SIMULATION OF CIRCULATORY RESPONSES TO CHANGES IN BODY POSITION BY THE ACTION OF A NEGATIVE PRESSURE ON THE LOWER LIMBS

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UDC 612.176-06: 612.76] -08.001.57

The cardiodynamics, hemodynamics, and arterial tone were compared in 10 healthy young subjects during passive turning movements with the head in the position 20° and 60° downward and 70° upward and during exposure of the lower limbs to a negative pressure of −70 mm Hg. The circulatory changes in the last case were less marked than during the orthostatic procedures.

Changes in the position of the human body in space are accompanied by changes in the hemodynamics [4, 6, 10, 12, 16, 19, 20, 22, 23], the cardiodynamics [4-8] and the arterial tone [1]. However, the mechanisms of postural reactions of the circulatory system have not yet been adequately studied. Accordingly it is interesting to simulate orthostatic reactions by exposing the lower half of the body to the action of negative (subatmospheric) pressure [3, 11, 13, 15, 17, 18, 21].

Application of a negative pressure, similar in magnitude to the mean hydrostatic pressure in the vessels of the lower limbs in the erect position, to the subject's lower limbs is a rational method of simulating these conditions. The investigation described below was devoted to this problem.

EXPERIMENTAL METHOD

The subjects were 10 healthy young persons including eight trained athletes whose activity was associated with changes in the position of the body in space. Passive postural procedures (the head −20° and −60° downward and +70° upward) were carried out with the aid of a turntable. The duration of stay in the positions with the head −20° and −60° downward was 7 min and in the erect position (head upward) 12 min.

With the aid of two special pressure chambers a negative pressure was created on the lower limbs (NPL) of the subjects up to the level of the upper third of the thigh, equal to −70 mm Hg. This value was obtained by calculating the mean hydrostatic pressure in the blood vessels of the lower limbs in the 70° head uppermost position [15].

The ECG in lead II, the phonocardiogram, and the sphygmogram of the carotid artery were recorded and the arterial pressure measured by Korotkov's method in the initial state and during these procedures. The phase structure of contraction of the left ventricle was analyzed [7]. The minute volume of the circulation (MVC) was determined by the CO_2 rebreathing method [9, 14]. The stroke blood volume (SV), the mean volume velocity of expulsion, and the general peripheral resistance (GPR) were calculated. During the passive orthostatic test and NPL the dynamics of the rate of spread of the pulse wave (RSPW) in the aorta and limb vessels was investigated by synchronous recording of the sphygmograms of the carotid and femoral arteries and the volume sphygmograms of the distal third of the leg or forearm [1, 2]. The RSPW was determined in the vessels of the lower limb during a stepwise change of pressure in one lower limb within the range from −100 to +60 mm Hg.

All-Union Research Institute of Physical Culture, Moscow. (Presented by Academician of the Academy of Medical Sciences of the USSR, A. M. Chernukh.) Translated from Byulleten' Éksperimental'noi Biologii i Meditsiny, Vol. 76, No. 10, pp. 17-20, October, 1973. Original article submitted August 28, 1972.

TABLE 1. Cardiodynamics and Hemodynamics during Passive Postural Tests and NPL (M ± m)

Parameter studied	Horizontal position	NPL, – 70 mm Hg	Horizontal position	Head downward –20°	Head downward –60°	Head upward
Heart rate	53±1,2	64±2,5	54±1,5	58±1,4	57±1,5	75±3,8
Minute volume of circulation (in liters/min)	4,26±0,24	3,85±0,28	4,19±0,24	5,00±0,11	5,84±0,34	3,49±0,26
Stroke volume (in ml)	80±4,7	60±5,2	78±4,3	77±5,5	102±5,3	48±5,0
Arterial pressure (in mm Hg)	120/70	116/74	123/73	126/74	125/78	118/84
General peripheral resistance (in dines/sec • cm⁻⁵)	1700	1900	1800	1500	1320	2260
Asynchronous contraction (msec)	59±3	66±3	58±3	57±2	59±3	63±2
Isometric contraction (msec)	41±2	53±3	45±2	36±2	35±2	57±2
Period of explusion (msec)	282±6	235±6	283±4	288±5	293±4	202±7
Intrasystolic index (in %)	87,0±0,6	81,6±1,3	96,3±0,4	88,0±0,6	88,8±0,8	78,0±1,1
Mean rate of increase of intraventricular pressure (in mm Hg/sec)	1540±99	1350±98	1530±95	1970±160	2200±145	1390±41
Mean rate of expulsion (in ml/sec)	280±18	253±20	270±13	300±20	348±5	237±19

EXPERIMENTAL RESULTS AND DISCUSSION

Application of NPL with a value of –70 mm Hg led in all experiments to an increase in the heart rate (HR), a decrease in SV and MVC, an increase in GPR, and changes in the phase structure of cardiac contraction, indicating the development of a phasic syndrome of myocardial hypodynamia (Table 1). These changes were evidently connected with the retention of blood in the vessels of the lower limbs, a decrease in the venous return, a decrease in the central blood volume and a decrease in the filling volume of the ventricles of the heart. Changes in the hemodynamics and the phases of systole of the left ventricle as the subjects moved into the head downward and upward position corresponded to those described in the literature [4-8, 12, 15]. Within the range of changes of body position investigated, SV varied as a linear function of the subject's angle of inclination to the horizontal plane (Fig. 1), in agreement with results [23] obtained during turns of ·10°-60° with the head upward. The dynamics of SV, of the mean volume velocity of expulsion, and of the phase indices during the postural exercises and NPL indicate a leading role of the Frank–Starling mechanism in the regulation of the cardiac contraction under these conditions [4-8].

It is clear from these results that NPL of –70 mm Hg and passive turning of the human body in the 70° head upward position leads to unidirectional changes in the circulatory system. However, the changes in most parameters during NPL were less marked. For instance, the increase in HR during NPL was much smaller than during the orthostatic tests (Fig. 2). The regression equation is of the form: $\Delta HR_{NPL} = 4.5 + 0.4 \Delta \times HR_{ortho}$, $\sigma = 3.55$. The mean decrease in SV during NPL was 66% of that observed in the upright position; from the relationship shown in Fig. 1 this value corresponds to the changes in this parameter during the passive orthostatic test with an angle of inclination of about 40°. Correlation analysis revealed a close connection between the increases in HR during these tests ($r = 0.84 \pm 0.08$), but correlation with respect to other parameters was low. The stability of the diastolic pressure during NPL and its regular increase in the upright position should be noted ($P < 0.05$).

During simulation of the effect of an increase in hydrostatic pressure in the lower limbs by means of NPL the dynamics of the circulatory system evidently was only partly reproduced in the erect position. Falls of hydrostatic pressure in the other vascular fields, although less marked than in the vessels of the lower limbs, play an important role in the development of orthostatic reactions. This conclusion is confirmed by the results obtained by changing the subject's position passively during exposure to NPL from recumbency to the sitting position by raising the trunk to an angle of 45° with the horizontal plane. The heart rate and indices of the phase structure of contraction of the left ventricle were practically the same as in the erect position (Fig. 3).

Changes in the RSPW during the passive orthostatic test agreed with those described by the writers previously [1]: it increased in the descending aorta (on the average by 46%) and

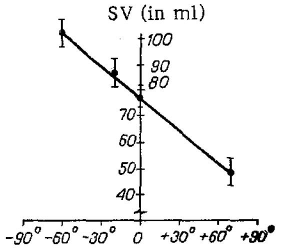

Fig. 1. Stroke blood volume in different positions of the body.

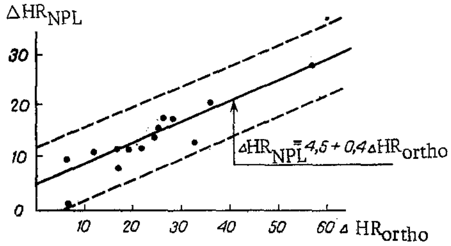

Fig. 2. Increase in heart rate during passive orthostatic test (ΔHR_{ortho}) and during NPL (ΔHR_{NPL}). Results of 14 experiments involving 10 subjects.

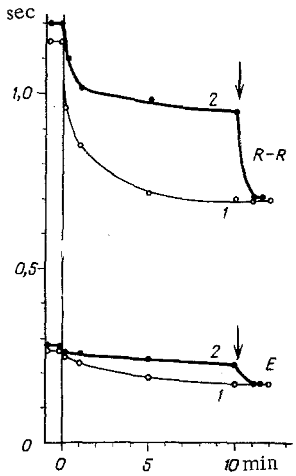

Fig. 3. Dynamics of duration of the cardiac cycle (R-R) and period of expulsion (E) in the erect position (1), during NPL (2) in recumbency, and during passive turning of the subject into the sitting position (marked by arrow) during exposure to NPL.

in the vessels of the limbs (47%), while the changes were very slight in the ascending aorta (−6%) and the arteries of the upper limb (+10%). During exposure to NPL of −70 mm Hg there was no change in RSPW in the arteries of the upper limb and the ascending and descending aorta. Its increase in the vessels of the lower limb was 64% of that observed during the passive orthostatic test. This difference was evidently attributable largely to the characteristics of the method: RSPW was determined in the segment from the femoral artery in the inguinal region to the lower third of the leg, while exposure to the negative pressure extended only to the upper third of the thigh, i.e., about three-quarters of the vascular segment tested. During the creation of pressure drops in one lower limb within the range from −100 to +60 mm Hg the changes in RSPW were a near-linear function of the pressure. In the arteries of the other lower limb RSPW remained unchanged under these conditions. These results suggest that the increase in RSPW in the arteries of the lower limbs in the erect position and during NPL and its decrease during turning in the head downward position [1] or an increase in the external pressure on the lower limbs are due to changes in the transmural pressure in these vessels.

Hence, both during orthostatic tests and during NPL the principal trigger mechanism of reactions of the circulatory system is an increase in the transmural pressure and the retention of blood in the peripheral vessels. A closer agreement with the reactions could possibly be obtained by more detailed simulation of the drops of hydrostatic pressure arising during the postural tests by local application of different degrees of subatmospheric pressure.

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