Chest wall mechanics in sustained microgravity

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Wantier, Muriel, Marc Estenne, Sylvia Verbanck, G. Kim Prisk, and Manuel Paiva. Chest wall mechanics in sustained microgravity. J. Appl. Physiol. 84(6): 2060–2065, 1998.—We assessed the effects of sustained weightlessness on chest wall mechanics in five astronauts who were studied before, during, and after the 10-day Spacelab D-2 mission (n = 3) and the 180-day Euromir-95 mission (n = 2). We measured flow and pressure at the mouth and rib cage and abdominal volumes during resting breathing and during a relaxation maneuver from midinspiratory capacity to functional residual capacity. Microgravity produced marked and consistent changes (Δ) in the contribution of the abdomen to tidal volume [ΔVab/(ΔVab + ΔVrc)], where Vab is abdominal volume and Vrc is rib cage volume, which increased from 30.7 ± 3.5 (SE) % at 1 G head-to-foot acceleration to 58.3 ± 5.7% at 0 G head-to-foot acceleration (P < 0.005). Values of ΔVab/(ΔVab + ΔVrc) did not change significantly during the 180 days of the Euromir mission, but in the two subjects ΔVab/(ΔVab + ΔVrc) was greater on postflight day 1 than on subsequent postflight days or preflight. In the two subjects who produced satisfactory relaxation maneuvers, the slope of the Konno–Mead plot decreased in microgravity; this decrease was entirely accounted for by an increase in abdominal compliance because rib cage compliance did not change. These alterations are similar to those previously reported during short periods of weightlessness inside aircrafts flying parabolic trajectories. They are also qualitatively similar to those observed on going from upright to supine posture, however, in contrast to microgravity, such postural change reduces rib cage compliance.

The normal chest wall is exquisitely sensitive to gravity. Experiments performed during parabolic flights, which produce gravity-free conditions, have shown that abdominal volume and pressure at end-expiration decrease, whereas abdominal contribution to tidal volume and abdominal compliance increase (4, 12). The opposite results were observed during hypergravity in a human centrifuge as head-to-foot acceleration (+Gz) was increased (6). Measurements obtained during parabolic flights, however, only provided information on the short-term response to weightlessness because periods of microgravity lasted <30 s. It is not known, therefore, whether prolonged exposure to microgravity, as occurs during spaceflight, would produce similar alterations in chest wall mechanics. In this study, we report measurements of short-term response to weightlessness because periods of microgravity lasted <30 s. It is not known, therefore, whether prolonged exposure to microgravity, as occurs during spaceflight, would produce similar alterations in chest wall mechanics. In this study, we report measurements of chest wall mechanics performed during sustained microgravity in three subjects on the Spacelab D-2 mission and in two subjects on the Euromir-95 mission.

Methods

Subjects and Data-Collection Schedule

Three subjects (S1, S2, S3) were studied before, during, and after the 10-day Spacelab D-2 mission, which flew in 1993. Their preflight age, height, and body mass ranged from 37–47 yr, 174–189 cm, and 87–97 kg, respectively. Preflight data collection was performed 138, 77, 56, and 13 days before launch, and postflight data collection 0, 2, 4, and 9 days after landing. Inflight experiments were performed on days 3 and 8 in subject S1, on days 4 and 8 in subject S2, and on days 8 and 9 in subject S3. Two subjects (M1, M2) were studied before, during, and after the 180-day Euromir-95 mission, which landed on February 29, 1996. Their preflight age, height, and body mass were 37 and 39 yr, 182 cm for both, and 76 and 71 kg, respectively. Preflight data collection was performed 173 or 170, 114, 73, and 31 days before launch, and postflight data collection 1, 7, 12, 25 or 26, and 118 days after landing. Inflight experiments were performed on days 6, 32, 53, 69, 82, 105, 123, 132, 145, 164, and 172 in subject M1 and on days 5, 63, 83, 118, 142, and 170 in subject M2.

Experimental Setup

Safehouse Laboratories developed to perform a wide range of physiological tests was used in Spacelab and Euromir, and functionally identical facilities were used on ground for training, preflight, and postflight data collection. The sub-systems utilized for the present study consisted of 1) a respiratory inductive plethysmograph (RIP), which measured variations of inductance of two wires sewed with a zigzag pattern around the rib cage (RC) and the abdomen (AB) in a suit tailored for each astronaut, and 2) a three-way nonre-breathing valve with a pressure transducer incorporated near the mouthpiece (a flow restrictor with a resistance of 10 s of mH2O·L·s measured at 0.2 L/s could be added to the expiratory path; the inspiratory port could be connected either to room air or to the gas mixture used for the multiple-breath nitrogen washouts (MBW)); and 3) an ultrasound flowmeter located between the mouth and the rotary valve. The instrumental dead space was 85 ml on Spacelab and 181 ml on Euromir. For Spacelab, the sampling rate was 100 Hz for the RIP signals, and 200 Hz for flow and mouthpiece pressure. Corresponding values for Euromir were 67, 100, and 33 Hz, respectively.

RIP Calibration

Spacelab experiments. Calibration of the RIP was performed by using the 20–25 one-liter inspirations taken from functional residual capacity (FRC) during the MBW. The calibration method used is a variant of the method described by Stagg et al. (14) for magnetometers. Each breathing sequence is first decomposed into individual breaths beginning and ending with zero flow. For each breath (n) and each acquisition (i) (i takes ~400 values for each breath, with i = 0 corresponding to the beginning of inspiration), the RIP volume-motion coefficients (A0 and B0) and a constant C0 are com-
CHEST WALL IN WEIGHTLESSNESS

puted such that the following function is minimal

\[ F_n = \sum (V_{n,i} - A_n AB_{n,i} - B_n RC_{n,i} - C_n)^2 \]  

(1)

where \( V_{n,i} \) is the volume obtained by flow integration, \( AB_{n,i} \) and \( RC_{n,i} \) are the RIP signals, and \( F_n \) is the residual sum of squares. For each acquisition, SD values are computed for \( A_n \) and \( B_n \), and the values are discarded if \( A_n \) or \( B_n \) is outside the 2-SD range. The final volume-motion coefficients \( A \) and \( B \) are then computed from the following equations

\[ A = \sum \frac{A_n}{F_n} \left( \sum F_n \right)^{-1} \]  

(2)

and

\[ B = \sum \frac{B_n}{F_n} \left( \sum F_n \right)^{-1} \]  

(3)

where \( n \) refers to the breath numbers inside the 2-SD range for both \( A_{n,i} \) and \( B_{n,i} \) distributions, i.e., the number of terms in Eqs. 2 and 3 is reduced by the number of terms in Eq. 1 where \( A_n \) or \( B_n \) are outside 2-SD range. In Eqs. 2 and 3, the selected \( A \) and \( B \) coefficients are weighted by the goodness of fit of individual breaths. It should be stressed that the reduction of terms used in Eqs. 2 and 3 was applied to the data of the MBW used for the determination of volume-motion coefficients but not to the data used in the physiological measurements described below.

The abdominal contribution to tidal volume for breath \( n \) is given by

\[ \frac{\Delta V_{ab,n}}{\Delta V_{ab,n} + \Delta V_{rc,n}} = \frac{A \cdot AB_n}{A \cdot AB_n + B \cdot RC_n} \]  

(4)

with

\[ AB_n = AB_{n,E} - AB_{n,0} \]  

(5)

and

\[ RC_n = RC_{n,E} - RC_{n,0} \]  

(6)

where \( \Delta V_{ab} \) and \( \Delta V_{rc} \) are the changes in abdominal and rib cage volumes, respectively, \( AB_{n,E} \) and \( RC_{n,E} \) are the RIP amplitudes at the beginning of the expiration of breath \( n \), and \( AB_{n,0} \) and \( RC_{n,0} \) are the RIP amplitudes at the beginning of the inspiration of breath \( n \).

Euromir experiments. Standard isovolume maneuvers were performed at FRC with a closed glottis. The ratio of volume-motion coefficients \( A/B \) is equal to the ratio of \( RC/AB \) signal amplitude during the isovolume maneuver

\[ \frac{\Delta V_{ab}}{\Delta V_{ab} + \Delta V_{rc}} = \frac{AB}{AB + \frac{B}{A} RC} \]  

(7)

Measurements

For the Spacelab mission, all measurements were performed with the subjects sitting on a cycle ergometer (with the trunk approximately vertical) and holding two vertical handgrips, with the arms horizontal and slightly bent. The Euromir subjects were also seated for the pre- and postflight acquisitions, but as there was no seat during the mission, the astronauts were asked to adopt a position approximately similar to that used for the ground experiments. All subjects were instructed to perform relaxation maneuvers, which consisted of several tidal breaths followed by an inspiration to a midinspiratory capacity, at which point the airway was occluded and the subject relaxed; when mouth pressure reached a stable value, the subject was allowed to expire passively through the flow restrictor. A representative maneuver obtained in one astronaut at 0 Gz is illustrated in Fig. 1A, which shows RIP-calibrated RC and AB volumes above FRC and mouth pressure as a function of time. The sharp increase in pressure corresponds to relaxation against the closed valve, and the rapid decrease corresponds to opening of the valve. Figure 1B shows changes in RC and AB volumes during tidal breathing (dashed loops) and relaxation (left continuous curve) on a Konno-Mead plot.

Data Analysis

For the Spacelab and Euromir experiments, the abdominal contribution to tidal breathing \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) was computed from the tidal breaths preceding the relaxation maneuver. In addition, for the Euromir experiments, \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) was also computed from tidal breaths recorded during a 3-min period of resting breathing with the mouthpiece. Relaxation curves were considered satisfactory if 1) mouth pressure on occlusion reached a stable value, and 2) mouth pressure, Vrc, and Vab showed a smooth and quasi-exponential decrease. On satisfactory relaxation curves, we computed the slope of the Konno-Mead plot \( (\Delta V_{rc}/\Delta V_{ab}) \) in the tidal volume range; in addition, we calculated the rib cage (Crc) and abdominal (Cab) components of the total respiratory system compliance as \( \Delta V_{rc}/\Delta P \) and \( \Delta V_{ab}/\Delta P \). For the sake of brevity, Crc and Cab will be referred to as rib cage and abdominal compliance.

A two-way analysis of variance was used to compare pre- and postflight sessions for the same subject. Scheffe’s multiple-comparison procedure was used to test significance between \( G \) levels for subject’s group. Except when stated otherwise, values are means ± SE. Significance was accepted at the \( P < 0.05 \) level.

RESULTS

All experiments and acquisitions were successfully performed, except data collection on Spacelab postflight day 0, which could not be carried out for logistical reasons.

Abdominal Contribution to Tidal Breathing

Figure 2 shows mean ± SD values of \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) recorded in each session for subjects M1 and M2. Values obtained immediately before the relaxation were similar to those obtained during periods of tidal breathing with the mouthpiece, but the SD was smaller for the latter. Weightlessness produced a marked increase in \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) in both subjects. Values recorded on ground before the flight and in space did not change significantly over time, and values recorded preflight and on postflight days 7, 12, 25 or 26, and 118 were not significantly different. In contrast, values of \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) recorded in the two subjects on postflight day 1 (31 and 40% for subjects M1 and M2, respectively) were significantly greater than those recorded both preflight and on subsequent postflight days (on average: 21 and 23% for subjects M1 and M2, respectively). In subjects S1-S3, values of \( \Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc}) \) recorded 2, 4, and 9 days after landing were not significantly different from preflight data.
Figure 3 and Table 1 give average values for $\Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc})$ for all subjects; for subjects S1-S3, pre- and postflight 1 G, data have been pooled, but for subjects M1 and M2 only preflight 1 G, data are provided. For comparison, Fig. 3 also shows values of $\Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc})$ obtained during two campaigns of parabolic flights (4, 12). Values of $\Delta V_{ab}/(\Delta V_{ab} + \Delta V_{rc})$ were invariably greater in space than on ground, and changes during spaceflights were qualitatively similar to those observed during parabolic flights.

**Relaxation Curve**

Only two subjects, one in each mission, produced satisfactory relaxation maneuvers. In subject S1, three relaxation maneuvers were satisfactorily performed preflight and on day 9 of the mission; $\Delta V_{rc}/\Delta V_{ab}$ was $3.39 \pm 0.89$ at 1 G, and $1.57 \pm 0.45$ at 0 G. In subject M1, 4 and 15 relaxation maneuvers were valid on ground and in space (at least one adequate maneuver was obtained on each mission day studied), respectively; $\Delta V_{rc}/\Delta V_{ab}$ averaged $7.47 \pm 2.46$ at 1 G, and $1.07 \pm 0.24$ at 0 G, and there was no significant change during the mission. These values are presented in Fig. 4, together with those obtained in two subjects during parabolic flights. Changes observed in short and prolonged exposure to microgravity were qualitatively similar.

Figure 5 shows individual values ($\pm$SD) for $C_{rc}$ and $C_{ab}$ in subjects S1 and M1. Microgravity produced a marked increase in $C_{ab}$ in the two subjects: in subject M1, $C_{ab}$ was $0.016$ l/cmH$_2$O at 1 G, and $0.079$ l/cmH$_2$O at 0 G; corresponding values for subject S1 were $0.037$ l/cmH$_2$O at 1 G, and $0.089$ l/cmH$_2$O at 0 G. On the other hand, $C_{rc}$ did not change significantly with changes in G.

**DISCUSSION**

Up until now, the only reported data of chest wall mechanics in microgravity were obtained in eight normal subjects during three campaigns of parabolic flights.
These studies showed that going from 1 to 0 Gz elicited
1) a dramatic increase in the contribution of the
abdomen to tidal volume; 2) a reduction in the tidal
expansion of the rib cage, particularly in its upper part;
3) a decrease in the slope of the Konno-Mead plot, with
an increase in abdominal compliance; and 4) a reduc-
tion in FRC, which was entirely accounted for by the
inward displacement of the abdomen. There was no
consistent effect of 0 Gz on the temporal pattern of
breathing, pulmonary resistance, and dynamic pulmo-
nary compliance.

Although safety and logistical reasons did not allow
us to repeat all these measurements in space, we found
that prolonged exposure to microgravity also increased
the abdominal contribution to tidal volume and de-
creased the slope of the relaxation curve on the Konno-
Mead plot. The validity of these results, however,
critically depends on the accuracy of the RIP calibra-
tion. In the parabolic flight and the Euromir experi-
ments, the calibration procedure was the classic isovol-
ume maneuver. During training of the astronauts for
the Spacelab mission, however, it appeared unlikely
that each of them could perform the maneuver prop-
erly. We decided, therefore, to use a multiple linear-
regression technique for the RIP calibration (14). We
used the integrated flow signal from the MBW, but,
unlike Stagg et al. (14), we included both the inspira-
tory and expiratory phases of the breathing cycle,
rather than the inspiratory phase alone, in the linear
regression. We used a standard statistical criterion to
exlude the breaths for which the multiple regression
yielded volume-motion coefficients that were very large
or very small (including negative values). Finally, we
designed a method that weighted the mean volume-
motion coefficients computed from each MBW by the
goodness of the fit of individual breaths (Eqs. 2 and 3).

Measurements in two subjects indicated that the
decrease in the slope of the relaxation curve at 0 Gz was
entirely accounted for by an increase in Cab because
Crc did not change significantly. In contrast, the rib
cage becomes less compliant on going from the upright
to the supine posture (1, 7, 10). Two mechanisms have
been proposed for this observation (7). First, because of
the different orientation of gravitational forces with
respect to the body, the rib cage at end expiration is

Table 1. Fraction of abdominal excursion

<table>
<thead>
<tr>
<th>Subject</th>
<th>n</th>
<th>∆Vab/(ΔVrc + ∆Vab)</th>
<th>n</th>
<th>∆Vab/(ΔVrc + ∆Vab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>48</td>
<td>38.4±1.2</td>
<td>16</td>
<td>52.4±2.7</td>
</tr>
<tr>
<td>S2</td>
<td>44</td>
<td>34.7±1.4</td>
<td>31</td>
<td>41.8±0.7</td>
</tr>
<tr>
<td>S3</td>
<td>49</td>
<td>34.3±0.9</td>
<td>10</td>
<td>58.9±1.0</td>
</tr>
<tr>
<td>Mean ± SE</td>
<td>35.8±1.3</td>
<td>51.0±5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>89</td>
<td>19.0±0.6</td>
<td>341</td>
<td>61.8±0.3</td>
</tr>
<tr>
<td>M2</td>
<td>185</td>
<td>27.2±0.4</td>
<td>276</td>
<td>76.7±0.4</td>
</tr>
<tr>
<td>Mean ± SE</td>
<td>23.1±4.1</td>
<td>69.25±7.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ΔVab/(ΔVrc + ∆Vab), means ± SE of %tial volume due to abdomi-
nal excursion on ground (1 G) and in space [microgravity (µG)],
computed from n respirations. ∆Vab, change in abdominal volume;
ΔVrc, change in rib cage volume. For each subject, µG values are
significantly larger (paired t-test; P < 0.001) than 1 G values.
more elliptical in the supine than in the upright posture (16), which might hinder the movements of the rib cage joints and cause a decrease in Crc. Second, the distensibility of the cage might decrease in the supine posture because of the development of passive tension in the diaphragm (7, 8). These mechanisms, however, are not expected to play a significant role in microgravity. Compared with 1 Gz, the rib cage at end expiration adopts a more circular, rather than a more elliptical, shape (5) and, although some passive tension develops in the diaphragm at 0 Gz, it is much smaller than that elicited in the supine posture. We have previously reported that the end-expiratory transdiaphragmatic pressure at 0 Gz was ~2 cmH2O (4), whereas Agostoni and Rahn (2) have reported values of ~10 cmH2O in the supine posture. Therefore, on this basis, it is possible to understand why going from 1 Gz to 1 Gx and from 1 Gz to 0 Gz has different effects on Crc.

The increase in Cab observed in space is consistent with our previous observations during parabolic flights (4) and with the effects of a change from supine to upright posture (1, 4, 7, 10). In the present studies, we measured the abdomen component of the total respiratory system compliance and not the actual compliance of the abdominal compartment. The relationships between volume and mouth pressure and volume and abdominal pressure may diverge at low lung volume when the diaphragm is passively stretched (1). As mentioned above, however, transdiaphragmatic pressure at FRC does not exceed ~2 cmH2O at 0 Gz (4), which is probably insufficient to make abdominal pathway compliance different from the actual compliance of the free abdominal wall.

The increase in Cab observed at 0 Gz and in the supine posture (1, 4, 7, 10) results primarily from release of passive tension in the ventral abdominal wall. Because this tension is determined by abdominal transmural pressure, changes in the orientation and magnitude of the hydrostatic gradient should produce immediate changes in Cab and, with it, in ΔVab/(ΔVab + ΔVrc). This is exactly what we observed during parabolic flights (4). In contrast, measurements in subjects M1 and M2 showed that ΔVab/(ΔVab + ΔVrc) was greater on postflight day 1 than on either preflight days or subsequent postflight days.

Because ΔVab/(ΔVab + ΔVrc) is also determined by the distribution of neural activation between the diaphragm and the rib cage inspiratory muscles, this observation might indicate a change in the neural control of respiratory muscles; for example, the reduction in the phasic inspiratory activity of the scalene and parasternal intercostal muscles that has been observed at 0 Gz (5) might persist to some extent after the flight. This possibility, however, appears very unlikely, since previous studies involving postural changes (9) and partial immersion (13) have shown that adjustments in neural activation between the diaphragm and the rib cage inspiratory muscles are synchronized with changes in diaphragm length.

Alternatively, the increase in ΔVab/(ΔVab + ΔVrc) on postflight day 1 might be due to a persistent change in abdominal compliance. Previous studies in rats (11, 15) have shown that 5–8 days of weightlessness produced atrophy of the soleus muscle, which has an important antigravity function in rodents. The abdominal muscles in humans also have a prominent postural function (3). They might, therefore, undergo some degree of atrophy in weightlessness, which, in turn, might increase the distensibility of the ventral abdominal wall. It should be stressed, however, that there are no data that we are aware of on the effects of muscle atrophy on abdominal compliance. In addition, because changes in muscle mass occur gradually over time, such changes would be expected to produce a progressive increase in Cab and ΔVab/(ΔVab + ΔVrc) in space and a progressive decrease to baseline values after landing, which was not readily observed in the present experiments. Therefore, further studies involving more subjects and repeated measurements during and after the flight are needed to assess the effects of sustained weightlessness on the static pressure-volume characteristics of the abdomen.

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