Atrial distension in humans during microgravity induced by parabolic flights

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Videbaek, Regitze, and Peter Norsk. Atrial distension in humans during microgravity induced by parabolic flights. J. Appl. Physiol. 83(6): 1862–1866, 1997.—The hypothesis was tested that human cardiac filling pressures increase and the left atrium is distended during 20-s periods of microgravity (µG) created by parabolic flights, compared with values of the 1-G supine position. Left atrial diameter (n = 8, echocardiography) increased significantly during µG from 26.8 ± 1.2 to 30.4 ± 0.7 mm (P < 0.05). Simultaneously, central venous pressure (CVP; n = 6, transducer-tipped catheter) decreased from 5.8 ± 1.5 to 4.5 ± 1.1 mmHg (P < 0.05), and esophageal pressure (EP; n = 4) decreased from 15 ± 1.6 to −4.1 ± 1.7 mmHg (P < 0.05). Therefore, intrathoracic pressure decreases during microgravity (µG) compared with the 1-G supine position. Left atrial diameter in humans, compared with the results obtained in the 1-G horizontal supine position, despite a decrease in CVP.

FOR A LONG TIME, it has been a generally accepted notion that central blood volume increases and the heart is distended during the initial phase of microgravity (µG). It is even believed that the cardiac filling pressures increase to a level above that of the horizontal supine body position on the ground (1, 12). This anticipation is based on observations from ground-based simulations of µG by head-down bed rest and water immersion (1, 9, 12, 13). Thus it has for several decades been hypothesized that cardiac filling pressures in humans increase during the initial phase of µG to above the level of the ground-based horizontal supine position.

Very recent measurements of central venous pressure (CVP) in humans during spaceflight have, however, indicated otherwise. Buckey et al. (2, 3) measured CVP in three astronauts before, during, and after launch of the space shuttle and observed a decrease in CVP compared with the 1-G horizontal supine position on the ground. Similar results were obtained by our group in one astronaut during the D2-Spacelab mission and during recent parabolic flight experiments (7). Thus direct measurements of CVP have indicated the opposite of what was expected, since CVP decreased during the initial phase of µG, compared with the 1-G supine position.

In contrast to the observations that CVP is decreased during µG, compared with the ground-based supine position before flight, Bungo et al. (4) and Buckey et al. (3) observed that the left ventricular end-diastolic dimension or volume index increased on the first day of space shuttle flights, and Prisk et al. (17) observed that cardiac output and stroke volume were unchanged or even tended to increase during the initial 2 days of µG. Thus, if the heart is distended during µG and CVP is simultaneously decreased, there is a theoretical possibility that intrathoracic (interpleural) pressure is decreased compared with that in the 1-G supine position (18). If intrathoracic pressure decreases during µG, CVP would apparently also decrease. If, in addition, intrathoracic pressure decreases more than does CVP, transmural CVP (TCVP) could increase. The apparent discrepant results of the effects of µG on CVP and intracardiac volumes, respectively, could thus be explained by the fact that interpleural (intrathoracic) pressure decreases during µG to a level below that observed in the horizontal supine position on the ground.

The purpose of this study was to test the hypothesis that cardiac filling pressures and the left atrial diameter (LAD) are increased by short-term µG during parabolic flights, compared with those of the 1-G horizontal supine position, and that the apparent decrease in CVP is caused by a decrease in intrathoracic (interpleural) pressure. Thus we performed simultaneous measurements of CVP, LAD, and esophageal pressure [EP; an index of changes in intrathoracic pressure (5, 8, 10, 11)] before, during, and immediately after parabolic flight maneuvers, with the test subjects placed in the horizontal supine position on the floor of the aircraft.

MATERIALS AND METHODS

Seven healthy men and one woman participated in the experiment after giving their informed consent (mean body weight 71 kg [range, 57–83 kg], height 184 cm [range, 165–205 cm], and age 34 yr [range, 25–48 yr]). The subjects had no history of previous diseases and were medically approved according to the rules for private pilot certification (class 2 medical certificate). The protocol was approved by the Medical Board of the European Space Agency (ESA) and the Scientific Ethics Committee of Copenhagen, Denmark (100.1234/88). The protocol was in compliance with the principles set forth in the Declaration of Helsinki. No complications occurred.

After a light breakfast, the subjects had a central venous catheter inserted, and they swallowed an esophageal balloon placed at the end of an air-filled plastic catheter. The catheter and the balloon were connected to recording units as described below. Thereafter, no intake of fluid and food took place until the end of the experiment (3-h period). In addition, the subjects were not allowed to ingest any kind of medication against motion sickness.

The parabolic maneuvers were conducted by a Caravelle airplane in collaboration with the ESA. The campaign lasted 3 days, with 30 parabolic maneuvers each day. A parabolic maneuver consisted of three phases lasting 20 s each: pull-up with an increased G load of up to 1.8 G, µG, and, again,
pullout of up to 1.8 G. Each subject was investigated during 12–15 consecutive maneuvers divided into sets of 3 each. There were 3 min from the start of one parabolic maneuver to the start of the next and more than 4 min in between each set. The G-level varied \(<10^{-2}\) during the 20 s of \(\mu\)G.

The subject was investigated while being as relaxed as possible in the supine position (Sup) on the floor of the aircraft, with straps fitted loosely around the waist and lower part of the legs to prevent floating in an uncontrolled way. The recordings were commenced during a 20-s period of 1 G, with straight and level flying before the start of the pull-up phase, and continued throughout all phases of the parabolic maneuver. The reasons for selecting the supine position were the following: 1) the main purpose of our investigation was to test the hypothesis that TCVP and LAD would increase above the levels at 1-G Sup during the initial phase of \(\mu\)G; 2) other investigators have previously used the supine position as the reference posture before spaceflight (1–4); and 3) when the test subjects were placed in Sup, the intervening 20-s high-G periods during the parabolic maneuver were thought to have less of an impact on the variables during the subsequent \(\mu\)G period than if the subjects had been placed in a more upright position. However, since previously we and other investigators have performed measurements with the subjects placed in other body positions (3, 7, 15), the subjects were, in addition, investigated in the following positions: seated upright in a flight chair (Seat) and supine, with the thighs vertical and the lower legs resting horizontally on a flight chair to mimic the launch posture in the space shuttle (Leg up). The subject maintained a specific posture (Sup, Seat, or Leg up) during a whole set of three parabolic maneuvers and thereafter changed to another posture between the sets. The sequence of postures was randomized in a balanced way among the subjects. The subjects were told to breathe normally and especially not to inhale or exhale deeply during the measurements. The cabin temperature varied between 18 and 24°C, and the cabin pressure was maintained at 800 mbar.

CVP was measured with the same equipment as described in detail by Foldager et al. (7) by using a fiber-optical catheter, where a pressure transducer was placed at the tip (Camino 110–4; Refs. 16, 19). The cabin pressure was used as reference. The equipment had previously been modified for the Space Transport System-55 Spacelab-D2 mission (7) to meet safety requirements for spaceflight and to improve accuracy and temperature stability. The equipment consisted of a central venous catheter, a preamplifier, and a tape recorder. After insertion of the catheter through a cubital vein into the superior vena cava (confirmed by X-ray determinations), the catheter was connected to the preamplifier, which, in turn, was connected to the tape recorder. For each subject, the mean value was estimated from continuous recordings by a computer program within each 20-s period of the parabolic maneuver as well as during 20-s periods of 1 G with straight and level flying before start of pull-up and subsequent to the pullout phase. Due to technical problems, CVP was measured in only six of the eight subjects. Furthermore, CVP was not measured during Seat, since the distance between the pressure transducer in the caval vein and the mid-right atrial level was not determined. Such a determination is mandatory when a subject is placed in the upright position during a condition with a G level different from 0.

EP was measured through a duodenal tube (Levin, OD 3.5 mm, Uno Plast) with an open end and side holes and covered by a latex balloon (length 5 cm, perimeter 7 cm) introduced through the nasal cavity by using local anesthesia (5% gel lidocaine). The tip was placed 35 cm from the nares. The system was connected to a pressure transducer, preamplifier, and tape recorder (identical to the CVP system but using the backside of the membrane) by air-filled tubes and was inflated with 2 ml of atmospheric air after the plane had reached flying altitude. The reliability of the EP system had previously been tested in vitro in a pressure box (8). It was possible to obtain reliable EP measurements in only six subjects during Sup, five during Leg up, and four during Seat because of the problems with 1) swallowing the esophageal tube, and 2) peristaltic contractions of the esophagus.

The tape recorders for CVP and EP recordings were synchronized before the start of the experiment. The tapes were replayed on a TEAC MR-10/20 at eight times recorded speed, analog-to-digital converted to 12 bits at 300 Hz per channel, and fed into a computer for analysis. Values are means determined by digital integration over selected time intervals by using software developed for this purpose. TCVP was calculated from CVP – EP in four subjects.

LAD was measured by echocardiography with the use of a portable Aloka equipment connected to a videotape recorder. Measurements were performed by using two-dimensional gray-scale and M mode in the parasternal long-axis view. LAD was measured continuously before, during, and after each parabola, and the recordings were stored on tape. During analysis, each parabolic maneuver was identified by markings made during the flight, and LAD was calculated according to Feigenbaum (6) as the mean value of at least three end-expiratory measurements within each 20-s segment of the parabolic maneuver.

Data analysis. The data are presented as means \(\pm\) SE. In regard to each subject, the data collected during Sup are presented as means of six \(\mu\)G periods of six parabolic maneuvers and are compared with the mean value of the 1-G periods of 20 s before and after the parabolas. An analysis of variance for repeated measures with each variable (CVP, EP, LAD, or TCVP) as the within-subject factors and posture as the between-subject factors was used to evaluate the effect of the G load on a variable in regard to each posture. Differences between means were evaluated by a post hoc Newman-Keuls multiple-range test (Statgraphics 5.0). A significance level of 0.05 was selected.

RESULTS

As indicated in Fig. 1 and Table 1, CVP decreased during Sup from a 1-G value of 5.8 \(\pm\) 1.5 mmHg to a \(\mu\)G value of 4.5 \(\pm\) 1.1 mmHg (n = 6, P < 0.05). During Leg up, CVP decreased from 7.0 \(\pm\) 1.5 mmHg (1 G) to 4.3 \(\pm\) 1.3 mmHg (\(\mu\)G, n = 6, P < 0.05). LAD during Sup increased from a 1-G value of 26.8 \(\pm\) 1.2 mm to a \(\mu\)G value of 30.4 \(\pm\) 0.7 mm (n = 8, P < 0.05) and was unchanged during Leg up (1 G: 30.0 \(\pm\) 1.1 mm vs. \(\mu\)G: 30.6 \(\pm\) 0.9 mm, n = 8, P > 0.05). During Seat, LAD increased from a 1-G value of 20.7 \(\pm\) 1.8 mm to a \(\mu\)G value of 29.2 \(\pm\) 1.0 mm (n = 7, P < 0.05). EP during Sup decreased from a 1-G value of 1.5 \(\pm\) 1.6 mmHg to a \(\mu\)G value of –4.1 \(\pm\) 1.7 mmHg (n = 6, P < 0.05) and during Leg up from 0.5 \(\pm\) 1.1 to –5.4 \(\pm\) 1.7 mmHg (n = 5, P < 0.05). EP during Sup increased from a 1-G value of 6.1 \(\pm\) 3.2 mmHg to \(\mu\)G value of 10.4 \(\pm\) 2.7 mmHg (n = 4, P < 0.05).
Because the data above, in regard to each subject, are based on mean values of the same G load during three to six parabolic maneuvers, we also evaluated the effects of only the initial parabolic maneuver on CVP, EP, and LAD in Sup subjects. In this regard, CVP decreased from a 1-G value of 5.3 ± 1.6 to 4.1 ± 1.3 mmHg during µG (P < 0.05), EP decreased from 1.1 ± 1.3 to −3.9 ± 1.9 mmHg (P < 0.05), and LAD increased from 26.8 ± 1.3 to 30.3 ± 0.7 mm (P < 0.05). Thus similar values to those presented above were obtained by just evaluating data from the initial parabolic maneuver.

DISCUSSION

The results of this study indicate that LAD and TCVP in humans increase during 20 s of µG created by parabolic flights compared with the 1-G horizontal supine position. This occurs despite the decrease in CVP. Because EP decreases more than CVP does during µG, the effective cardiac filling pressure and LAD are increased (Fig. 1). Therefore, µG induces distension of the atria of the heart as originally hypothesized (1), and since intrathoracic pressure decreases, measurements of CVP alone do not present a correct picture of the effects of µG on cardiac distension pressures.

The results of this study, indicating that TCVP and LAD increase to levels above those of the 1-G horizontal supine position, are in compliance with those of Bungo et al. (4) and Buckey et al. (3). These authors observed that the left ventricular end-diastolic dimension or volume index increased during the initial day of µG during space shuttle flights, compared with that of the ground-based supine position. Prisk et al. (17) measured cardiac output and stroke volume by a nitrous oxide rebreathing method in four subjects during a Spacelab mission (Spacelab Life Sciences-1) and observed that these variables were not decreased after 2 days of µG compared with those of the preflight supine position. Thus our results from very brief periods of µG are in compliance with those from spaceflight.

In a previous parabolic flight study (15), we observed that CVP increased during µG when the subjects were seated before, during, and after the parabolic maneuvers. The increase in CVP was of such magnitude that it even attained a value above that of 1-G Sup. Thus the conclusion of this previous study (15) and of this one is very similar, i.e., that cardiac filling pressures increase during weightlessness compared with those during Sup. The data on CVP, however, differ when results of this and of the previous study are compared, since, in the present study, we observed that CVP decreased to a level below that of 1-G Sup, whereas CVP increased to above this level in the previous study. The discrepant results might be explained by the difference in experimental design. In the previous study (15), the subjects were on all occasions seated upright during the parabolic maneuvers, and the 1-G supine reference measurements were made some minutes before. After these 1-G reference measurements, the subject changed position.

Table 1. Effects of increased G stress (1.8 G) and µG on CVP, EP, LAD, and TCVP in 4–8 human test subjects during parabolic flight maneuvers in an airplane, compared with a G stress of 1 during straight and level flying.

<table>
<thead>
<tr>
<th></th>
<th>1G</th>
<th>1.8 G</th>
<th>µG</th>
</tr>
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<tbody>
<tr>
<td>CVP, mmHg</td>
<td>5.8 ± 1.5</td>
<td>7.6 ± 1.5*</td>
<td>4.5 ± 1.1*</td>
</tr>
<tr>
<td>Leg-up</td>
<td>7.0 ± 1.5</td>
<td>10.0 ± 1.8*</td>
<td>4.3 ± 1.3*</td>
</tr>
<tr>
<td>EP, mmHg</td>
<td>1.5 ± 1.6</td>
<td>5.0 ± 1.5*</td>
<td>−4.1 ± 1.7*</td>
</tr>
<tr>
<td>Leg-up (n = 5)</td>
<td>0.5 ± 1.1</td>
<td>5.8 ± 1.4*</td>
<td>−5.4 ± 1.7*</td>
</tr>
<tr>
<td>Seat (n = 4)</td>
<td>−6.3 ± 2.3</td>
<td>−7.2 ± 2.3*</td>
<td>−4.6 ± 2.0*</td>
</tr>
<tr>
<td>LAD, mm</td>
<td>26.8 ± 1.2</td>
<td>22.9 ± 1.4*</td>
<td>30.4 ± 0.7*</td>
</tr>
<tr>
<td>Leg-up</td>
<td>30.0 ± 1.1</td>
<td>25.7 ± 1.8*</td>
<td>30.6 ± 0.9</td>
</tr>
<tr>
<td>Seat (n = 7)</td>
<td>20.7 ± 1.8</td>
<td>16.2 ± 1.8*</td>
<td>29.2 ± 1.0*</td>
</tr>
<tr>
<td>TCVP, mmHg</td>
<td>6.1 ± 3.2</td>
<td>3.6 ± 3.1</td>
<td>10.4 ± 2.7*</td>
</tr>
<tr>
<td>Leg-up</td>
<td>6.9 ± 3.1</td>
<td>3.7 ± 3.0</td>
<td>10.3 ± 2.8</td>
</tr>
</tbody>
</table>

Values are means ± SE of n = 6 [transmural central venous pressure (TCVP = CVP − EP)], n = 4–6 [esophageal pressure (EP)], n = 6 [central venous pressure (CVP)], or n = 7–8 subjects (left atrial diameter [LAD]); µG, microgravity; Sup, horizontal supine position, with subject lying on back on airplane floor; Leg-up, supine leg-up position, with lower legs horizontal on a flight chair, thighs vertical, and upper body horizontal on the floor. Seat, upright seated position in a flight chair. *P < 0.05 compared with other G conditions.
from supine to seated, and then recordings of CVP were continued. In contrast, the subjects in the present study were supine before, during, and after the parabolic maneuver, and the reference measurements were performed in tight conjunction with those made during the parabolic maneuver, without having the subjects move in between. Furthermore, the intervening periods of up to 1.8 G during the parabolic maneuver might have interfered with the observations in the previous study, since this effect is probably more pronounced when the subjects are seated than when they are supine.

The most important discovery of this study is that EP decreases during µG, compared with the results obtained during the horizontal supine position, and that this decrease is more pronounced than the decrease in CVP. This decrease in EP could explain the increase in TCVP and LAD (Table 1 and Fig. 1). The reason for the decrease in EP of 5.6 mmHg during µG merits comment. There is a possibility that the shape of the thoracic cage changes when the subject enters µG and that the diaphragm is displaced toward the head. In support of this view, Estenne et al. (5) concluded that during brief periods of µG the rib cage at end expiration is displaced in the cranial direction and adopts a more circular shape. It is, however, reasonable to assume that, if the rib cage adopts a more circular shape during µG, compared with that of the 1-G upright seated position, it would also attain a more circular structure compared with the 1-G supine position, especially since the thorax is compressed in the anteroposterior direction during the 1-G horizontal supine position. Measurements comparing rib shape configurations during µG with those during 1-G Sup are, however, required to substantiate this hypothesis.

The observation in this study that LAD and TCVP increase during µG, compared with the 1-G horizontal supine position, is in accordance with previous anticipations (1, 14). It is likely that these observations of very short periods of µG also reflect the effect of µG during more prolonged periods (2-4, 17) and that an increase in central blood volume during the initial hours of spaceflight should be taken into account to understand the subsequent physiological adaptations. Thus our observations support the classic hypothesis that the heart is distended during the initial period of µG. Measurements of CVP per se do not, however, correctly reflect the effects of µG on cardiac distension (transmu-ral) pressures.

Theoretical limitations in interpreting the results. One must be cautious in using EP as an accurate indicator of the magnitude of change in intrathoracic pressure. The changes in EP in humans during changes in posture are more pronounced than the changes in interpleural pressures (10). Therefore, the decrease in EP in this study during µG might have been more pronounced than the decrease in interpleural (intrathoracic) pressure. Furthermore, it could be argued that the decrease in EP during µG with the subjects in Sup also to some degree reflected the loss of the weight of the heart acting on the esophagus during 1-G conditions when the subjects were lying on their back. It is, however, very likely that the change in EP correctly reflected the direction of change in intrathoracic pressure of the supine subjects when they entered µG.

The decrease in CVP when going from 1G to µG with the subjects in Sup and Leg up positions could theoretically be explained by the abolishment of the hydrostatic pressure in the anteroposterior direction of the fluid column above the transducer. For this to be the case, it would require that the tip transducer was always resting on the posterior wall of the vein during 1-G Sup or Leg up. We do not know whether this was the case.

It cannot be assured with absolute certainty that the increase in LAD during change from the 1-G supine position to µG reflected the true increase in atrial size, as we only measured LAD in one direction. The increase in LAD could thus theoretically be explained by the change in geometry of the left atrium, e.g., by a change from an ellipsoid to a more spherical form during µG without a simultaneous change in atrial volume. If this had been the case, a similar geometric change would have been expected during Leg up. LAD, however, was unchanged during Leg up when measurements during µG were compared with those during 1G. This indicates that the change in LAD reflected the change in atrial size. It would be advantageous in the future, however, to measure LAD in two different directions during µG and compare the measurements with those of 1-G Sup.

Despite these theoretical limitations, the magnitude and direction of the simultaneous changes in the three variables (CVP, EP, and LAD) fit into a coherent picture of a distended heart during µG compared with values of 1-G Sup.

In conclusion, short periods of µG during parabolic flights induce an increase in TCVP and LAD in humans, compared with the results obtained in the 1-G supine position, despite a decrease in CVP. Thus these results confirm the classic hypothesis that central blood volume in humans is augmented during the initial period of µG.

Perspectives. The observations in this study point to the importance of intrathoracic (interpleural) pressure changes on central cardiovascular variables and have provided insight into the lung-heart interaction during changes in gravitational stress. The most important observation is that even the transverse gravitational stress (+1 Gx) in humans, when they are lying on their backs, has a significant effect on cardiac filling pressures, because total abolishment of this stress by µG induces a decrease in intrathoracic pressure with a subsequent increase in the size of the left atrium. Future investigations should focus on the effects of more prolonged changes in the transverse gravitational stress (± Gx) in humans on central cardiovascular variables and question to what degree these changes


affect other physiological systems, such as, for example, fluid volume regulation.

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REFERENCES


