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ORIGINAL ARTICLE

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An electrical admittance based index of thoracic intracellular water during head-up tilt in humans

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Abstract During 50° head-up tilt (HUT), the number of erythrocytes within the thorax has been shown to be reduced by approximately 25% and this level is retained during a maintained tilt, whilst that in the thigh increases by approximately 70%. To evaluate whether the electrical admittance of intracellular water (ICW) may be used to monitor this redistribution of red cells in humans, we determined the regional difference in the reciprocal value of the impedance at 1.5 and 100 kHz for the thorax ($thorax_{ICW}$) and for the leg (leg_{ICW}). In ten subjects all variables remained unchanged during head-down tilt but during HUT, presyncopal symptoms were induced in eight subjects after a mean of 27 (SEM 7) min as mean heart rate dropped from 85 (SEM 4) to 66 (SEM 3) beats $\cdot$ min^{-1}, mean arterial blood pressure from 80 (SEM 3) to 60 (SEM 5) mmHg, and mean oxygen saturation of venous blood from 76 (SEM 2)% to 73 (SEM 3)% ($P < 0.05$). The mean haematocrit increased from 50 (SEM 5)% to 52.5 (SEM 3.5)% ($P < 0.01$) and mean central venous pressure decreased during tilting (from a mean of 1 (SEM 1) to a mean of −1 (SEM 1) mmHg; $P < 0.05$) and returned to value at rest during the maintained tilt. Mean thoracic impedances increased by 7.0 (SEM 1.0) Ω (1.5 kHz) and 5.4 (SEM 1.2) Ω (100 kHz), and mean leg impedances decreased by 9.3 (SEM 1.2) Ω (1.5 kHz) and 3.1 (SEM 1.0) Ω (100 kHz) ($P < 0.01$). Mean $thorax_{ICW}$ decreased at 40° HUT and remained reduced by 11 (SEM 2) $S \cdot 10^{-4}$ ($P < 0.05$) until the presyncopal symptoms developed, at which time it was lower by 16 (SEM 2) $S \cdot 10^{-4}$ ($P < 0.01$). Mean leg_{ICW} increased from 97 (SEM 15) to 99 (SEM 15) $S \cdot 10^{-4}$ ($P = 0.08$) during HUT but decreased during maintained tilt (to 94 (SEM 15) $S \cdot 10^{-4}$; $P < 0.05$). The results suggested that during HUT, the difference in electrical admittance at a high and a low frequency current reflects the reduced number of red cells within the thorax.

Key words Central venous O_2 saturation · Central venous pressure · Heart rate · Leg and thorax electrical impedance · Mean arterial pressure

Introduction

Electrical impedance may be used in non-invasive estimates of body fluid content. In situations such as when bleeding or during anaesthesia the sitting position reduce venous return (Buhre et al. 2000), thoracic electrical impedance (TI) has been used to evaluate the filling of the heart (Matzen et al. 1990; Hanel et al. 1994; Pawelczyk et al. 1994; Cai et al. 2000a). Using two frequencies, it has been found that TI will distinguish between the extracellular (ECW) and total body water (TBW; Thomasset 1963; Segal et al. 1991; Petersen et al. 1994). The use of two frequencies for determination of TI relies on the assumption that at a low frequency the cell membrane will insulate the intracellular space, while at higher frequencies this influence diminishes and current flows through both the intracellular water (ICW) and ECW. Thus, the difference in the reciprocal value of the impedance (the admittance) between a high and a low frequency current may reflect changes in ICW (Lichtenbelt et al. 1994; Siconolfi et al. 1996; Cai et al. 1998).

During acute changes it is assumed that it is the distribution of erythrocytes that accounts for most of the regional variations in ICW. Thus the reduction of electrical admittance of intracellular water in the thorax ($thorax_{ICW}$) has been shown to reflect the reduced

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erythrocyte volume in the heart during lower body negative pressure (Cai et al. 2000a). This was the case even though thorax$_{ICW}$ was calculated as the difference between the reciprocal values of impedance at two frequencies and in doing so did not take into account a possible influence of the phase angle. When not taking the phase angle of the electrical current into account, the reliability of thorax$_{ICW}$ in the evaluation of the thoracic blood volume needs further physiological evaluation, especially in situations where the erythrocyte and plasma volumes do not vary in parallel.

During a maintained 50° head-up tilt (HUT) the number of erythrocytes in the thorax has been shown to decrease by approximately 25% to a level which is maintained for the remainder of the tilt whether the subjects develop presyncopal symptoms or they remain normotensive (Matzen et al. 1991). Conversely in the thigh the number of red cells increases by approximately 70%. Presyncopal symptoms have then been shown to appear as there is a further decrease in the circulating plasma volume leading the blood volume to be reduced by about 30%, when heart rate (f_c) and mean arterial pressure ($\overline{BP}_a$) decrease (Matzen et al. 1991). During HUT Matzen et al. (1991) showed that TI at 2.5 kHz becomes more elevated than when determined at 100 kHz, and conversely, the decrease in leg impedance (LI) was more pronounced at 2.5 kHz than that at 100 kHz. It would thus seem that thorax$_{ICW}$ decreases during HUT while leg electrical admittance of intracellular water (LI$_{ICW}$) would increase. To evaluate whether the difference in admittance between high and low frequency currents would be satisfactory for monitoring the variations in erythrocyte volume in the thorax and in the leg we conducted this study in young healthy subjects. In addition to HUT, head-down tilt (HDT) was also used to manipulate the distribution of blood between thorax and leg, and an impedance apparatus was developed to improve the stability of the readings and to display the difference in electrical admittance between two frequencies.

Methods

Ten male subjects participated in study. Their mean age was 28 (range 23–34) years, mean height 187 (172–200) cm, and mean body mass 79 (68–87) kg. The Ethics Committee of Copenhagen approved the project, and informed consent was obtained from the subjects.

Procedure

The subjects were investigated on 2 days. On the 1st day they were placed supine for 30 min on a tilt table provided with a bicycle saddle but with no footboard (Fig. 1). Passive 50° HUT was performed over 5 min and interrupted at each 10° increment for measurement of variables. The subjects remained in the 50° head-up position (maintained HUT) for 1 h or until the appearance of pre-syncopal symptoms. They were then returned to the horizontal position for 30 min. To evaluate the sensitivity of thorax$_{ICW}$ and LI$_{ICW}$ responses to the different body positions, 7–10 days later the 30 min of rest whilst supine was followed by passive HUT to 15° and 30°, and by the supine position and HDT to −7.5° and −15° for 20 min each, the order being randomized. During HUT and HDT, the subjects were asked not to move their legs.

A cannula (1.0 mm i.d., 19.5 G) was placed in the brachial artery of the non-dominant arm for the measurement of $\overline{BP}_a$, pulse pressure (PP) being taken as the difference between the systolic and the diastolic pressures. A blood sample was obtained from the artery for determination of haematocrit (Hct). Another cannula (1.4 mm i.d., 14 G) was introduced into the superior caval vein via the left basilic vein for the measurement of central venous pressure (CVP) and central venous O_2 saturation (S_vO_2). Blood samples for Hct and S_vO_2 were placed immediately on ice and analysed within minutes using an ABL 510 apparatus (Radiometer, Copenhagen, Denmark). A three-lead electrocardiogram was used to record f_c, while pressures were measured using Bentley transducers (Uden, Holland) positioned at the level of the right atrium in the mid-axillary line and fastened to the subject. The transducers were connected to a Dialogue 2000 monitor (IBC-Danica, Copenhagen, Denmark).

We developed a body impedance monitor (C-guard, Danmeter, Odense, Denmark) which integrated values over 15 s to diminish the influence of respiration on TI. Using a 200 μA current TI and LI were measured at 1.5 and 100 kHz. The skin was cleaned with alcohol swabs. Pairs of electrodes (Q-10–25, Medicotest, Denmark) were placed on the right sternocleidomastoid muscle and on the upper left ribs in the midaxillary line with an interelectrode distance of 5 cm. This pattern of electrode placement has also been used when the correlation with changes in central blood volume (CBV) was evaluated (Matzen et al. 1991; Perko et al. 1994, 1996; Hanel et al. 1994, 1997). For the determination of LI, one pair of electrodes was placed on the caput tibiae and a second on the lateral malleolus of the right leg. Changes in LI were calibrated against the volume of the lower leg as measured by its circumference (Belanger et al. 1998). Total body impedance (TBI) was determined to ascertain whether it follows LI rather than TI as a result of room temperature changes (Cai et al. 2000b). The TBI was measured using a BIA 101-Fitness apparatus (Akern-RJL systems, Detroit) which uses currents at 50 kHz. For TBI, the electrodes were placed on the dorsal surfaces of the hand and foot. For all electrode placements, the outer two electrodes provided the electrical field, while the inner

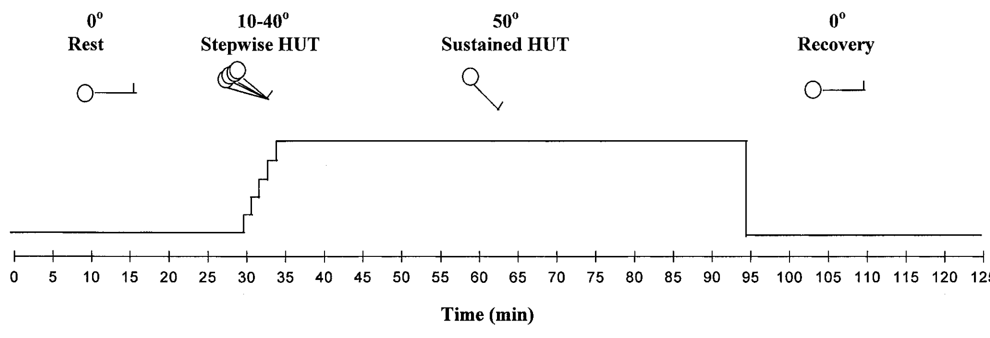

Fig. 1 Diagram of the experiment protocol. Data were collected every 5th min at rest and during maintained head-up tilt (*HUT*) and during the recovery. During stepwise *HUT* data were collected every minute. The *HUT* was maintained for 1 h or until the appearance of presyncopal symptoms and data were normalized to the mean length of tilt (27 min)

pair were used as sensors. Changes in thorax$_{ICW}$ and in leg$_{ICW}$ were estimated as the difference between the electrical admittance at 1.5 and 100 kHz (1/Impedance$_{100kHz}$ − 1/Impedance$_{1.5kHz}$) (Lichtenbelt et al. 1994; Siconolfi et al. 1996; Cai et al. 1998).

Statistics

Results are given as mean and SEM for the eight subjects who developed presyncopal symptoms before the scheduled 60 min of 50° HUT. Because this hypotension occurred at different times, the time scale for each individual was normalised with respect to a mean tilt time (27 min) for all subjects (Matzen et al. 1990). Tilt-related changes were assessed by the Friedman test, and for comparisons, the Wilcoxon test was used. The stability of the body impedance monitor was evaluated by calculating the coefficient of variation between repeated measurements during rest whilst supine before maintained HUT. The limit of significance was $P < 0.05$.

Results

During 50° HUT, eight out of the ten subjects developed presyncopal symptoms (nausea, paleness and a feeling of heat) associated with decreases in $\overline{BP}_a$ and f_c. In one subject the presyncopal symptoms developed during 40° HUT and another subject remained normotensive through maintained HUT. These two subjects are reported separately.

Graded tilting

All variables remained constant during rest whilst supine and HDT. At 30° HUT, mean f_c increased from 54 (SEM 1.2) to 60 (SEM 2.6) beats · min^{-1} ($P < 0.05$), while $\overline{BP}_a$ remained constant (Fig. 2). The mean CVP was reduced from 1 (SEM 1) to −1 (SEM 1) mmHg and mean S_vO_2 from 76.1 (SEM 1.1) to 72.7 (SEM 1.3)% ($P < 0.05$). The mean TI increased by 2.5 (SEM 1.1) (1.5 kHz) and 2.2 (SEM 1.0) (100 kHz Ω; $P < 0.05$), and mean LI decreased by 3.4 (SEM 1.7) (1.5 kHz) and 1.7 (SEM 1.5) (100 kHz Ω; $P < 0.05$). The mean thorax$_{ICW}$ dropped by 5 (SEM 1) S · 10^{-4} ($P < 0.05$), while leg$_{ICW}$ did not change significantly.

Maintained HUT

All variables remained stable during rest whilst supine. In the subjects who developed presyncopal symptoms, mean f_c increased from 58 (SEM 3) to 85 (SEM 4) - beats · min^{-1} and mean $\overline{BP}_a$ from 81 (SEM 3) to 90 (SEM 2) mmHg, while mean PP [57 (SEM 4) mmHg] remained unchanged (Fig. 3). The mean S_vO_2 decreased from 76.2 (SEM 1.7) to 66.0 (SEM 2.8)%, while mean Hct increased from 49.6 (SEM 4.6) to 51.0 (SEM 4.1)%.

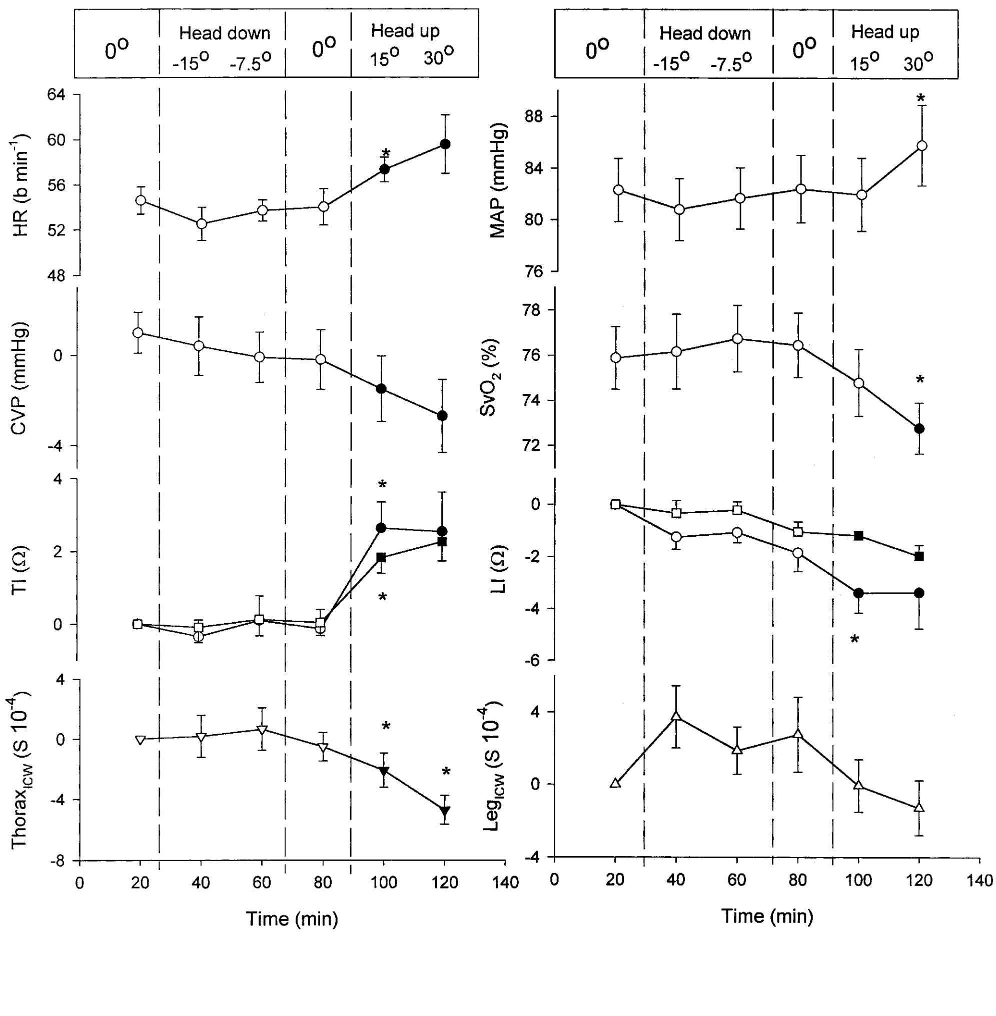

Fig. 2 Heart rate (*HR*), mean arterial blood pressure (*MAP*), central venous pressure (*CVP*), central venous oxygen saturation (S_VO_2), changes in thoracic (*TI*) and leg (*LI*) impedance at 1.5 kHz (*circle*) and 100 kHz (*square*), and in electrical admittance of intracellular water of the thorax (*thorax*$_{ICW}$) and the lower leg (*leg*$_{ICW}$) in ten subjects from rest (0–20 min) to head down tilt at 15° and 7.5° for 20 min each (20–60 min), supine rest (60–80 min) and head up tilt at 15° and 30° for 20 min each (80–120 min). Data show mean and SEM. *Filled symbol* different from baseline. *Different from preceding value, $P < 0.05$

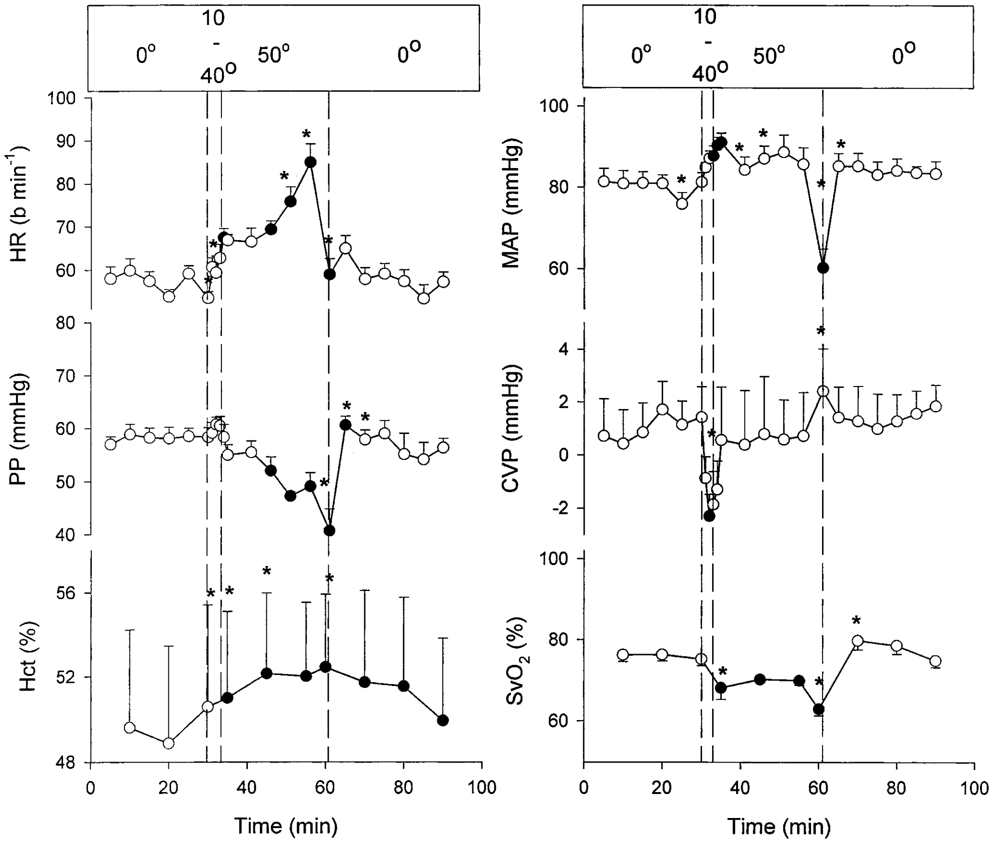

Fig. 3 Heart rate (*HR*), mean arterial blood pressure (*MAP*), pulse pressure (*PP*), central venous pressure (*CVP*), haematocrit (*Hct*) and central venous O_2 saturation (S_vO_2) in eight subjects during rest whilst supine (10–20 min), stepwise tilt from 10° to 40° (30–34 min) and head up tilt at 50° (34–60 min), appearance of presyncopal symptoms (61 min) and recovery (61–90 min). Data represent mean and SEM. *Filled symbol* different from baseline. *Different from preceding value, $P < 0.05$

After a mean of 27 (SEM 7) min presyncopal symptoms appeared associated with decreases in mean f_c to 66 (SEM 3) beats · min^{-1}, in mean $\overline{BP}_a$ to 60 (SEM 5) mmHg, in mean PP to 41 (SEM 4) mmHg and in mean S_vO_2 to 73 (SEM 3)%, while mean Hct increased to 52.5 (SEM 3.5)%. The mean CVP decreased from 1 (SEM 1) to −1 (SEM 1) mmHg during stepwise tilt and returned to the rest value during the maintained tilt and did not change significantly when the presyncopal symptoms appeared. In all subjects cardiovascular variables returned to control levels within 20 min of recovery.

The TI and thorax$_{ICW}$ remained constant during rest whilst supine. The average coefficient of variation for $TI_{1.5kHz}$, TI_{100kHz} and thorax$_{ICW}$ was 0.8%, 0.9% and 1.7%, respectively. The mean TI [35.7 (SEM 2.1) Ω (1.5 kHz); 27.2 (SEM 2.0) Ω (100 kHz)] increased at 30° HUT and was elevated by 7.0 (SEM 1.0) Ω (1.5 kHz) and 5.4 (SEM 1.2) Ω (100 kHz) ($P < 0.01$) when the presyncopal symptoms appeared (Fig. 4). The mean thorax$_{ICW}$ [90 (SEM 6) S · 10^{-4}] was significantly reduced at 40° HUT and it was lower by 11 (SEM 2) S · 10^{-4} during 50° HUT. The mean thorax$_{ICW}$ dropped further to reach 16 (SEM 2) S · 10^{-4} at the time the presyncopal symptoms developed ($P < 0.01$).

The average coefficient of variation for $LI_{1.5kHz}$, LI_{100kHz} and leg$_{ICW}$ was 0.5%, 0.8% and 1.5%, respectively. The mean LI [69.2 (SEM 4.3) Ω (1.5 kHz); 43.5 (SEM 5.2) Ω (100 kHz)] was reduced at 15° HUT and decreased by 9.3 (SEM 1.2) Ω (1.5 kHz) and 3.1 (SEM 1.0) Ω (100 kHz) when the presyncopal symptoms developed. The mean leg$_{ICW}$ tended to increase [from 98 (SEM 15) to 99 (SEM 15) S · 10^{-4}; $P = 0.08$] during 10° to 40° HUT, but it decreased during maintained HUT [to 94 (SEM 15) S · 10^{-4}]. The mean TBI [342 (SEM 16) Ω] was reduced by 18 (SEM 4) Ω when the presyncopal symptoms appeared.

The thorax$_{ICW}$ and leg$_{ICW}$ returned to the control value within 10 min after HDT. However, after 30 min of recovery, mean TI remained 3.1 (SEM 1.1) Ω (1.5 kHz) and 2.2 (SEM 0.4) Ω (100 kHz) above the value at rest. Conversely, mean LI remained 3.2 (SEM 1.1) Ω (1.5 kHz) and 1.4 (SEM 1.3) Ω (100 kHz) and mean TBI remained 7 (SEM 2) Ω lower than the value at rest.

In the subject who developed presyncopal symptoms at 40° HUT, mean TI increased by 3.4 (1.5 kHz) and 3.0 (100 kHz; Table 1) Ω, while mean LI decreased by 1.3 (1.5 kHz) and 0.8 (100 kHz) Ω. The mean thorax$_{ICW}$ decreased by 18 S · 10^{-4} and mean leg$_{ICW}$ increased by 2 S · 10^{-4}. In the subject who remained normotensive throughout the 1 h of HUT, mean TI had increased 9.4 (1.5 kHz) and 6.6 (100 kHz) Ω at the end the hour and mean LI had decreased by 8.3 (1.5 kHz) and 1.8 (100 kHz) Ω. The mean thorax$_{ICW}$ dropped by 13 S · 10^{-4} at 50° HUT and it remained at this level through the maintained HUT, while mean leg$_{ICW}$ decreased by 10 S · 10^{-4}.

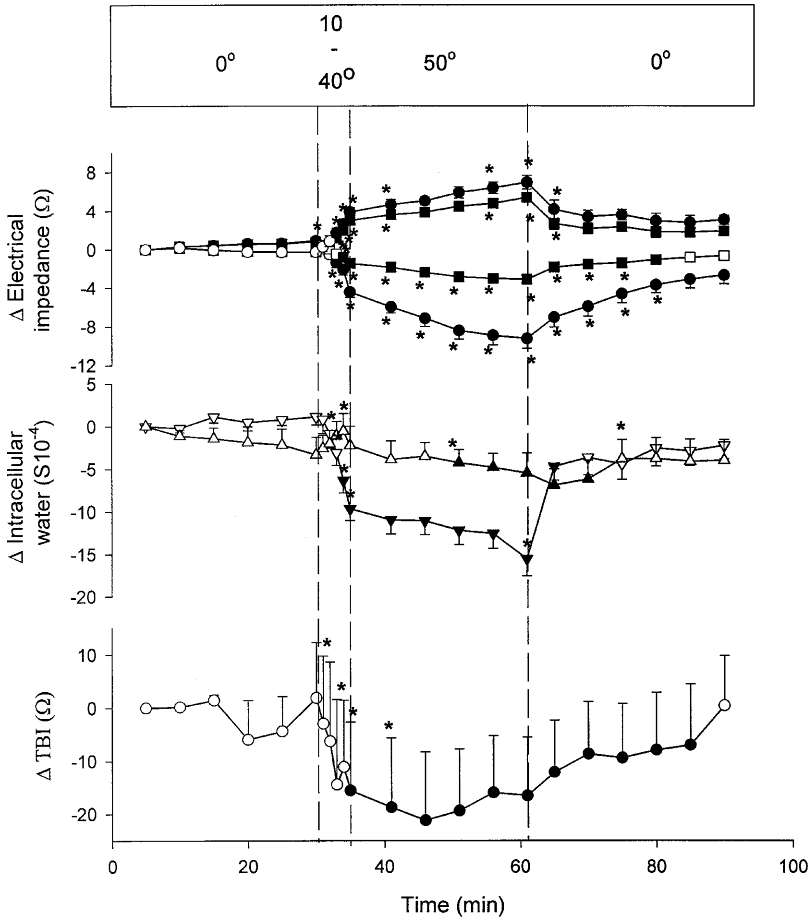

Fig. 4 Changes (Δ) in thoracic and leg electrical impedance at 1.5 kHz (*circle*) and 100 kHz (*square*), and changes in electrical admittance of intracellular water of the thorax (triangle pointing downwards) and of the leg (triangle pointing upwards) and changes in total body impedance (Δ *TBI*) for eight subjects. For further details, see legend to Fig. 2

Discussion

The HUT was maintained until the appearance of presyncopal symptoms in eight male volunteers. The redistribution of fluid between the thorax and the legs was indicated by the elevated TI and the reduced LI. Also the difference in electrical admittance of the thorax between 1.5 and 100 kHz appeared to reflect the reduction in the number of erythrocytes within the thorax (Matzen et al. 1991). This was the case although $thorax_{ICW}$ did not take into account a possible influence of the phase angle of the electrical current.

Leg_{ICW} during maintained HUT

That the HUT induced venous pooling in dependent vascular beds was verified by the recording of LI. The technetium-99-m (^{99m}Tc) labelled erythrocyte activity over the thigh has been shown to increase by approximately 70% during tilting (Matzen et al. 1991). It

Table 1 Data for one subject who developed presyncopal (*Hypotensive*) symptoms at 40° head-up tilt (*HUT*) and one subject who remained normotensive during maintained *HUT* (*Normotensive*). f_c Heart rate, $\overline{BP}_a$ mean arterial blood pressure, $TI_{1.5kHz}$ thoracic impedance at 1.5 kHz, TI_{100kHz} thoracic impedance at 100 kHz, $thorax_{ICW}$ the difference between $1/TI_{100kHz}$ and $1/TI_{1.5kHz}$, $LI_{1.5kHz}$ lower leg impedance at 1.5kHz, $LI_{100\,kHz}$ lower leg impedance at 100 kHz, LI_{ICW} the difference between $1/LI_{100kHz}$ and $1/LI_{1.5kHz}$

	Hypotensive			Normotensive		
	Rest	Presyncopal	Recovery	Rest	Maintained HUT	Recovery
f_c (beats · min^{-1})	65	59	60	67	78	60
$\overline{BP}_a$ (mmHg)	79	42	67	93	103	80
$TI_{1.5kHz}$ (Ω)	33.4	36.8	34.6	40.3	49.7	44.6
TI_{100kHz} (Ω)	24.1	27.1	24.9	30.1	36.7	32.2
$Thorax_{ICW}$ (S · 10^{-4})	116	97	113	84	71	86
$LI_{1.5kHz}$ (Ω)	54.6	53.3	55.0	60.2	51.9	59.5
LI_{100kHz} (Ω)	32.8	32.0	32.9	33.9	32.1	34.0
LI_{ICW} (S · 10^{-4})	122	124	122	129	119	126

remains at the increased level for the remainder of the tilt and it regains the pretilt value within 2 min of the return to the horizontal position. The leg_{ICW} increased during 10° to 40° HUT, while it decreased slightly during maintained HUT. This discrepancy between the movement of red cells and leg_{ICW} may relate to the different regions of the leg that were examined. For the determination of LI, only the lower leg was evaluated as the upper limit of impedance apparatus was 100 Ω, but it would be unlikely that the intracellular volumes of the thigh and the lower leg did not follow one another. Also during lower body negative pressure leg_{ICW} appears not to follow the elevated red cell volume of the leg (Cai et al. 2000a).

The failure of leg_{ICW} to illustrate the erythrocyte volume within the lower leg is probably because maintained HUT induces intracellular and interstitial oedema, as indicated by $LI_{1.5kHz.}$ The leg_{ICW} increased within 4 min during 10° to 40° HUT and then dropped later during maintained HUT. This was also the case in the subject who remained normotensive through maintained HUT. In the subject who developed the presyncopal symptoms at 40° HUT, leg_{ICW} did show an increase in erythrocyte volume of the leg. Whether, during maintained HUT, the decrease in leg_{ICW} relates to a change in the phase angle when intracellular or interstitial oedema develop is not known.

Graded tilting

A period of 20 min HDT did not evoke haemodynamic changes large enough to be observed as changes in the cardiovascular variables. Arjamma et al. (1996) reported that CVP was increased after 5 min HDT and then decreased during the maintained tilt. We did not notice such a transient elevation in CVP during HDT, but during HUT, CVP decreased and then stabilised at the resting value during the maintained HUT.

During HDT no impedance value changed significantly and in such situations the variations in blood volume distribution have been found to be small (Perko et al. 1994). $Thorax_{ICW}$ started to drop at HUT 15° suggesting that $thorax_{ICW}$ is sensitive to the decrease in thoracic blood volume, while leg_{ICW} did not change significantly.

$Thorax_{ICW}$ during maintained HUT

Unlike the regulated cardiovascular variables, deviations in electrical impedance relate to the volume of the monitored region (Secher et al. 1992; Pawelczyk et al. 1994). During heating an increase in TI and a decrease in LI suggest a redistribution of blood from the thorax to the extremities and a decrease in $thorax_{ICW}$ indicates a reduced CBV (Cai et al. 2000b). With the improved impedance apparatus HUT was found to have reduced $thorax_{ICW}$ to 16 $S \cdot 10^{-4}$ at the time the presyncopal symptom developed. Equally in the subject who became ill during 40° HUT, $thorax_{ICW}$ demonstrated a decrease of 18 $S \cdot 10^{-4}$, while for the subject who did not develop the presyncopal symptoms, the decrease was by only 13 $S \cdot 10^{-4}$. $Thorax_{ICW}$ returned to the pre-tilt value in 10 min after return to horizontal position in accordance with the ^{99m}Tc activity (Matzen et al. 1991).

Changes in TBI followed LI rather than TI during HUT, suggesting that TBI is dominated by the impedance of the extremities. Also during heating, TBI and LI have been found to decrease while TI increases (Cai et al. 2000b). At both 1.5 and 100 kHz, TI increased during maintained HUT reflecting the redistribution of plasma from the thorax to the leg (Matzen et al. 1991). $Thorax_{ICW}$ remained reduced (by 11 $S \cdot 10^{-4}$) until the presyncopal symptoms developed when it dropped further. Thus, the initial loss of erythrocytes in the thorax together with the further decrease in the plasma volume led to the presyncopal symptoms. This was confirmed in one subject who remained normotensive through 1 h of maintained HUT, where TI increased continuously and $thorax_{ICW}$ remained at the level established when 50° HUT was reached. In an another subject who developed the presyncopal symptoms at 40° HUT, the increase in TI was less, while $thorax_{ICW}$ dropped more.

Extravasation of fluid in the lower body during tilt resulted in an elevated Hct. According to Tjin et al. (1998), a 10% change in Hct increases resistivity by only 0.9%. Accordingly, it seemed unnecessary to compensate for the small change in admittance that may have arisen from the 3% increase in Hct noted in this study. Also it might be considered that $thorax_{ICW}$ can be used to indicate changes of ICW (erythrocyte volume) in the thorax. The $thorax_{ICW}$ was calculated without taking into account any possible influence of the phase angle. We used 1.5 and 100 kHz as the low and high frequencies, respectively, because the precision changes little with the use of 1–5 kHz in predicting ECW, and with the use of 50–1000 kHz in predicting TBW (Patel et al. 1994). Together with the results from experiments using lower body negative pressure (Cai et al. 2000a), and those derived from body heating (Cai et al. 2000b), it appears that during acute changes in circumstance, the redistribution of erythrocytes dominates the changes in thoracic intracellular water as reflected in the difference in electrical admittance at a high and a low frequency current.

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