VASCULAR DYNAMICS

*Impedance Plethysmograph Study During a Standardized Tilt Table Procedure**

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Abstract. A study, using the four-electrode impedance plethysmograph system, was completed to evaluate simultaneous variations in conduction of upper and lower body segments relative to displacement of blood volume during change in body position. Measurements of cardiac output were compared with simultaneous results by dye dilution methods as a means of assessing the use of impedance techniques to determine cardiac output during tilt table studies. Two groups, 48 healthy private pilots and 22 patients with diabetes mellitus, were tested and the results were compared.

Control and test heart rate values were higher in the afternoon than in the morning for the same healthy subjects, and the blood pressure and heart rate changes paralleled the variations in stroke volume and calf blood pulse changes. The results in the patients with diabetes differed markedly in terms of the magnitude of the cardiovascular changes and indicated the value of the tilt table in assessing 'fatigue' in the circulatory system as a result of metabolic disturbance. The change from horizontal to 65 degree head up position in the patients with diabetes showed a marked fall in thoracic stroke and conductive volume in contrast to the minimal decrease observed in healthy subjects.

1. Introduction

For many years, tilt table studies have been used for evaluating mechanisms of cardiovascular adjustment to changes in posture. Interest in control of orthostatic hypotension (Abelman and Fareeduddin, 1967; Allen *et al.*, 1945; Asmussen *et al.*, 1940; Henry, 1943), the effect of weightlessness on cardiovascular dynamics (Beaconsfield and Ginsberg, 1955; Dermksian and Lamb, 1958; Ellis, 1921; Graveline *et al.*, 1961; Graveline and Balke, 1961; Graybiel and Clark, 1961) and the need for assessing cardiovascular competency (Lagerof *et al.*, 1951; Nielsen *et al.*, 1939; Vogt, 1967; Vogt and Johnson, 1967; Vogt, 1964) have resulted in many experimental designs related to degree of attitude, time of stress, and variation in head up or head down position. Generally, heart rate and blood pressure have been the measured parameters without information concerning simultaneous central and peripheral vascular effects or consideration of the mechanisms for these effects.

The responses of the cardiovascular system to changes in posture reflect the vasomotor activity in central and peripheral segments during adjustments of the biologic system to displacements of blood volume in and out of the torso. Little attention has been given the rate and magnitude of blood volume displacements from the thorax when subjects change from a horizontal to a 65 degree head up position. Although

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the variations in heart rate and blood pressure have been presumed to result from changes in cardiac return, a systematic study of simultaneous central and peripheral vascular dynamics (as a means of establishing the mechanisms of the responses) during a standardized tilt table procedure has not been reported.

Graybiel and McFarland (1941) suggested the use of the tilt table test to determine aptitude for flying and to assess susceptibility to fainting and ease of 'blacking out' during unusual aircraft attitudes. Despite the variability of tilt table test results, Shvartz (1968) reported a consistent relationship between heart rate and blood pressure data during tilt table tests and suggested systolic blood pressure as the most reliable measurement during orthostasis. Neither study provided information concerning simultaneous central and peripheral blood pulse volume changes.

To provide some of the needed information, a four electrode impedance plethysmograph was used to (1) study central and peripheral cardiovascular changes in healthy subjects during a standardized tilt table test to furnish a comparative basis for laboratory and flight data; (2) compare the results of tilt table studies performed on the same individual in the morning and in the afternoon; (3) compare the results of tilt table studies on healthy private pilots with those obtained on patients with diabetes mellitus as a means of evaluating the circulatory 'fatigue' associated with pathologic changes; and (4) measure (in addition to heart rate, systemic blood pressure, cardiac output, and calf blood flow) the total change and the rate of change in conductive volume as the blood leaves the thorax and enters the lower extremity during change to upright attitudes.

2. Materials and Methods

The study was organized in two parts. Part I concerned 48 healthy pilots. Part II was related to tests in 22 patients with diabetes mellitus.

All tests were conducted in a room with constant temperature (25 °C) and humidity (45%). Subjects, dressed in trousers and shoes, were without medication for at least 48 hours and without cigarettes for at least 12 hours before the test. Studies were performed between 9 and 10 a.m. and between 4 and 5 p.m. Diabetic patients were selected at random without regard to age, sex, therapy, or severity of disease.

A motorized seven-foot X-ray table with a 0 to 90 degree arc of motion was used. A full-length foam pad (thickness, 4 in.) was placed on the table with a foot stop attached to one end to support the subjects in the head up position. The time for change of position (from 0 to 65 degrees) was 15 seconds.

Following application of electrodes for measuring impedance changes in the chest and calf segments, the subjects were instructed to lie supine on the padded tilt table. Following a five minute control study, the table was adjusted to a 65 degree position. Cardiovascular parameters were measured immediately (<1 minute) and at one minute intervals for 15 minutes. The table was returned to the horizontal (0 degrees) attitude; records of cardiovascular changes were obtained immediately (<1 minute) and at one minute intervals for a five minute recovery period. Of particular interest was the change in thoracic and calf segment resistance as conductive changes occurred relative to blood and tissue fluid volume displacement during the change in attitude from the horizontal to the head up position and during the return to the control level (0 degrees) (Figures 1 and 2).

	Control minutes	65° Head up minutes	0° Horizontal minutes
Heart rate (ECG)	1 2 3 4 5	Immediate 1 2 5 10 15	Immediate 1 3 5
Thoracic pulse volume	×______×	×____________×	×________×
Thoracic conductive volume shift	×______×	×____________×	×________×
Calf pulse volume	×______×	×____________×	×________×
Calf blood flow	×______×	×____________×	×________×
Calf conductive volume shift	×______×	×____________×	×________×
	Table 0°	Table 65° Head up	Table 0°

×______× Parameters measured at designated time intervals.

Fig. 1. Experimental protocol.

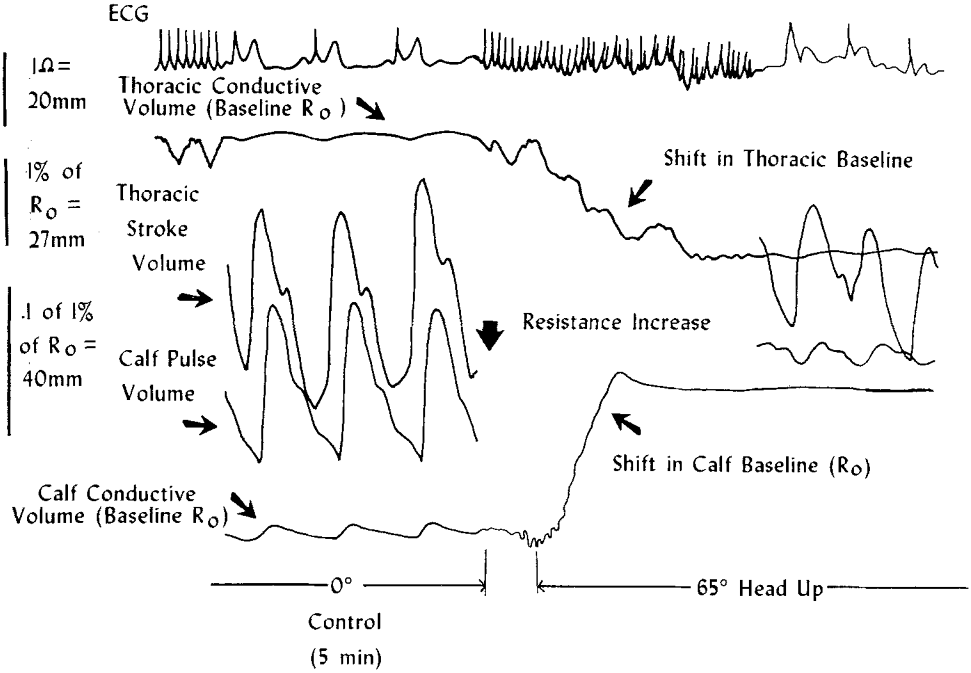

Fig. 2. Records of cardiovascular parameters during tilt table test (healthy subject).

A. IMPEDANCE PLETHYSMOGRAPH (MANUAL BALANCING)

In the four-electrode plethysmograph system used for calf segment measurements, current (0.12 mA at 120 mV) is introduced to an outer set of electrodes (I_1, I_2), and variation in conduction of the current (as a function of blood pulse volume in thoracic and calf segments) is detected between inner electrodes (E_1, E_2). The electrical plethysmograph system used in these studies has been described by Bagno and Liebman (1959); Nyboer, (1959). Output from the plethysmograph was connected to an Ampex FR 300 seven-channel magnetic tape recorder and output from this system conditioned through Sanborn preamplifiers and recorded on a 1508 Visicorder with a 40 cps galvanometer. In practice, circumferential electrodes were connected to the calf segments, the bridge was balanced, and pulsations were recorded. Following the study, the electrode leads were electrically switched to a decade substitution box and the segmental resistance substituted by means of a variable potentiometer (0–500 ohms) to balance the bridge. A 0.1 of 1% change in balanced segmental resistance (R_0) was recorded for comparison with recorded pulses. The pulses were calibrated in ohms and quantitatively analyzed for volume information. Each pulse volume multiplied by heart rate expressed blood flow to calf segments. The minute volume divided by segmental volume/100 ml tissue expressed flow/100 ml tissue.

B. IMPEDANCE PLETHYSMOGRAPH (SELF BALANCING)

The modified Kelvin double bridge circuit used for thoracic studies minimizes movement artifacts by automatically rebalancing following marked baseline shifts. The four-terminal bridge eliminates the voltage drop at the input from the measurement circuit by feeding a constant current into the ends of the segments in which the impedance measurements are to be taken. Two other electrodes pick off the potential across the portion of the studied segment. This potential is then adjusted by means of a rheostat in the current circuit until it is equal to 1/50th of the voltage feeding the bridge. This is accomplished by using a 50 to 1 resistance voltage divider in the other legs of the bridge circuit and subtracting the potential across the segment to be measured from the potential across the smaller of these voltage divider resistors. The resistance of the measured segment can be calibrated by the adjustment of the rheostat in the current lead. Because the cardiac impedance change is in the order of 0.1% of the segment impedance, artifacts due to the subject motion can greatly interfere with the measurements and force the bridge out of balance. The modified bridge minimizes these artifacts by automatically keeping the bridge in balance despite marked body movements and detects resistance of the measured segment (baseline) as well as the pulsating resistance changes synchronous with the cardiac cycle (Allison and Bagno, 1967). The self-adjusting time delay is made a function of the bridge unbalance so that a large unbalance ($>10\%$) returns to balance within approximately 1 cardiac cycle, while a small unbalance ($<3\%$), within the range of the recorder requires approximately 20 cardiac cycles to return to stable balance. The DC diode current is recorded as total resistance of the measured segment on one recorder, and the pulsatile information can be recorded on another recorder.

In practice, electrodes were connected to the subject, and the bridge was manually balanced to null; the balancing circuit switched to automatic, and when the subject's breath was held, at an end tidal level, pulsatile and baseline (R_0) information was recorded. The baseline and pulsatile output from the unit was connected to the Ampex tape recorder and the output from this unit connected to a 1508 Visicorder through 40 cps galvanometers. Following each study, the electrode leads were electrically switched to a resistance substitution network (0–800 ohms with 0.1, 1, and 10 ohm steps) and the bridge rebalanced on manual position. Following return to automatic balance configuration, 1-ohm-increase steps and 1% changes in segmental resistance were recorded for calibration of the baseline (1 ohm) and pulsatile (1%) information.

C. PHYSIOLOGIC PARAMETERS

(1) *Heart Rate*

Stainless steel electrodes (3 cm x 5 cm) were fastened to ankles and wrists by means of rubber straps, and the electrocardiographic cable was connected to a preamplifier (Electronic Medical Specialties Company). Lead II was recorded on the 1508 Honeywell Visicorder. Heart rate was calculated from paper speed (25 mm/sec) and paper travel (mm) equivalent to 5 cardiac cycles.

(2) *Blood Pressure*

A pneumatic cuff (14 cm wide) was fastened to the right brachial region by means of Velcro fasteners. The cuff was coupled to a mercury column, and systolic and diastolic pressures were recorded in the usual auscultatory manner. An extension tube was connected between the stethoscope ear pieces and the diaphragm button which was held in place over the antecubital region by means of an elastic band. Pressures were taken at one-minute intervals throughout the tilt table procedure.

(3) *Thoracic Blood Pulse Volume (Stroke Volume × Heart Rate = Cardiac Output)*

Aluminum strip electrodes (0.25 in. wide) backed with adhesive tape were fastened to the neck, posterior thorax, and lumbar region following application of a sparing amount of ECG paste. The upper electrode (I_1) was placed circumferentially around the neck; the second (E_1) was placed at the level of the seventh cervical vertebra; the third (E_2) at the level of the twelfth thoracic vertebra; and the fourth (I_2) at the level of the second lumbar vertebra. The second, third, and fourth strips were 30 cm in length, and placed on the back horizontally (Allison *et al.*, 1962; Allison, 1963; Allison *et al.*, 1964). Leads from the self-balancing impedance plethysmograph were connected to the aluminum electrodes by means of alligator clip leads. Current (0.12 mA at 120 mV) was introduced to I_1-I_2, and variation in conduction of the current as a function of thoracic blood volume was detected between E_1-E_2. The bridge was balanced (manual position), and a switching circuit was activated for standardization. The substitution resistance network (0–800 ohms with 0.1-, 1-, and 10-ohm steps) was adjusted to balance the plethysmograph unit; the unit was switched to automatic balance control; and a signal equivalent to 1% of the balance resistance was introduced and recorded on the visicorder for standardization of the pulsatile information. The output signal from the baseline impedance change was connected to a Sanborn 350–2700 preamplifier. The 50-mV standard signal output to the visicorder was adjusted for an output of 180 mm (2 cm less than full scale on 200-mm-width paper) and attenuated 200 times (10 ×). The tracing was positioned 5 cm from the left edge of the paper, and 1-ohm-increase steps in resistance were recorded for standardizing baseline changes. The plethysmograph unit was switched from the substitution network to the subject, who was instructed to 'hold his breath' at a resting end expiratory position for several seconds (5–7 heart cycles) while thoracic blood pulse volumes and baseline changes were recorded at 1-minute intervals. The baseline information (R_0) represented the conduction of the thorax detected between E_1-E_2 and was a reference for the pulsatile information (ΔR).

Five recorded pulses were extrapolated along the pulse slope following peak systole to the beginning of the cycle as a means of predicting the maximal volume change for the pulse cycle (Allison, 1960). The amplitude of the intercept with a vertical line corresponding to beginning systole was calibrated in ohms and applied to the formula:

$$\frac{\Delta R}{R_0} = \frac{\Delta V}{V_0^*} \quad \text{for calculation of thoracic stroke volume}$$

$$\Delta V = \frac{(V_0)(\Delta R)}{R_0} \qquad V_0^* = \varrho \frac{L^2}{R_0},$$

where ϱ = resistivity (ohm cm) of whole blood at 37°C, L = distance between detecting electrodes E_1, E_2 in cm and R_0 = resistance of the thoracic segment between E_1 and E_2 in ohms.

(4) *Calf Blood Pulse Volumes*

One pair of circumferential aluminum strip electrodes was placed 5 cm distal to the patella on each lower leg segment and a length of 20 cm was marked off. Another pair of circumferential electrodes was fastened on each lower calf following application of sparing amounts of electrocardiographic paste to the electrodes. The inner pairs of strips on each leg were connected to the corresponding strips of the other leg by means of a connecting clip lead. In this manner, the calf segments were connected in parallel (electrically) and measured as a total segment (Allison, 1960; Allison, 1966). The manual-balancing impedance plethysmograph leads were connected to the leg electrodes by means of alligator clip leads. Current was introduced to the outer set of electrodes (I_1, I_2), and variations in the conduction of the signal through both calf segments were detected between E_1-E_2. Prior to recording blood pulse volumes, the leads from the subject were connected (electrically) to an internal adjustable resistance substitution circuit, and the bridge balanced by adjusting the resistance values which were arranged in units of 10 and 0.1-ohm steps on a vernier controlled potentiometer (100 ohm-10 turn). A standard signal equal to 0.1 of 1% of the balanced resistance was introduced into the circuit, and the output recorded on the visicorder for calculation of blood pulse volume and blood flow information.

D. THORACIC CONDUCTIVE VOLUME DISPLACEMENT DURING TILT TABLE PROCEDURES

The measured segmental resistance of the thorax between E_1-E_2 varied as subjects changed from a horizontal to a 65 degree head up position. The shift in baseline recorded on the visicorder was measured (mm) and calibrated in ohms as a change in resistance (ΔR). The conductive volume of the thorax in terms of blood was calculated: $V_0 = (\varrho L^2/R_0)$, where ϱ = resistivity of whole blood at 37°C (150 ohm cm), L = distance between detecting electrodes (E_1-E_2) in cm, and R_0 = resistance of the thoracic segment between detecting electrodes (E_1-E_2) in ohms. The change in resistance (ΔR) of the thoracic segment between detecting electrodes (E_1-E_2) in ohms which occurred at <1, 1, 5, 10, and 15 minutes at 65 degrees head up position was applied to the ratio $\Delta R/R_0 = \Delta V/V_0$, and $\Delta V = (V_0)(\Delta R)/R_0$ was calculated (Schaeffer *et al.*, 1968).

E. CALF CONDUCTIVE VOLUME CHANGES DURING TILT TABLE PROCEDURES

When subjects were placed on the tilt table and shifted from the horizontal to the 65 degree head up position, the volume of calf segments initially increased. The increase in segmental volume resulted in a decrease in segmental resistance of the calf segments. The change in resistance (ΔR) which was obtained during each substitution procedure was applied to the following formula: $\Delta V = \varrho(L^2/R_p)$, where ϱ = resistivity of blood (ohm cm), L = distance between detecting electrodes E_1-E_2 (cm), and R_p = the resistance due to the parallel electrical shunting which occurred as the new volume of blood entered the segment (Allison, 1966). The change in conductive volume during postural changes was expressed as percentage of the total conductive volume of the calf segment ($V_0 = \varrho(L^2/R_0)$ where R_0 = resistance of the calf segment between electrodes E_1-E_2 separated by a distance $L = 20$ cm).

F. DETERMINATION OF CARDIAC OUTPUT – CARDIOGREEN DYE DILUTION METHOD

In each subject, the right elbow was prepared using sterile technique and draped. The right brachial artery was carefully palpated and localized; the skin overlying it was infiltrated with xylocaine (1% solution). The right brachial artery was cannulized with a Cournand needle (No. 16), and the needle was taped down. A three-way stopcock attached to the Cournand needle connected it to the tubing system and permitted flow of blood from the right brachial artery through the cardiodensitometer cuvette to a 50 cc glass syringe utilized to withdraw the blood by means of a constant withdrawal pump system. A heparin saline solution was utilized intermittently throughout the procedure to flush the Cournand needle so as to avoid blood clotting. The left elbow flexure was then draped and prepared under sterile technique. The skin was infiltrated with xylocaine (1% solution), and a large intracatheter needle was inserted into the left cepahlic vein. The needle was withdrawn following advancement of the catheter, the plastic catheter taped into position, and a three-way stopcock was connected to the catheter. A syringe (10 ml) containing normal saline, utilized for flushing, was connected to the stopcock as well as a sterile disposable syringe (2.5 ml) which was utilized to inject the cardiogreen dye solution.

Control studies were begun which consisted of: (1) starting the constant pump withdrawal mechanism; (2) turning the stopcock of the Cournand needle to allow arterial blood flow through the cardiodensitometer and withdrawal system so that the baseline could be recorded on the cardiodensitometer record; (3) injecting 1.5 cc of cardiogreen dye solution (5 mg/ml) through the intravenous catheter quickly turning the stopcock and flushing the same catheter with approximately 3 to 4 ml of normal saline with a syringe (10 ml); (4) observing the cardiac output curve recorded by the cardiodensitometer and the recirculation that occurred. Following this, the stopcock connected to the Cournand needle was turned so it would permit the heparin-normal saline solution to flow through the arterial needle to flush it clear of blood in preparation for the next study.

The optical section of the cardiodensitometer scans the optical density of the blood pulled through the cuvette, and results are presented as a curve on a moving paper chart. The curve is linear with the concentration of the dye in the bloodstream. A mechanical integrator computes the area under the curve, and, with the aid of a nomogram, cardiac output is calculated. Division of cardiac output values by heart rate determined stroke output. In practice, the impedance measurements were made simultaneously with the cardiogreen dye dilution curve measurements for comparative purposes. Calculated blood pulse volumes were multiplied by heart rate and expressed cardiac output.

3. Results and Discussion

A. DETERMINATION OF STROKE VOLUME AND CARDIAC OUTPUT

When a high frequency signal (50 or 120 kHz) is introduced to electrodes placed on the chest, the conduction of the signal is dependent upon the electrical properties of body tissue, fluid, blood, and relative difference between conductive media and volume of gas in the chest. During systole, as a new volume of blood is delivered to the chest and pulmonary circulation, the conduction of the signal increases in a pulsatile manner. It is correct to discuss pulmonary stroke volume and cardiac output determinations in terms of conductive volumes (Allison, 1966). Previous animal experiments have established the association of thoracic impedance pulsations with the pulmonary circulation rather than the systemic circulation (Allison, 1966), presumably due to current distribution into the highly perfused lung fields. The mathematical interpretation of pulsatile variations in electrical resistance of the chest depends upon several assumptions. The chest is considered to be a cylinder of constant cross section and a length determined by the distance between detecting electrodes (E_1-E_2). The resistivity of blood is assumed to be constant (150 ohm cm at 37 °C). The velocity changes related to each blood pulse volume are minimal compared with the volume-conductive changes, and the measured resistance between the detecting electrodes (as determined by a four-electrode impedance network) is the result of the resistivity of tissues in the field and the distribution of current in the 'conductive' volume which may not correspond to geometric dimensions. The correlations between calculated cardiac output based on thoracic impedance changes and cardiogreen dye dilution studies provide an

TABLE I

Comparison of cardiac output determinations by dye dilution studies and impedance studies during control periods[a])

Subject	Age (yrs)	Height (cm)	Weight (kg)	Chest circumference (cm)	Cardiogreen cardiac output (l/min)		Impedance cardiac output (Pulmonary) (l/min)	
AT	24	160	61	83	(1) 1.25	(2) 1.6	(1) 1.11	(2) 1.05
SE	32	173	68	93	(1) 1.77	(2) 2.65	(1) 2.8	(2) 2.2
HE	21	175	75	93	(1) 7.8	(2) 7.0	(1) 5.4	(2) 3.7
BO	22	175	75	94	(1) 6.2	(2) 6.9	(1) 6.1	(2) 7.1
FE	31	179	70	97	(1) 1.45	(2) 1.17	(1) 2.4	(2) 2.1
AM	25	175	75	101	(1) 4.4	(2) 5.5	(1) 4.7	(2) 4.6
CR	28	179	80	109	(1) 4.6	(2) 4.5	(1) 3.7	(2) 4.4
				Mean	3.9	4.2	4.0	3.7
				Std. dev.	±2.05	±2.44	±1.6	±1.79

[a] Subjects horizontal in supine position.

empirical basis for the assumptions of the impedance measuring system (Allison, 1966; Allison, 1966; Kinnen *et al.*, 1964).

It is clear that any change in resistance (ΔR) must refer to the 'electrical' reference volume, e.g., $\Delta R/R_0 = \Delta V/V_0$, where $V_0 = \varrho(L^2/R_0)$. The impedance studies closely approximated the dye dilution results (Table I). The first studies differed by 3%, and the second by 11%. The latter discrepancy may reflect the technique of both methods or the change in thoracic dynamics encouraging the pulmonary circulation to respond differently from the systemic. The most probable reason for discrepancy between the dye dilution studies and the impedance cardiac output determinations is the fact that the conventional cardiogreen dye method reflects primarily the systemic cardiac output and the impedance system reflects the pulmonary output. The assumption that both systems respond similarly to given stimuli and environments may be in error. Because of the questionable reactive error introduced by needles and catheters, cardiac output comparisons by dye dilution methods were not obtained during head up tilt table procedures. The inherent potential of syncopal attack discouraged the additional risk to subjects often precipitated by the dye dilution techniques while subjects were in the head up position. All responses were referred to control values, and it seemed reasonable on the basis of the correlated studies to accept the impedance information during control periods (Kinnen *et al.*, 1964). The consistency of results in all groups during tilt table procedures suggests the reliability of the impedance system during these dynamic stages.

B. PART I

Tilt table procedures, a total of 90 separate tests, were performed on 48 healthy private pilots (Table II). Sixty of these tests were paired results in 30 subjects studied in the morning and in the afternoon. Although on different days, the results were compared

TABLE II

Average values for subjects according to age groups and time of study (civilian pilots)

Age	Groups	No.	Age (years)	Height (cm)	Weight (kg)	Thoracic circumference (cm)	Calf[a] volume (ml)	Flight hours
19–29								
	A.M.	6	24 ± 4	182 ± 9	76 ± 9	94 ± 3	3228 ± 342	188 ± 196
	P.M.	4	28 ± 2	186 ± 9	81 ± 6	96 ± 2	3331 ± 186	262 ± 203
	Unpaired	3	25 ± 1	181 ± 5	77 ± 5	95 ± 3	3161 ± 243	1023 ± 1046
	Average		26 ± 2	183 ± 2	78 ± 2	95 ± 0.8	3240 ± 70	691 ± 659
30–39								
	A.M.	8	36 ± 2	181 ± 7	87 ± 10	102 ± 0.5	3846 ± 429	509 ± 701
	P.M.	10	37 ± 2	178 ± 7	83 ± 10	101 ± 5	3712 ± 449	498 ± 651
	Unpaired	8	36 ± 2	183 ± 7	88 ± 7	102 ± 3	3645 ± 345	486 ± 612
	Average		36 ± 0.5	181 ± 2	86 ± 2	102 ± 3	3734 ± 84	497 ± 88
40–49								
	A.M.	17	44 ± 3	177 ± 4	78 ± 9	99 ± 7	3544 ± 464	726 ± 1376
	P.M.	13	44 ± 3	177 ± 4	79 ± 10	99 ± 8	3402 ± 475	844 ± 1539
	Unpaired	14	45 ± 4	176 ± 7	79 ± 12	99 ± 9	3399 ± 470	839 ± 1478
	Average		44 ± 0.5	177 ± 0.5	79 ± 0.5	99	3448 ± 68	816 ± 66
50–59								
	A.M.	2	54 ± 4	179 ± 4	81 ± 8	99 ± 4	3200 ± 121	760 ± 640
	P.M.	2	54 ± 4	179 ± 4	81 ± 8	99 ± 4	3200 ± 121	760 ± 640
	Unpaired	2	54 ± 4	178 ± 3	82 ± 9	103 ± 4	3200	3573 ± 3427
	Average		54	179 ± 0.5	81 ± 0.5	102 ± 2	3200	1698 ± 1326
60–69								
	A.M.	1	61	179	84	103	3331	1000
	P.M.	1	61	179	84	103	3331	1000
	Unpaired	–	–	–	–	–	–	–
	Average		61	179	84	103	3331	1000
Grand total average ± = Std. dev.			40 ± 10	180 ± 2	81 ± 3	100 ± 3	3405 ± 212	940 ± 413

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[a] Calf volume represents combined volume of bilateral calf segments.

for possible diurnal variations. The remaining 26 tests were performed, 16 in the morning and 10 in the afternoon, without consideration of diurnal variation.

Control values for the total group (Table III) were characterized by individual differences between morning and afternoon studies. Although the average changes for given age groups were not markedly different, heart rates tended to be higher during control and tilt table procedures during the afternoon test periods. This was particularly true for the age groups, 19 to 39 years. The paired and unpaired subject responses to the 15 minute 65 degree head up attitude were characterized by a slight increase in systolic blood pressure at 15 minutes, with a more pronounced increase in diastolic pressure (Tables IVa, b; Figure 3); an increase in heart rate which was more pronounced during afternoon studies in the paired subjects (Tables IVa, b); and a con-

TABLE III

Average control values for thorax and calf segments (healthy subjects)

Age group	Blood pressure		Thorax				Calf segments (20 cm)			
	Systolic (mm Hg)	Diastolic	Segmental[a] resistance (ohms)	Stroke volume (ml)	Cardiac output (l/min)	Cardiac index (l/min/m^2)	Segmental[a] resistance (ohms)	Pulse[b] volume (ml)	Pulse rate (per min)	Blood flow (ml/min/100 ml)
Same Subject										
19–29										
A.M. (N = 4)	121 ± 11	66 ± 7	30 ± 5	95 ± 24	5.873 ± 1.3	4.04 ± 0.7	30 ± 4	1.0 ± 1.8	60.8 ± 6	3.8 ± 1.3
P.M. (N = 6)	117 ± 5	69 ± 7	27 ± 1.5	101 ± 26	7.351 ± 2.6	4.95 ± 1.8	26 ± 3	1.9 ± 1.0	71.0 ± 8	4.5 ± 2.3
Combined avg.	119 ± 2	68 ± 1.5	29 ± 2	98 ± 3	6.7 ± 0.8	4.50 ± 0.45	28 ± 2	2.1 ± 0.1	65.9 ± 5	4.1 ± 0.35
30–39										
A.M. (N = 9)	118 ± 9	76 ± 5	31 ± 4	68 ± 39	5.590 ± 2.1	3.66 ± 1.5	30 ± 3	1.9 ± 0.8	71.5 ± 5	3.9 ± 1.6
P.M. (N = 9)	117 ± 12	86 ± 20	32 ± 5.5	73 ± 30	4.756 ± 1.5	3.16 ± 1.0	27 ± 4	1.8 ± 0.9	68.0 ± 8	3.5 ± 1.4
Combined avg.	118 ± 0.5	81 ± 5	32 ± 0.5	71 ± 3	5.173 ± 0.42	3.41 ± 0.3	28 ± 2	1.9 ± 0.1	69.7 ± 1.7	3.7 ± 0.20
40–49										
A.M. (N = 15)	121 ± 16	79 ± 11	30 ± 5	66 ± 20	4.424 ± 1.5	3.06 ± 1.0	31 ± 5	1.9 ± 1.4	69.0 ± 14	3.6 ± 2.4
P.M. (N = 15)	115 ± 12	74 ± 10	28 ± 1.9	65 ± 23	4.605 ± 1.2	3.04 ± 1.0	32 ± 5	1.8 ± 1.0	70.0 ± 10	3.7 ± 3.0
Combined avg.	118 ± 3	79 ± 6	30.5 ± 0.5	66 ± 0.5	4.515 ± 0.1	3.05 ± 0.01	32 ± 0.5	1.9 ± 1.0	70.0 ± 0.5	3.65 ± 0.05
50–59										
A.M. (N = 2)	144 ± 14	90 ± 6	31 ± 4	63 ± 14	3.54 ± 0.4	2.50 ± 0.13	34 ± 0.5	1.2 ± 0.5	58.0 ± 7	2.2 ± 1.0
P.M. (N = 2)	151 ± 7	87 ± 4	29 ± 1	53 ± 2	3.29 ± 0.2	2.30 ± 0.3	26 ± 8.0	2.0 ± 1.3	62.0 ± 2	4.0 ± 3.0
Combined avg.	148 ± 4	89 ± 2	30 ± 1	58 ± 5	3.40 ± 0.1	2.50 ± 0.2	30 ± 4.0	1.6 ± 0.4	60.0 ± 2	3.1 ± 0.8
60–69										
A.M. (N = 1)	127	83	39.1	58.8	4.182	2.86	30.9	1.43	73	3.14
P.M. (N = 1)	127	64	34.1	48.0	4.350	2.98	30.6	4.01	91	10.9
Combined avg.	127 ± 0	74 ± 9	37 ± 3	53 ± 5	4.2 ± 0.1	2.92 ± 0.1	30.7 ± 0.2	2.7 ± 1	82 ± 9	7.02 ± 4
Unpaired										
A.M. (N = 16)	121 ± 9	77 ± 13	29 ± 4	94 ± 45	5.711 ± 2.3	3.60 ± 1.5	32.3 ± 5.7	1.8 ± 0.71	68.0 ± 11	3.5 ± 1.3
P.M. (N = 10)	126 ± 14	79 ± 12	29 ± 3	79 ± 39	4.775 ± 1.8	3.30 ± 1.3	30.0 ± 5.5	1.8 ± 0.66	66.0 ± 9	2.8 ± 0.56
Combined avg.		78 ± 1	20 ± 0.0	87 ± 8	5.243 ± 0.47	3.50 ± 0.15	31.1 ± 1.2	1.8 ± 0.00	67.0 ± 1	3.2 ± 0.35
± = Std. dev.	124 ± 3									

[a] Resistance between detecting electrodes E_1–E_2. [b] Pulse volume of both calf segments (20 cm) measured simultaneously.

TABLE IVa

Paired cardiovascular responses during 65° head up attitude and recovery in healthy subjects

Paired A.M. studies (N = 34)	Blood pressure systolic (mm Hg)	Diastolic	Pulse rate (per min)	Stroke volume (ml)	Cardiac output (l)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
Control (Table 0°)	125 ± 10	79 ± 5	66 ± 6	73 ± 13	4.811 ± .959	–	1.70 ± .3	3.3 ± .6	–
Table 65° Head Up Responses:									
< 1 min	130 ± 13	85 ± 5	71 ± 9	53 ± 8	3.907 ± .703	−265 ± 128	1.10 ± 1.0	2.7 ± .7	+28
1 min	129 ± 9	85 ± 5	75 ± 9	55 ± 3	4.151 ± .674	−310 ± 48	1.50 ± 0.1	2.8 ± .9	+70
2 min	128 ± 9	87 ± 6	77 ± 9	61 ± 7	4.684 ± .312	−178 ± 101	1.20 ± 0.4	2.7 ± .1	+76
5 min	129 ± 9	87 ± 7	76 ± 6	56 ± 7	4.692 ± .762	−152 ± 96	1.41 ± 0.3	3.1 ± .8	+88
10 min	131 ± 12	89 ± 41	76 ± 7	54 ± 7	4.102 ± .769	−159 ± 2	1.33 ± 0.3	3.1 ± .8	+114
15 min	130 ± 9	87 ± 7	76 ± 7	63 ± 3	4.663 ± .795	−141 ± 62	1.41 ± 0.5	3.2 ± 1.2	–
Table 0° Responses:									
< 1 min	125 ± 7	85 ± 8	68 ± 8	63 ± 1	4.29 ± .96	+96 ± 1	1.90 ± 0.06	3.7 ± .9	–
5 min	127 ± 10	82 ± 7	65 ± 6	73 ± 13	4.75 ± .96	–	1.80 ± 0.3	3.5 ± .4	–

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[a] $v_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

TABLE IVb

Paired cardiovascular responses during 65° head up attitude and recovery in healthy subjects

Paired P.M. studies (N = 30)	Blood pressure Systolic (mm Hg)	Diastolic	Pulse rate (per min)	Stroke volume (ml)	Cardiac output (l)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
Control Table 0°	125 ± 14	73 ± 8	72 ± 10	70 ± 21	4.905 ± 1.40	–	2.26 ± 0.9	2.22 ± 0.44	–
Table 65° Head Up Responses:									
< 1 min	121 ± 13	81 ± 8	86 ± 14	53 ± 9	4.602 ± 0.98	− 212 ± 181	1.70 ± 1.1	4.80 ± 4.00	+ 88
1 min	125 ± 14	82 ± 10	86 ± 13	53 ± 8	4.490 ± 0.77	− 176 ± 95	1.20 ± 0.4	3.40 ± 2.00	+ 52
2 min	125 ± 15	84 ± 10	89 ± 83	55 ± 10	4.749 ± 0.12	− 162 ± 77	1.50 ± 0.5	3.70 ± 1.30	+ 116
5 min	126 ± 15	85 ± 7	84 ± 13	55 ± 11	4.794 ± 0.12	− 181 ± 123	2.90 ± 0.2	5.30 ± 0.3	+ 110
10 min	127 ± 13	80 ± 14	85 ± 13	46 ± 24	4.770 ± 0.12	− 197 ± 140	2.10 ± 0.8	5.30 ± 3.0	+ 2
15 min	126 ± 15	85 ± 10	86 ± 12	50 ± 9	4.560 ± 0.74	− 102 ± 26	2.10 ± 0.9	5.50 ± 0.3	+ 166
Table 0° Responses:									
< 1 min	123 ± 9	77 ± 6	75 ± 11	74 ± 1	3.740 ± 1.20	+ 93 ± 32	2.30 ± 0.2	5.64 ± 6.0	–
5 min	128 ± 13	81 ± 6	72 ± 10	70 ± 21	4.905 ± 0.1	–	1.50 ± 0.5	4.73 ± 3.0	− 58

[a] $v_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

TABLE IVc

Unpaired cardiovascular responses during 65° head up attitude and recovery in healthy subjects

Unpaired studies (N = 26)	Blood pressure Systolic (mm Hg)	Diastolic	Pulse rate (per min)	Stroke volume (ml)	Cardiac output (l)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
A.M. = 16									
P.M. = 10									
Control									
(Table 0°)	119 ± 12	76 ± 12	62 ± 8	81 ± 38	4.986 ± 2.04	-	1.7 ± 0.7	3.02 ± 1.1	-
Table 65°									
Head Up									
Responses:									
< 1 min	125 ± 12	83 ± 12	78 ± 12	64 ± 34	4.604 ± 2.03	− 244 ± 198	1.1 ± 0.7	2.70 ± 1.7	+ 58
1 min	126 ± 14	84 ± 15	76 ± 11	55 ± 30	4.482 ± 2.20	− 114 ± 52	1.2 ± 0.6	2.70 ± 1.6	+ 34
2 min	126 ± 15	88 ± 17	76 ± 11	65 ± 64	4.968 ± 2.20	− 148 ± 129	1.2 ± 0.6	2.50 ± 1.2	+ 74
5 min	125 ± 13	86 ± 14	78 ± 12	66 ± 32	5.123 ± 2.50	− 134 ± 142	6.4 ± 0.2	3.10 ± 2.0	+ 78
10 min	126 ± 16	88 ± 13	76 ± 12	71 ± 48	4.95 ± 2.80	− 139 ± 131	1.4 ± 0.8	3.00 ± 1.7	+ 90
15 min	128 ± 16	87 ± 15	76 ± 10	68 ± 39	5.24 ± 3.20	− 166 ± 145	1.3 ± 0.1	3.30 ± 3.0	+ 122
Table 0°									
Responses:									
< 1 min	124 ± 11	83 ± 14	64 ± 8	83 ± 10	7.85 ± 3.10	+ 105 ± 98	1.8 ± 0.9	3.30 ± 1.6	− 132
5 min	124 ± 10	79 ± 13	60 ± 7	81 ± 38	4.96 ± 2.00	-	1.6 ± 0.9	2.90 ± 1.4	-

[a] $V_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

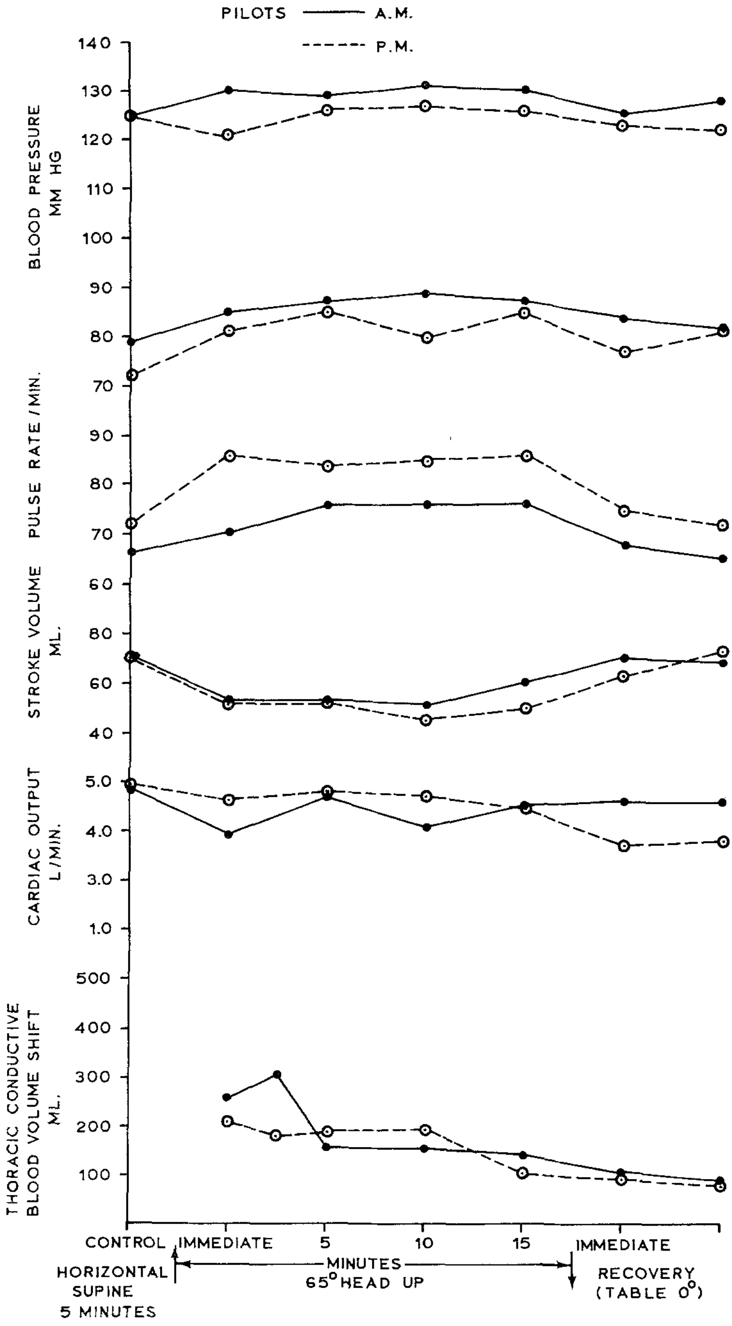
PILOTS
A.M.
P.M.
BLOOD PRESSURE MM HG
PULSE RATE / MIN.
STROKE VOLUME ML.
CARDIAC OUTPUT L/MIN.
THORACIC CONDUCTIVE BLOOD VOLUME SHIFT ML.
140
130
120
110
100
90
80
70
90
80
70
60
80
60
40
5.0
4.0
3.0
1.0
500
400
300
200
100
CONTROL
IMMEDIATE
5
10
15
IMMEDIATE
HORIZONTAL SUPINE 5 MINUTES
MINUTES
65° HEAD UP
RECOVERY (TABLE 0°)

Fig. 3a.

sistent decrease in stroke volume and cardiac output immediately following the change to a 65 degree head up attitude observed and associated with the increase in heart rate (Tables IVa, b, c). The tilt table procedure was associated with a decrease followed by an increase in calf blood pulse volume associated with an increase in conductive volume in the calf segments as the head up time (65 degrees) approached 15 minutes. The increase in calf blood flow during the head up attitude reflects the increase in heart rate and conductive volume (Tables IVa, b, c; Figure 3).

In the healthy group, the average percent change of systolic blood pressure from control values ranged, at 15 minutes, from −3.2 to +8, and the diastolic pressure ranged from +10 to −16. The pulse rate change (+19) was higher in the afternoon studies than in those completed in the morning (+15). The unpaired group was characterized by a greater increase in heart rate than the paired morning or afternoon studies (+23). This finding is consistent with a lower control heart rate in the unpaired group (Table

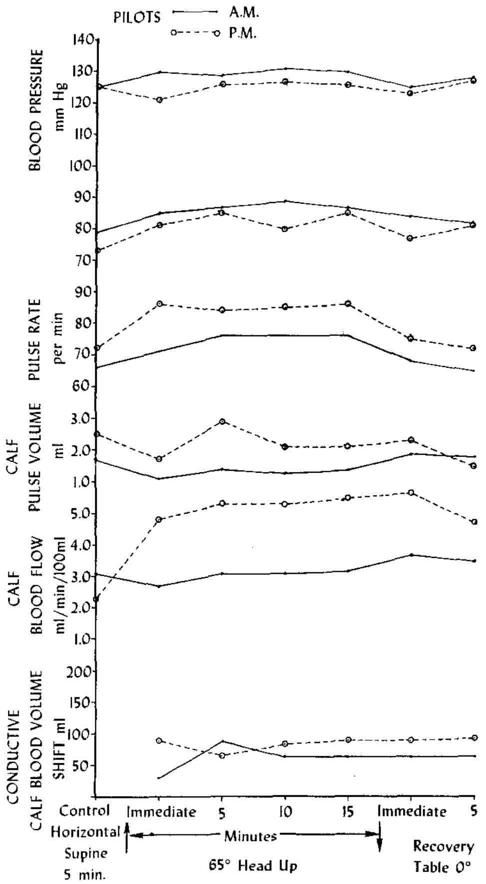

Fig. 3b.

Fig. 3. Comparison of morning and afternoon responses to tilt table stress in healthy pilots. (a) Thoracic studies. (b) Calf segment studies.

TABLE Va

Cardiovascular changes expressed as percent of control
(Immediately following and fifteen minute intervals during tilt 65° head up)

Grouped A.M. Studies (N = 34)	Blood pressure Systolic (mm Hg)	Diastolic	Pulse rate (per min)	Stroke vol. (ml)	Cardiac output (l)	Thoracic conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf conductive volume shift (ml)
						$(V_0 = 5176)^a$			$(V_0 = 1923)^a$
Control	125	79	66	73	4.811	—	1.7	3.3	—
< 1 min	130	85	71	53	3.907	−265	1.1	2.7	28
15 min	130	87	76	63	4.663	−141	1.4	3.2	114
Percent Change from control	+4	+8	+8	−27	−20	−5	−35	−18	+1.5
	+4	+10	+15	−14	−2	−3	−18	−3	+6.0
Grouped P.M. Studies (N = 30)						$(V_0 = 5468)^a$			$(V_0 = 2135)^a$
Control	125	73	72	70	4.905		2.26	2.22	
< 1 min	121	81	86	53	4.602	−212	1.7	4.80	88
15 min	126	85	86	50	4.560	−102	2.1	5.55	166
Percent Change from control	−3.2	+11	+19	−24	−6.2	−4	−24	+118	+4
	+0.8	+16	+19	−29	−6.1	−2	−9	+150	+8

[a] $V_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

TABLE Vb

Cardiovascular changes expressed as percent of control

Unpaired studies N = 26 AM = 16 PM = 10	Blood pressure Systolic (mm Hg)	 Diastolic	Pulse rate (per min)	Stroke vol. (ml)	Cardiac output (l)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
						($V_0 = 5582$)[a]			($V_0 = 1917$)[a]
Control	119	76	62	81	4.986	—	1.7	3.02	—
< 1 min	125	83	78	64	4.604	−244	1.1	2.70	98
15 min	128	87	76	68	5.240	−166	1.3	3.30	132
Percent	+5	+9	+26	−21	−8	−4	−35	−11	+5
From control	+8	+14	+23	−16	+5	−3	−20	+9	+7
Diabetics (N = 20)						($V_0 = 3966$)[a]			($V_0 = 936$)[a]
Control	132	79	79	170	14.46		1.0	5.9	
< 1 min	124	81	87	114	12.41	−446	0.8	5.3	+32
15 min	128	87	96	92	12.20	+96	0.7	4.5	+114
Percent	−6	+3	+10	−33	−14	−11	−20	−10	+3
From control	−3	+10	+22	−46	−16	+2	−30	−24	+12

[a] $V_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

V). The decrease in stroke volume in less than 1 minute after 65 degree head up attitude ranged from -6.2% in the afternoon group to -20% in the morning group. This is in keeping with increased cardiac return associated with a moderately elevated heart rate, and it probably reflects an early protective mechanism to conserve central blood volume as a 'fatigue defense'. Generally, the 'fatigued' circulatory system is characterized by a pronounced fall in stroke volume despite an increase in heart rate. The observed moderate reduction in stroke volume in the afternoon studies would certainly be consistent with a compensatory response if fatigue was a factor in the results of the subjects studied in the afternoon. Changing from horizontal to 65 degree head up position was associated with a decrease in calf pulse volume and blood flow despite an increase in pulse rate observed in the morning studies. The decreased calf pulse volume observed in the afternoon studies was compensated by an increase in heart rate and increased blood flow associated with increased conductive volumes to the calf segments during the 15 minute head up position. It is probably more significant to observe a decrease in pulse volume and blood flow to calf segments without a corresponding exaggerated increase in heart rate than to observe a compensated increase in blood flow due to heart rate response when considering factors related to fatigue.

The segmental resistance of the calf segments measured in the subjects studied in the morning was higher, with less increase in the conductive volume of the calf segments immediately after reaching the 65 degree head up position. These results suggest a higher vascular tone with better volume compensation than was true for the afternoon group. It is particularly interesting to observe that the decrease in conductive volume in the thorax (-2 to -5%) of the healthy subjects during the 15-minute attitude is associated with an increase in conductive volume of the calf segments ($+1.5$ to 7%) (Table V). The percent changes are in reference to the corresponding thorax and calf volumes and are consistent with relative decreases and increases of corresponding segmental volumes. It is probably more nearly correct to speak of the shifts in baseline as the results of changes in total conductive volume rather than in blood volume alone because of extravascular fluid displacements in the tissues. It is questionable whether a measure of total blood volume or plasma volume would parallel the changes observed (using the impedance system) in the thorax and calf segments during the tilt table procedures.

C. SYNCOPE DURING THE TILT TABLE STUDY

One subject (not included in the normal group) experienced syncopal episodes on three separate tilt table studies. In a summary, the studies (Figures 4a, b) were characterized by a decrease in systolic and diastolic blood pressure and pulse pressure, an increase and then decrease in heart rate, and a decrease in stroke volume and thoracic conductive volume immediately before syncope. Within one minute following the 65 degree head up attitude, a marked increase in calf conductive volume was observed without a corresponding order of magnitude change in thoracic conduction. Presumably, the loss in blood volume to the lower extremities (in terms of rate and order of magnitude and the inability of the cardiovascular system to compensate rapidly

TABLE VIa

Diabetic subject information

Patient	Age (yrs)	Height (cm)	Weight (kg)	Blood pressure Systolic/ diastolic (mm Hg)	Fasting Blood sugar (mg %)	ECG	Eyeground changes	Nerve conduction reflexes (m/sec)			Therapy
									R.	L.	
G., J.H. (M)	51	211	91	160/100	140	Normal	None	Deep peroneal Post. tibial	no response 31.1	 35.4	NPH 60 units/day
McD., W.R. (F)	69	150	47	146/90	170	Normal	None	None			Lente 30 units/day
G., F.J. (M)	68	180	79	114/66	102	Normal	None	None			Diabinese 500 mg/day
W., E.R. (F)	49	158	71	160/110	108	Normal	Neg.	None			Orinase 500 mg/day
R., S.R. (M)	65	178	77	140/86	138	Normal	None	None			Orinase 500 mg/qid
J., W.H. (M)	65	178	72	164/104	58	Abnormal	None	None			None
C., E. (F)	67	158	75	190/90	164	Normal	None	None			Lente 50 units/day
C., D.L. (M)	30	162	73	140/92	216	Normal	Neg.	Deep peroneal Post. tibial	44.7 39.6	47.8 39.3	Lente 90 units/day
I., M.E. (F)	58	165	72	160/90	104	Abnormal	Neg.	Deep peroneal Post. tibial	47.1 49.4	41.7 40.1	Insulin 20 units/day
K.R. (M)	53	208	114	128/74	126	Normal	Neg.	Deep peroneal Post. tibial	41.9 36.4	41.7 37.4	Dymelor 250 mg/day
G., R.M. (M)	59	178	113	160/108	124	Abnormal	None	None			None
C., E.W. (M)	63	182	73	120/80	118	Normal	Neg.	None			NPH 16 units/day (controlled)
McI., W. (M)	70	178	72	132/78	172	Normal	Incomplete	None			NPH 60 units/day (uncontrolled)

TABLE VIb

Diabetic subject information

Patient	Age (yrs)	Height (cm)	Weight (kg)	Blood pressure Systolic/ diastolic (mm Hg)	Fasting blood sugar (mg %)	ECG	Eyeground changes	Nerve conduction reflexes (m/sec)	R.	L.	Therapy
J., N.L. (F)	56	162	69	124/80	198	Normal	None	None			Diabinese 500 mg/day
C., C.W. (M)	33	152	51	114/70	282	Normal	Neg.	Deep peroneal Post. tibial	36.8 36.4	35.2 37.4	Insulin 20 units/day
C., J.B. ()M)	36	188	72	142/90	228	Normal	Neg.	None			Lente 60 units/day
M. D. (F	47	153	67	108/75	108	Normal	None	None			Controlled
L., B.W. (M)	41	182	88	120/70	126	Not done	None	None			Diabinese 250 mg/day
E., T.A. (F)	74	159	67	134/80	118	Normal	None	None			NPH 24 units/day
W., G.D. (F)	66	167	68	140/80	126	Abnormal	Neg.	None			Insulin 50 units/day (controlled)
W., S.C. (F)	50	167	68	95/60	114	Abnormal	None	None			NPH 18 units/day
O., J. (M)	73	170	82	170/90	96	Abnormal	None	None			Orinase 500 mg/day
S., B. (F)	30	167	50	92/60	192	None	None	None			Diabinese 250 mg/day
Average	55	172	74	132/79							
Std. dev.	±14	±16	±16	±18/±10							

M = male, F = female.

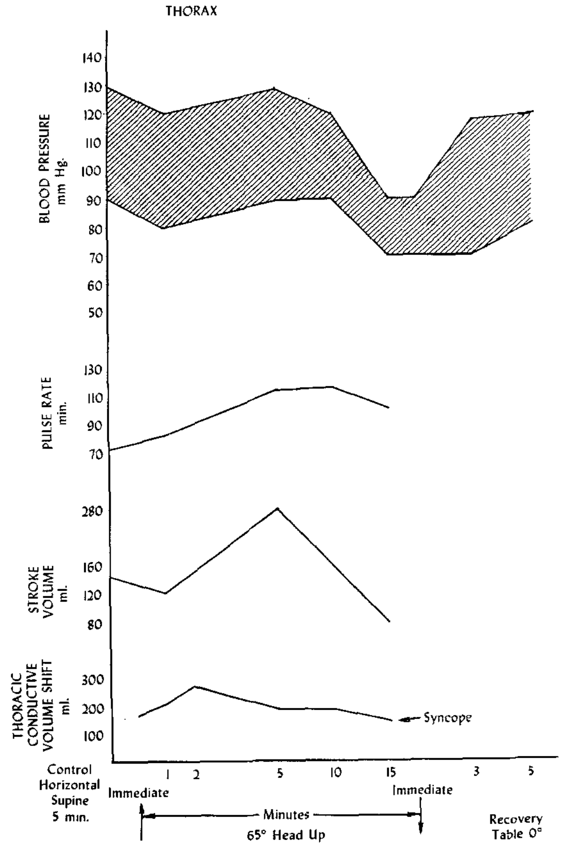

Fig. 4a.

enough) results in conditions which produce syncope. The absence of further heart rate increase is coincident with the beginning of systolic pressure decline. In this subject, a fall in pulse pressure from 36 mm Hg to 15 mm Hg within 10 minutes produced a syncopal attack. The fact that the systolic pressure at the time of syncope was equivalent to the control diastolic pressure may be significant in terms of predicting the vascular changes necessary to produce loss of consciousness. It is not clear why the marked reduction in stroke volume was not associated with a more pronounced increase in heart rate during the five to eight minute interval.

D. PART II. PATIENTS WITH DIABETES MELLITUS

Twenty-two patients with diabetes mellitus were selected for tilt table studies without regard to age, sex, or time of study. The diabetic condition in all of the patients selected, with one exception, was reasonably well controlled by oral or injectable insulin compounds (Table VI). One patient had hypertension (control diastolic pressure, 100 mm Hg), with an average control blood pressure level for the group of 132/79 mm Hg (Table VII). Immediately following the transition from the horizontal

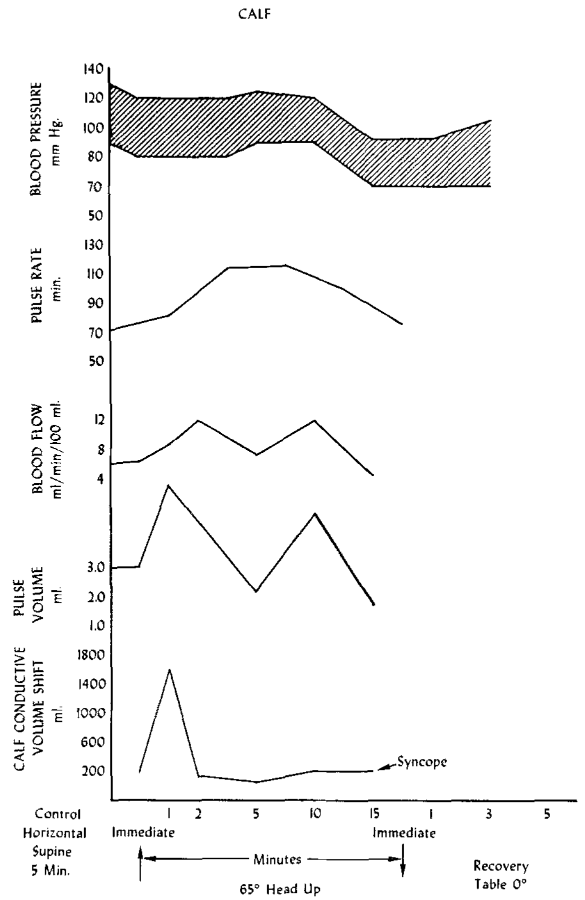

Fig. 4b.

Fig. 4. Effect of syncope on cardiovascular parameters during tilt table procedures. (a) Thoracic studies, A.M. (b) Calf segment studies, A.M.

0 degree to the 65 degree head up position, the diabetic group had a characteristic decrease in systolic pressure and a slight increase in diastolic pressure, with a more gradual increase during the 15 minute head up position. Individual studies are not presented because of the heterogeneous nature of the population; however, the group responses during the tilt table procedures are presented (Table VIII, Figures 5a, b). A marked increase in pulse rate during the head up attitude was characteristic for the group and probably indicated stress and possible compensatory mechanisms for other changes in the cardiovascular system (Table V). The 10% increase in heart rate immediately following the change in posture from the 0 degree to 65 degree head up position was associated with a 33% decrease in stroke volume within the first minute and a 46% decrease within 15 minutes. A 14% and a 16% decrease in cardiac output occurred during one and 15 minutes. The changes in central blood pulse volumes were associated with subsequent peripheral changes (Table V). The blood pulse volume in

TABLE VII

Blood pressure changes during tilt table procedure (diabetic subjects)

Subject	Control	Immediate[a] (65°)	5 min.	10 min.	15 min.	Immediate[a] (0°)	Recovery 3 min	5 min
G., J.H.	148/80	110/80	136/84	134/84	132/82	150/82	142/82	150/86
McD., W.R.	160/86	150/84	152/80	132/80	124/80	130/74	130/70	130/72
G., F.J.	130/72	90/68	96/66	98/70	96/74	124/72	130/70	120/72
W., E.E.	134/80	130/90	130/90	126/90	126/94	116/80	140/92	126/90
R., S.R.	140/74	134/80	134/80	130/80	130/84	130/80	140/74	134/80
J.W.H.	140/100	120/90	120/80	120/90	130/90	110/80	132/90	142/90
C., E.	162/72	158/80	150/78	148/78	160/80	168/80	160/78	148/78
C., D.L.	106/86	116/88	106/82	104/84	104/80	106/80	96/72	100/76
T., M.E.	156/94	152/100	160/100	150/96	166/104	156/100	160/92	162/96
K., R.	144/94	150/100	150/104	158/100	154/110	146/110	146/100	154/100
G., R.M.	144/84	136/86	154/94	150/90	154/86	154/100	150/100	150/100
C., E.W.	128/72	120/76	136/86	140/88	134/96	138/74	124/74	134/74
McI., W.	132/78	(Control calf segment study only)						
J., N.L.	124/80	124/90	130/90	124/90	136/90	146/90	140/90	134/90
C., C.W.	132/86	130/90	124/84	130/90	124/90	120/90	134/80	130/84
C., J.B.	120/74	114/76	122/80	116/86	120/86	124/80	130/88	126/84
M., D.	108/76	110/68	114/74	110/74	110/74	100/74	100/64	100/64
L., B.W.	120/82	110/82	120/92	120/94	124/94	120/84	130/88	126/88
E., T.A.	120/60	110/60	106/60	112/56	110/60	124/60	134/64	120/60
W., G.D.	140/80	(Control calf segment study only)						
W., S.C.	130/78	(Control calf segment study only)						
O., J.	136/74	120/70	138/80	138/80	126/110	138/76	118/80	134/80
S., B.	94/56	86/60	94/66	94/70	102/70	104/64	100/56	96/60
Avg.	132/79	124/81	129/83	127/84	128/87	130/81	132/80	131/81
Std. dev.	±18/±10	±19/±11	±19/±11	±17/±10	±19/±12	±18/±12	±17/±12	±17/±12

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[a] Indicates response within 1 min.

TABLE VIII

Average cardiovascular responses during 65° head up attitude and recovery in diabetic subjects

Diabetic studies (N = 20)	Blood pressure Systolic (mm Hg)	 Diastolic	Pulse rate (per min)	Stroke volume (ml)	Cardiac output (l)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood flow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
Control									
Table 0°	132 ± 18	79 ± 10	79 ± 13	170 ± 101	14.46 ± 0.43	–	1.0 ± 0.4	5.9 ± 2.2	–
Table 65°									
Head up									
Responses:									
< 1 min	124 ± 19	81 ± 11	87 ± 18	114 ± 78	12.41 ± 0.64	+ 135	0.8 ± 0.3	5.3 ± 2.0	+ 32
5 min	129 ± 19	83 ± 11	91 ± 16	96 ± 53	11.20 ± 0.71	− 446	0.7 ± 0.3	4.5 ± 2.0	+ 114
10 min	127 ± 17	84 ± 10	91 ± 16	94 ± 44	12.8 ± 0.59	+ 57	0.7 ± 0.3	4.6 ± 2.0	+ 114
15 min	128 ± 19	87 ± 12	96 ± 18	92 ± 42	12.2 ± 0.44	+ 95	0.7 ± 0.3	4.5 ± 2.0	+ 104
Table 0°									
Responses:									
< 1 min	130 ± 18	81 ± 12	79 ± 15	133 ± 79	13.6 ± 0.42	+ 28	0.9 ± 0.4	5.5 ± 2.0	–
5 min	131 ± 17	81 ± 12	83 ± 15	117 ± 60	10.2 ± 0.37	+ 551	1.3 ± 1.4	5.7 ± 3.0	+ 62

[a] $V_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

calf segments decreased by 20% in the first minute and 30% within 15 minutes. These changes were associated with a decrease in calf blood flow despite a marked increase in calf conductive volume. The decrease in thoracic conductive volume (−11%) accompanied an increase in calf conductive volume (+12%) during the 65 degree head up tilt table position. A consistent finding in the diabetic patients was the reduced calf blood pulse volume during control and 65 degree head up position studies. The measured segmental resistance of calf segments in patients with diabetes was greater than in healthy subjects (Figure 5b).

E. COMPARISON OF RESULTS OF TILT TABLE STUDIES IN HEALTHY SUBJECTS AND IN PATIENTS WITH DIABETES MELLITUS

The control blood pressure measurements and changes in blood pressure during the 65 degree head up position in patients with diabetes were not appreciably different from those in healthy subjects (Table IX). The control pulse rate and the relative difference in pulse rate change during the tilt table procedure was higher in the patients

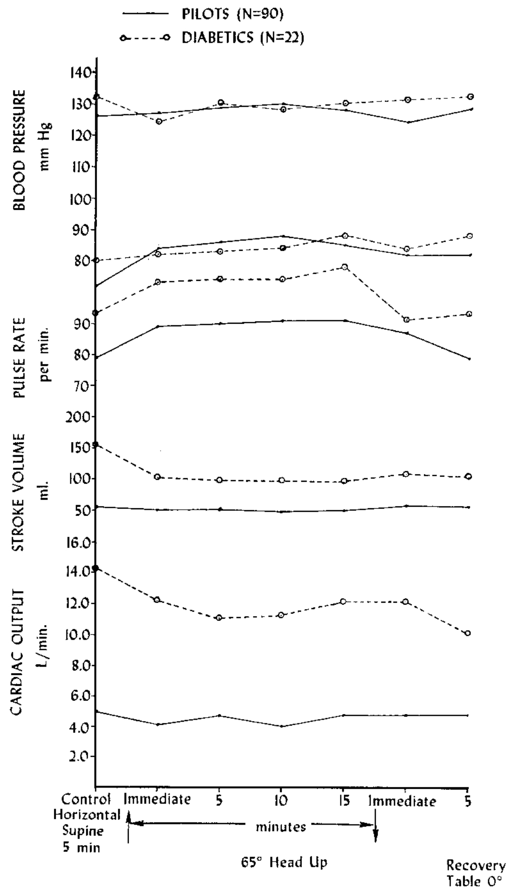

Fig. 5a.

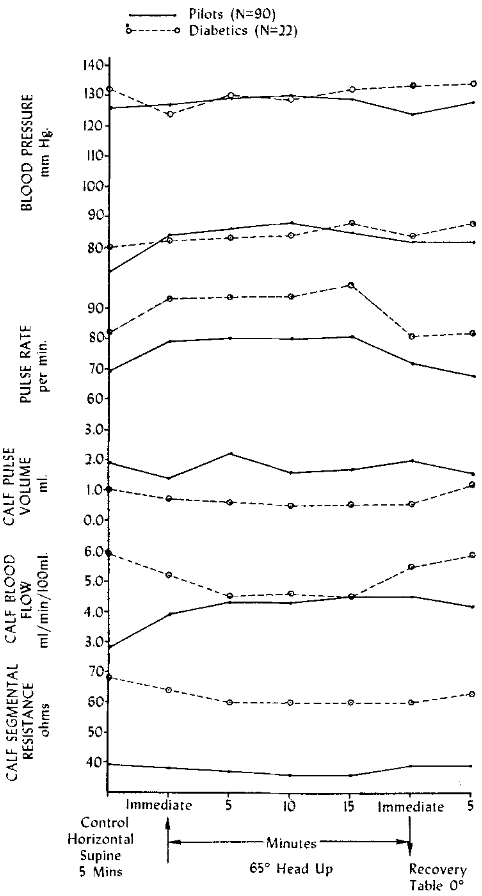

Fig. 5b.

Fig. 5. Comparison of average cardiovascular responses of 48 pilots to tilt table stress with responses of patients with diabetes mellitus. (a) Thoracic studies. (b) Calf segment studies.

with diabetes (Figure 5a). The stroke volume and cardiac output (during control periods and during tilt table tests) was greater in the diabetic than in the healthy subjects. The calf pulse volume was lower in the group with diabetes, which is consistent with the higher segmental resistance of the calf segments during control and during test periods (Figure 5b). Systolic blood pressure decreased (−6%) in the patients with diabetes when compared with healthy subjects, and the maximal decrease in stroke volume (−46%), cardiac output (−16%), calf pulse volume (−30%), and calf blood flow (−24%) at the 15 minute interval was greater in the diabetic than in the healthy subjects (Figure 6).

F. ERRORS IN MEASUREMENT AND LIMITATIONS OF THE IMPEDANCE SYSTEM

The theoretical basis for determining cardiac output by impedance plethysmography depends upon the identification of an appropriate thoracic volume by positioning

TABLE IX

Comparison of average percent of control changes for healthy and diabetic subjects

	Blood pressure Systolic (mm Hg)	Diastolic	Pulse rate (per min)	Stroke vol. (ml)	Cardiac output (l/min)	Thoracic[a] conductive volume shift (ml)	Calf pulse volume (ml)	Calf blood fllow (ml/min/100 ml)	Calf[a] conductive volume shift (ml)
Healthy (N = 90)									
< 1 min	+2	+ 9	+18	−24	−11	− 4	−31	+40	+ 3.5
15 min	+3	+13	+19	−20	+ 5	− 3	−16	+43	+ 7.0
Diabetics (N = 20)									
< 1 min	−6	+ 3	+10	−33	−14	−11	−20	−10	+ 3.0
15 min	−3	+10	+22	−46	−16	+ 2	−30	−24	+12.0

[a] $V_0 = \varrho(L^2/R_0)$, where $\varrho = 150$ ohm cm.

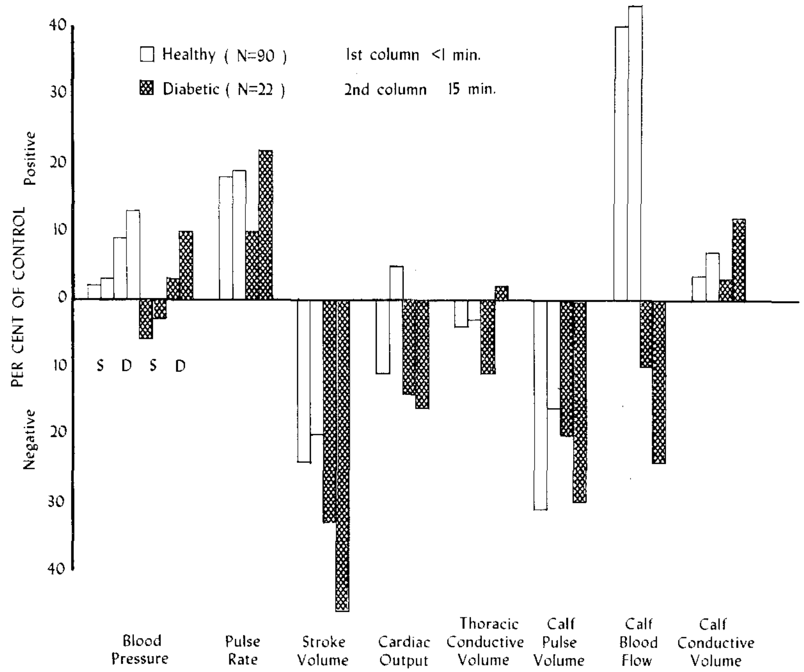

Fig. 6. Comparative effects of tilt table test in healthy subjects and patients with diabetes mellitus.

detecting electrodes and consequential recording of conductivity changes in the chest. The area between C_7 and T_{12} defines the upper and lower limits of the lung field, and the upper border can be defined without great difficulty. However, the lower limit is more difficult to define because of the border of the twelfth rib and the ability to mark off the level corresponding to the posterior attachments of the diaphragm (Allison, 1963; Allison *et al.*, 1964; Allison, 1960; Allison, 1966; Schaeffer *et al.*, 1968; Allison, 1966). It is obvious that the ratio $\Delta R/R_0 = \Delta V/V_0$ is dependent on R_0, which varies directly with the distance (L) between detecting electrodes E_1-E_2. It is also clear that $V_0 = \varrho(L^2/R_0)$ is dependent upon L. The calculated impedance values for cardiac output have a tendency to overestimate cardiac output determinations by other methods because of the inability to localize the level of the posterior attachment of the diaphragm with greater precision. The variability in cardiac output determinations between studies on the same subject on different days probably reflects the human error in not positioning the detecting electrodes at exactly the same levels. The average distance between detecting electrodes in the healthy group was 34 ±3 cm, with a range of 28 cm to 37 cm. Radiographic evidence prior to impedance studies would help to properly position the lower detecting electrodes (in terms of locating the diaphragm). The detected resistance of the thorax is affected by the amount of blood or gas in the chest at any one time. Inspiration and expiration are associated with increased and decreased thoracic resistance, respectively; whereas, increase in blood volume is associated with decreased resistance. When records of thoracic blood pulse volume are obtained, it is important that the subject hold his breath at an end expiratory position. Untrained subjects may hold their breath at an increased or decreased resting level and, thus, modify the recorded segmental and pulsatile resistance.

It is advisable to comment briefly concerning preparation of the aluminum strip electrodes. The paired 0.25 inch strips are separated (by 0.25 inch) on the 1-inch tape. If an excessive amount of electrode paste is applied prior to application to the skin, an electrical shunting between current and detecting electrodes occurs and produces erroneous resistance information. Another source of error in the cardiac output and calf blood flow measurements was related to standardization. As previously described, the sensitivity for the thoracic conductive baseline shift (Figure 2) was adjusted with the 50-mV calibrate signal on the Sanborn preamplifier and then attenuated. Great care was taken to insure a constant sensitivity from subject to subject because this recorded baseline information was directly related to the volume of conductive media in the chest. The average 1% of R_0 change was 47 ±8 mm, and the average 1-ohm step change was 68 ±2 mm for the thoracic studies. The average 0.1 of 1% of R_0 change for calf segments was 39 ±10 mm, and the baseline standard used for calculation of calf conductive volume change was 3.1 ±3 mm. The output voltage to the recorder by both the manual and the self-balancing plethysmograph units is determined by the segmental resistance (e.g., the higher the resistance, the lower the output); consequently, the standards which are recorded as 1% or 0.1 of 1% or 1-ohm steps in reference to the balanced segmental resistance will vary in accordance with the balanced resistance value. The average thoracic resistance for the healthy subjects was 29.8 ±5 ohms for an average distance between detecting electrodes of 34 ±3 cm. The average resistance for the 20 cm calf segments connected electrically in parallel was 20 ±2 ohms. The similarity between the thoracic and calf resistance values relates to the reduction in measured calf resistance by electrical coupling of the calf segments in parallel. The resistance for single calf segments in healthy subjects approximates 70–80 ohms.

The self-balancing impedance plethysmograph performed satisfactorily throughout this study and insured continuous registration of central blood pulse volume changes despite the motion attending variations in the tilt table attitude. The greatest limitation of impedance plethysmography in biological studies relates to the difficulty of obtaining readable records on subjects during motion. The self-balancing bridge has minimized this problem.

Despite the limitations and precautions necessary in using the four-electrode impedance plethysmograph correctly, the results have been extremely promising and background data has been accumulated as a reference for studies during aircraft maneuvers and for evaluation of pilots before and after prolonged missions.

4. Summary

A four-electrode, self-balancing impedance plethysmograph system was used for

measuring cardiac output during a standardized tilt table study. Blood pressure, heart rate, central and peripheral blood pulse volume, and conductive changes in the thorax and calf segments (as an index of blood volume) were studied in 48 healthy private pilots. Blood pulse volume and blood volume shifts were investigated.

Comparative results between the impedance system and dye dilution techniques for determining cardiac output indicated that the impedance system is a reliable system for determining cardiac output during controlled studies. When the results of the tilt table studies in the healthy subjects were compared with similar studies in 22 patients with diabetes mellitus, the diabetic patients had greater decreases in stroke volume and conductive volume in the thorax and a greater increase in heart rate when positioned at a 65 degree head up attitude for 15 minutes.

The results of this study provide sufficient basis for comparing laboratory data with flight data; in particular, the responses in the healthy group provide values for comparing the characteristic circulatory fatigue levels in patients with diabetes. Simultaneous central and peripheral vascular studies clearly aid in understanding the cardiovascular response mechanism associated with tilt table studies and establish an effective approach to the use of the tilt table for cardiovascular evaluations.

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Symbols

ϱ	resistivity, ohm cm
L	length or distance between detecting electrodes E_1-E_2, cm
E	voltage, volts
I	current, amps
R_0	segmental resistance between detecting electrodes E_1-E_2, ohms
V_0	segmental volume equivalent to $\varrho(L^2/R_0)$, ml
ΔV	change in volume, ml
ΔR	change in resistance, ohms

Terms

Impedance plethysmography – Measurement of change in volume due to variation in electrical resistance of a segment to a 50 or 120 kHz signal. The impedance at these frequencies is primarily resistive.

Four electrodes – Two electrodes for introduction of the reference signal to the exam-

ined segment and two electrodes for detecting variation in conduction of the signal.
Conduction – The reciprocal of resistance measured in mohs.
Conductive volume – The volume defined by $V_0 = \varrho(L^2/R_0)$ containing electrolytes including whole blood and plasma.

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