloid osmotic pressure (2.2 mmHg) after water drinking cannot account for the observed increase in effective filtration pressure. Furthermore, the ingestion of isotonic saline, causing the same degree of fall in the plasma protein concentration as induced by water drinking did not increase the reduced calf volume during the observation period.

The third possibility that the increase in effective filtration pressure is due to the rapid decrease in crystalloid osmotic pressure of plasma seems most plausible. As shown in Fig. 5, the equilibration of electrolyte concentration among the extra- and intracellular fluids and the ingested water decreases the total osmotic pressure of plasma by about 5 mOsm/KgH\(_2\)O, corresponding to 97 mmHg. The equilibration between the ingested water and plasma is faster than the equilibration between plasma and the interstitial fluid. Consequently, when the crystalloid osmotic pressure of plasma is rapidly falling, it remains lower than that of the interstitial fluid. This discrepancy will amount about 8 mmHg for 15-30 min after the water drinking.

Two pieces of evidence as follows obtained in the present study support the view that the fluid movement was brought about chiefly by a decrease in crystalloid osmotic pressure. First, the period during which the total osmotic pressure of plasma was falling coincided with the period of the increase in the reduced calf volume. Secondly, the drinking of isotonic saline, which did
not decrease the total osmotic pressure of plasma, induced no detectable increase in the reduced calf volume.

SUMMARY

The rate of outward capillary filtration induced by water drinking was measured by means of the pressure plethysmography in the calf of two healthy young men. The maximum rate of filtration was 0.026 and 0.024 ml/min/100 ml calf after drinking water of 1% of body weight. Ingestion of 0.9% saline, however, caused no such fluid movement. Capillary filtration coefficient (CFC) of calf, estimated at the same time, was 0.0030 and 0.0033 ml/min/100 ml calf/mmHg. From these data, the maximum increase in effective filtration pressure after water drinking was estimated to be 8.7 and 7.3 mmHg. No change in calf blood flow and CFC was observed after water drinking. The decrease in plasma protein concentration was 0.4 g/100 ml, corresponding to 2.2 mmHg fall of plasma colloid osmotic pressure. The plasma osmolality was decreased by 4 and 6 mOsm/KgH₂O after water drinking, but remained unchanged after saline drinking. It was concluded that a decrease in crystalloid osmotic pressure caused the observed fluid movement.

REFERENCES