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Effective Compliance of the Circulation in the Upright Sitting Posture*

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Abstract. The effective compliance is defined as the relation of change in blood volume to change in central venous pressure. It was measured in 8 upright sitting male subjects and amounted to 3.3 ml/(mm Hg × kg BW). It is, therefore, by about 50% greater than the effective compliance in the supine subject which amounts to 2.3 ml/(mm Hg × kg BW). This difference is probably due to the posture dependent blood volume distribution in the low pressure system whose "upper" and "lower" sections have nonlinear pressure-volume characteristics. Immersion to the neck reduces the effective compliance to about half the control value (1.9 ml/(mm Hg × kg BW) which probably constitutes the effective compliance of the intrathoracic circulatory compartment.

Key words: Immersion – Effective circulatory Compliance – Posture.

Introduction

Two possible routes for the control of blood volume have been discussed extensively: According to Guyton and Coleman [8], the increased filling of the heart leads to an increase in cardiac output and blood pressure and hence to an increased fluid excretion by the kidney. Gauer et al. [4, 7] proposed the theory that the increased distension pressure stimulates receptors in the heart which via the CNS and neural and hormonal effector mechanisms modulate renal function, fluid uptake and capillary filtration in the microcirculation. In both cases the result would be a reduction in extracellular fluid volume. Regardless of whether we subscribe to a mechanical feedback mechanism or whether we favor the idea of a reflex volume control via mechanoreceptors in the heart, either mechanism can only function properly if the rise or fall of intracardiac pressure is a sharply defined function of the change in blood volume. This is indeed the case. When plotting changes of total blood volume against changes in central venous pressure, the effective compliance of the circulation is obtained. This is 2.3 ml/(mm Hg × kg BW) and identical in dog and man when in the supine posture [2]. By the application of positive pressure (+50 mm Hg) to the body below the diaphragm by the use of a pressure box, the distensibility of the vascular bed of the lower body is neutralized and it is possible to estimate the compliance of the intrathoracic compartment. This was estimated to be 1.0 ml/(mm Hg × kg BW) [2]. This means the intrathoracic compartment contributes 50% to the compliance of the total circulation. When assuming the upright posture, about 10% of the estimated blood volume is displaced into the lower extremities. It can then be predicted that the compliance of the upper half of the low pressure system will increase, while the compliance of the lower half may decrease. Since the pressure-volume relationships of the two compartments are nonlinear, the effective compliance of the total circulation cannot be predicted. It was therefore measured.

Methods

Eight male students of very similar physique (age 24.3 ± 2.0 years, weight 71.0 ± 4.9 kg, height 177.1 ± 3.5 cm) volunteered as subjects. Central venous pressure was recorded via a float-in-catheter (1.0/1.5 mm, 70 cm long, Vygon®) which was inserted from the right antecubital vein into the neighbourhood of the right atrium. For the measurement of peripheral venous pressure, a vein was punctured with a short plastic catheter (Braunüle No. 1) in the distal third of the right lower arm. 23 PB Statham strain gauges served as pressure transducers. They were fixed at the hight of the mamilla. Heart rate was determined from the ECG which was recorded together with the pressure tracings on an Offner Dynograph (Beckman). Arterial blood pressure was measured after Riva-Rocci-Korotkov. The left antecubital vein was cannulated with a Braunüle No 2. It was used for hemorrhage and transfusion. The sites of the punctures were protected by Nobecutan® spray. Quick and constant changes in

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blood volume were achieved with the help of a Harvard finger pump. Hemorrhage was facilitated by use of a Riva-Rocci cuff which was inflated on the left upper arm to below systolic pressures. Change of blood volume was ± 500 ml for all subjects.

The subject was seated comfortably in an armchair which was reclining 70° and which could be lowered into a water bath of thermoneutral temperature. After 20 min of quiet sitting plasma volume (^{125}I human serum albumine) and hematocrit were determined.

The experiment was started with an infusion of 500 ml 6% Dextran-solution (Macrodex®). Ten minutes were allowed for the mixing of the Dextran with the blood of the subject. Then 500 ml of blood were withdrawn for later infusions. The now existing blood volume was taken as control volume. The mean blood volume of the eight subjects was 5059 ± 422 ml. The volume change of 500 ml was close to 10% (9.9 ± 0.8%) of the total blood volume.

All experiments were conducted according to the following regime:

a) Infusion of 500 ml of the previously withdrawn heparinized blood in 2.8 min; 1.5 min pause.

b) Withdrawal of 1000 ml blood in 9.8 min; 1.5 min pause.

c) Reinfusion of 500 ml blood in 3.0 min.

The average duration of the whole cycle was 18.6 min. The procedure was repeated 3 times under the following conditions:

1. Subject sitting in air of 28° C (control condition).
2. Subject sitting and immersed in the water bath of 35° C up to the xiphoid.
3. Subject sitting and immersed up to the neck.

Water- and room temperatures were thermostat controlled at 35° C and 28° C respectively. The statistical calculations were carried out by the t-test for matched pairs [10].

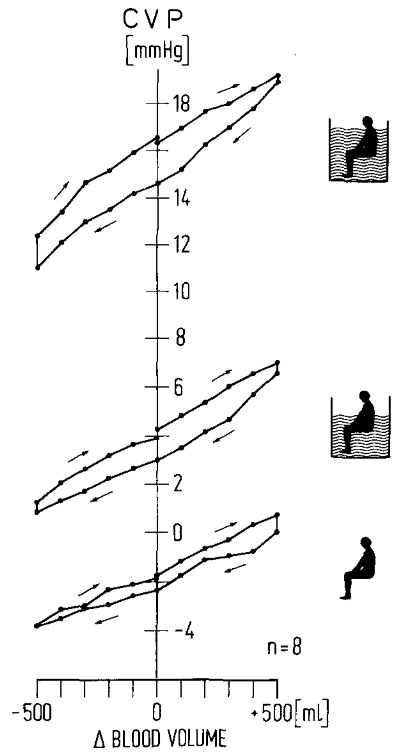

Fig. 1. Changes of central venous pressure under control conditions, immersion to the diaphragm and to the neck during a change of blood volume of ± 500 ml. The experiments began with infusion. The sequence of events is indicated by the arrows. The whole cycle was completed within 18.6 min

Results

Central Venous Pressure (CVP)

Figure 1 shows the behavior of central venous pressure of 8 subjects during blood volume changes of ± 10% under three conditions.

a) Under control conditions (sitting in air) the pressure in the central veins averages −1.7 mm Hg. During infusion of 500 ml blood in 2.8 min it rises by 2.4 mm Hg. 1.5 minutes later it has fallen to 0 mm Hg. After hemorrhage of 1000 ml in 9.8 min CVP falls to −3.9 mm Hg. Reinfusion in 3 min brings it up to −1.9 mm Hg. This is not significantly different from the control value.

b) When immersing the subject to the xiphoid, CVP rises from control of −1.7 mm Hg by 5.9 ± 1.1 mm Hg to 4.2 mm Hg ($P < 0.0001$). Infusion of 500 ml brings it up to 7 mm Hg. During subsequent hemorrhage of 1000 ml it falls to 0.8 mm Hg. After reinfusion of 500 ml, CVP rises from 1.2 − 3.9 mm Hg, reaching almost control value.

c) When the water level is brought up to the neck (C 7), CVP rises from 4.2 mm Hg by 12.1 to 16.3 mm Hg ($P < 0.0001$). Infusion of 500 ml raises CVP to 19.3 mm Hg. Hemorrhage of 1000 ml reduces it to 11.0 mm Hg. During the short pause it rises slightly and reinfusion of 500 ml brings it up from 12.4 to 16.6 mm Hg.

All pressure-volume curves show hysteresis. Under immersion the loops are steeper and wider than under control conditions.

Figure 2 presents the mean values as well as the standard deviation of the mean of CVP during infusion and hemorrhage. During immersion to the xiphoid the steepness of the volume-pressure curve increases slightly. It becomes more pronounced during immersion to the neck. Under control conditions (Fig. 2 below) a volume change of 1000 ml induces a pressure difference of 4.2 mm Hg. From these values the effective compliance of the sitting subjects can be calculated. It is 3.3 ml/(mm Hg × kg BW). During immersion to the xiphoid the pressure change for a volume change of 1000 ml is 5.8 mm Hg and the effective compliance 2.4 ml/(mm Hg × kg BW). During neck immersion the pressure change for the same volume change is 7.4 mm Hg and the calculated effective compliance 1.9 ml/(mm Hg × kg BW).

Peripheral Venous Pressure (Arm Vein)

The pressure in the arm vein is not influenced by immersion up to the xiphoid. Only when the water level reaches the neck, the peripheral veins are coupled to the

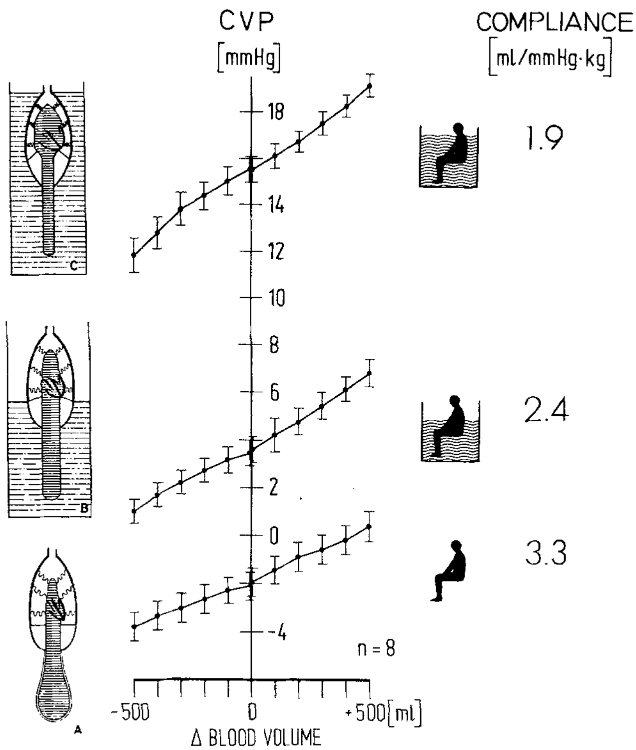

Fig. 2. Mean effective compliance (change of blood volume/change of CVP) in subjects under control conditions and immersion. The diagrams on the left side [5] indicate the distribution of blood volume in the low pressure system. Note the rise in CVP and the decrease of compliance with increasing depth of immersion

central vascular bed and the pressure in the arm vein rises from 12.8 ± 3.3 to 19.3 ± 2.7 mm Hg ($P < 0.05$). During infusion and hemorrhage of 500 ml the peripheral venous pressure rises and falls in parallel with the CVP, with blood loss in excess of 500 ml the peripheral venous pressure remains unchanged. It may even rise a little.

Heart Rate

Under control conditions the heart rate of the sitting subject was 74.4 ± 9.2 beats/min. During immersion to the xiphoid it falls to 67.2 ± 8.5 beats/min ($P < 0.02$). With further immersion to the neck it rises again to 73.4 ± 8.7 ($P < 0.005$). Infusion of 500 ml under control conditions accelerates the heart by 11.4 beats/min ($P < 0.001$). During immersion to the xiphoid the same hemorrhage raises the heart rate by 3.7 beats/min ($P < 0.05$). When 500 ml of blood are taken during neck immersion heart rate showed a slight insignificant decrease.

Arterial Blood Pressure

During immersion average arterial blood pressure rises from 116 ± 15/63 ± 11 mm Hg (control) to 123 ± 12/67 ± 13 mm Hg (xiphoid) and 124 ± 14/70 ± 9 mm Hg (neck). The differences are not significant with exception of the systolic pressure rises effected by control/neck immersion ($P < 0.05$).

Discussion

Since the pressure transducers were fixed relative to the body, the changes of CVP at various degrees of immersion need no correction. They are comparable with the results of previous measurements [3, 9]. During neck immersion CVP rises to 16.3 mm Hg as compared to 16 mm Hg [1] and 15.2 mm Hg [3]. The control values show relatively greater scatter: −1.7 mm Hg versus 3.4 mm Hg [3]. During immersion to the xiphoid the CVP is 4.2 mm Hg.

The changes in CVP mirror the changes of blood volume distribution induced by postural changes and immersion. The suggestion [5] that immersion of the upright subjects to the hydrostatic indifference point, that is the xiphoid, would lead to a blood volume distribution which is very similar to that in the supine posture has been confirmed [9]. The present investigation shows that the effective compliance in the upright sitting subject immersed to the xiphoid (2.4 ml/(mm Hg × kg BW) is identical with that of the supine man [2,9,11]. When the external support of the capacitance vessels of the lower extremities by the hydrostatic pressure of the bath is eliminated and the subject is sitting in air, blood is drained from the intrathoracic compartment. Heart volume is reduced and the pulmonary vascular bed, particularly in the apical regions, is partially emptied [9]. We may therefore expect a considerable increase in distensibility of the intrathoracic circulation. If this increase is not compensated by a simultaneous decrease in distensibility of the dependent circulatory bed, the effective compliance of the circulation of man must rise when he assumes the upright posture. This is probably the explanation for the observation that the effective compliance in the upright posture is by 50% greater than in the supine posture (3.3 versus 2.4 units).

When curtailing volume and distensibility of the extrathoracic circulation by immersing the subject to the neck, the effective compliance falls to 1.9 ml/(mm Hg × kg BW). The greater portion of this compliance can be attributed to the compliance of the introthoracic vascular bed. It constitutes about half that of the upright sitting subject.

The existence of a well defined effective compliance shows that the combined responses to moderate blood volume changes of venous tone and the mechanisms regulating fluid shift between intra- and extravascular compartments are not alert enough to homeostatically regulate CVP. Although it must be admitted that the present experiments allowed little time for such corrections, previous experiments [6] have demonstrated that extension of the observation period to 50 min does not principally change the picture. Even if vascular tone is affected in some vascular beds, the response does not suffice to bring central venous pressure back to normal. A moderate change in blood volume leads to a change of the filling pressure of the heart and this in turn seems to constitute the adequate stimulus for measures correcting blood volume. Whether this correction occurs through a change in cardiac output [8] or a volume control reflex [4] or both is irrelevant.

The decrease in heart rate when immersing an upright sitting subject up to the xiphoid is comparable to the change when assuming the supine posture in air. The increase in heart rate when bleeding 500 ml depends on the size of the central blood volume. If we take heart rate as a sign of sympathetic drive, we find a significant moderate increase when the initial filling of the heart is smallest (sitting in air). When by immersion to the xiphoid central volume is increased to that of a supine subject, we observed only a slight tendency towards an increase. When the central compartments are "overfilled" during neck immersion, blood loss induces a slight reduction in heart rate. These observations can be taken as an illustration of the well known fact [11] that the immediate defences against low output failure are much stronger than those preventing hyperactivity of the circulation.

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References

1. Arborelius, M., Jr., Balldin, U. I., Lilja, B., Lundgren, C. E. G.: Hemodynamic changes in man during immersion with the head above water. Aerospace Med. **43**, 592–598 (1972)
2. Echt, M., Düweling, J., Gauer, O. H., Lange, L.: Effective compliance of the total vascular bed and the intrathoracic compartment derived from changes in central venous pressure induced by volume changes in man. Circ. Res. **34**, 61–68 (1974)
3. Echt, M., Lange, L., Gauer, O. H.: Changes of peripheral venous tone and central transmural venous pressure during immersion in a thermo-neutral bath. Pflügers Arch. **352**, 211–217 (1974)
4. Gauer, O. H., Henry, J. P.: Neurohormonal control of plasma volume. Intern. Rev. Physiol., Cardiovascular Physiology II, Vol. 9, pp. 145–190 (A. C. Guyton and A. W. Cowley, eds.). Baltimore: University Park Press 1976
5. Gauer, O. H., Thron, H. L.: Postural changes in the circulation. Handbook of Physiology, Sec. 2: Circulation, Vol. III, pp. 2409–2439 (1965)
6. Gauer, O. H., Henry, J. P., Sieker, O. H.: Changes in central venous pressure after moderate hemorrhage and transfusion in man. Circ. Res. **4**, 79–84 (1956)
7. Gauer, O. H., Henry, J. P., Sieker, H. O., Wendt, W. E.: Heart and lungs as a receptor region controlling blood volume. Am. J. Physiol. **167**, 786 (1951)
8. Guyton, A. C., Coleman, T. G.: Long-term regulation of the circulation: Interrelationships with body fluid volumes. In: Physical bases of circulatory transport: Regulation and exchange, pp. 179–201 (E. B. Reeve, A. C. Guyton, eds.). Philadelphia-London: Saunders 1967
9. Risch, W. D., Koubenec, H. J., Beckmann, U., Lange, S., Gauer, O. H.: The effect of graded immersion on heart volume, central venous pressure, pulmonary blood distribution, and heart rate in man. Pflügers Arch. **374**, 115–118 (1978)
10. Sachs, L.: Angewandte Statistik, Planung und Auswertung. Methoden und Modelle, 4. Aufl. Berlin-Heidelberg-New York: Springer 1974
11. Thron, H. L., Brechmann, W., Wagner, J., Keller, K.: Quantitative Untersuchungen über die Bedeutung der Gefäßdehnungsreceptoren im Rahmen der Kreislaufhomoiostase beim wachen Menschen. I. Das Verhalten von arteriellem Blutdruck und Herzfrequenz bei abgestufter Veränderung des transmuralen Blutdrucks im Bereich des Carotissinus. Pflügers Arch. **293**, 68–99 (1967)

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