Paradoxical redistribution of pulmonary blood flow in prone and supine humans exposed to hypergravity

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Submitted 30 December 2004; accepted in final form 2 September 2005

Gravity, and therefore changes in body posture, affects lung function through its influence on the regional distributions of ventilation, perfusion, and lung parenchyma. Furthermore, exposure to hypergravity impairs gas exchange in a posture-dependent manner. In seated healthy volunteers even moderate levels of hypergravity induce severe hypoxemia as a result of the combined circulatory and respiratory effects of hypergravity (2, 8, 9, 35, 39). In recumbent volunteers arterial desaturation occurs in both prone and supine postures during hypergravity whereas oxygenation is better maintained when prone (37, 43, 44). Because reduced arterial oxygenation is not explained by hypoventilation (37), it is likely to be caused by increased heterogeneity of regional ventilation and perfusion.

Gravity influences regional ventilation and perfusion through its effect on lung mechanics and pulmonary vascular pressures, causing a preferential distribution of both blood flow and ventilation to dependent lung regions (25, 46). However, recently gravity has been demonstrated to be a minor, but still important, determinant of regional lung perfusion (11, 12). At present, the influence of gravity on regional perfusion remains an area of debate. Efficient gas exchange depends on a high correlation between regional ventilation and perfusion. During exposure to hypergravity, increased gradients in hydrostatic vascular and pleural pressures and distortion of lung parenchyma presumably increase ventilation and perfusion heterogeneity and perfusion of nonventilated regions. Arterial desaturation might be the result of redistribution of blood flow, ventilation, or both.

It has been demonstrated that ventilation to dependent lung regions is reduced in volunteers exposed to hypergravity in the supine posture (7). In the present study we used SPECT (single-photon-emission computed tomography, a nuclear imaging method) to explore the redistribution of lung blood flow in healthy volunteers during exposure to hypergravity in the prone and supine postures. Our hypothesis was that exposure to hypergravity causes a redistribution of blood flow to dependent lung regions. If proven true, we would speculate that the redistribution of blood flow is one factor contributing to the impairment of gas exchange during exposure to hypergravity. Pulmonary blood flow distribution at normal gravity has been reported to be more uniform in the prone posture than in the supine posture (31). Similarly the increase in blood flow heterogeneity during exposure to hypergravity has been suggested to be more pronounced in the supine posture (36). Experiments were therefore performed in both the supine and prone postures.

METHODS

Subjects

Four healthy volunteers (three men and one woman), ages 21–28, were studied. All subjects were of normal weight (range 67–74 kg), height (range 170–180 cm), and body mass index (range 21–25). We recruited subjects less than 180 cm in height to ensure that all lung regions would fit into the scanning field of the SPECT camera. None of the subjects had any history of cardiopulmonary disease, and all were nonsmokers. The subjects received written information about the procedure, and informed verbal consent was obtained. The local ethical committee and the local radiation safety committee approved the study.
Equipment and Measurements

The hypergravity experiments were conducted in the human centrifuge at Karolinska Institutet, Stockholm, Sweden. The centrifuge has two arms: one with a gondola and one with a platform. A support structure was mounted on this platform. The subject was placed on a padded support surface that could be adjusted to be perpendicular to the resultant of the normal-gravity (G) and the centrifugal-G vectors. The subject was secured on the surface by a five-point safety belt. During the centrifuge run, the head and torso of the subject were covered with a cowling to reduce air draft, noise, and visual inputs. The rotational radius of the centrifuge was 7.2 m at the middle of the support surface. Slip rings at the center of rotation allowed for audiovisual monitoring, power supply, and transmission of physiological signals between the platform and a control room. The subject wore a nose clip and breathed through a mouthpiece with a pneumotachometer (type 3719, Hans Rudolph, Kansas City, MO), coupled to a pressure transducer (model CD12, Validyne, Northridge, CA), with its membrane mounted parallel to the plane of rotation (i.e., the horizontal plane) so as to eliminate the influences of centrifugal G on the transducer. The volume of the instrumental dead space was 150 ml. Electrocardiogram was monitored from chest electrodes with a clinical monitoring system (type AS2, Datex, Helsinki, Finland). The subjects had a finger probe for pulse oximetry (Datex, Ohmeda Division). An accelerometer was positioned on the support surface perpendicular to the rotational radius and the support surface. Continuous signals were recorded at 200 Hz per channel in a digital data-acquisition system (Biopac, Goleta, CA). Before and after each experiment, the pneumotachometer was calibrated with a 3-liter syringe within the experimental flow range. In the centrifuge the 99mTc-labeled macroaggregates were injected by a remote-controlled syringe pump. To avoid sedimentation of the macroaggregates in the syringe during hypergravity, a small magnet was placed within the solution in the syringe. The magnet was kept in motion by a second external magnet that revolved around the syringe.

Experimental Protocol

Figure 1 provides an overview of the experiments. The study protocol was designed to ensure that we would be able to compare the distribution of blood flow in identical lung regions. This was achieved by first imaging the distribution of macroaggregates (marking regional lung perfusion) administered at hypergravity; thereafter a second dose of macroaggregates was administered and imaging was repeated while the subject remained in the camera without moving. Although this approach made it impossible for us to randomize the order in which blood flow distributions at the two levels of gravity were studied, the order of the two postures was randomized. The methodology only allows two experiments in the same day. Each subject was therefore studied at two separate occasions; at the first occasion the distribution of lung perfusion was studied during normal (1 G) and three times normal gravity (3 G) in either the supine or prone posture. The subject then returned at least 48 h later when the distribution of lung perfusion was again studied at both levels of gravity but in the other posture. Thus four data sets were obtained for each individual.

At each occasion the subject first arrived at the human centrifuge where the first dose of macroaggregates was administered in the centrifuge ~7.5 min after reaching 3 G. Tracer administration lasted

![Supine: Ventral-to-dorsal force](image1)

![Prone: Dorsal-to-ventral force](image2)
100–120 s, and 3-G conditions were maintained for 4 min after completion of the injection. The subject was then transported by car to the SPECT laboratory at the Karolinska University Hospital Solna, Stockholm, Sweden. Transportation required ~10 min. A first set of images was then acquired with the subject in the same posture as in the centrifuge; acquisition started within 45 min of the radiotracer administration. As described above, the subject then remained in the SPECT camera without moving and the second dose of radiotracer was administered followed by a second period of image acquisition. The subjects breathed air at all times, and the macroaggregates were administered during continuous spontaneous breathing. At the second occasion the experimental procedure was identical but the opposite posture was maintained during radiotracer administrations and image acquisitions.

**SPECT Imaging**

**Radiopharmaceuticals.** Regional distribution of perfusion was marked by using intravenously administered macroaggregates of albumin (LyoMAA, Mallinckrodt Medical, Petten, The Netherlands) labeled with radioactive technetium ($^{99m}$Tc). At each occasion, 50 MBq were administered during 3-G conditions in the human centrifuge and a second dose of 100 MBq was administered during 1-G conditions. The subjects were estimated to receive a total effective dose of ~5 mSv.

**SPECT.** The SPECT technique used in this study was a single-isotope variant of a dual-isotope technique that has previously been presented in detail (32, 41). In brief, SPECT images were obtained with a three-headed gamma camera (TRIAD XLT 20, Trixion Research Laboratory, Twinsburg, OH) equipped with low-energy general-purpose parallel-hole collimators. SPECT scans were performed in 72 projections, 62 s per projection by use of a two-energy window acquisition protocol. Thus two images ($128 \times 128$ pixels with a pixel size of $3.56 \times 3.56$ mm$^2$) were obtained at each data-acquisition angle. An additional transmission tomography with a moving $^{99m}$Tc line source was performed to obtain data for the attenuation correction routine. The set of projected images was corrected for photon scattering and attenuation as well as for the radioactive decay before image reconstruction. Reconstructions were made respectively from data obtained during the first image acquisition (representing the distribution of blood flow during 3-G conditions) and from data obtained by subtracting the first acquisition from the second (representing blood flow distribution during 1-G conditions). The lung area was delineated in the reconstructed transverse transmission images by using a previously described edge detection algorithm (41). To verify that only lung tissue was included in the images, they were reviewed by a radiologist. In a few of the images, a small number of peripheral pixels were considered nonlung tissue and therefore were removed.

Spatial coordinates and number of events per voxel within the total delineated lung region were extracted from original reconstructed transverse SPECT $^{99m}$Tc-MAA image data. The data sets thus consisted of a number of voxels, each with a number of counts representing regional perfusion and coordinates for each voxel in the left-right, ventral-dorsal, and cranial-caudal directions. The size of the voxels was $3.56 \times 3.56 \times 3.56$ mm$^3$. Although this voxel size was below the spatial resolution of the SPECT system, we used the original voxel size because the results of the data analysis were not influenced by voxel size.

**Data Analysis**

Some of the image sets contained small areas with high activity, “hot spots.” To avoid influence from the hot spots on the results, four consecutive transversal lung sections well separated from the hot spots were chosen for data analysis. Together the four sections correspond to a 1.4-cm-thick transverse section of the lung. The sections were located at approximately the same cranial-caudal position in all subjects, corresponding to 1/2 to 2/3 of the distance from the most cranial to the most caudal lung section. For each individual the sections were located at the same cranial-caudal position in both postures. Number of events per voxel was normalized to the mean number of events for all voxels of the analyzed lung section. The voxel data thus represent the amount of perfusion for each voxel relative to the mean flow for all voxels. Distribution of blood flow was visualized by plotting mean flow per voxel at each vertical height up the lung. The redistribution of blood flow caused by hypergravity was estimated by comparing the ratio of blood flow to the nondependent and the dependent half of the lung section (ND/D ratio) and the slopes of linear regression of blood flow as a function of vertical height up the lung in each situation. For one data set without any hot spots, the vertical blood flow distribution within the chosen lung section was compared with the distribution for the entire lung. For the distributions imaged during 3-G conditions in the supine posture, ND/D ratios were also compared separately for the right and left lung.

**Statistics**

Physiological measurements were compared by ANOVA (Statistica 7.0, Statsoft, Tulsa, OK) with repeated-measures design with two independent factors (level of gravity and posture) to test for differences between G levels and posture and interaction between these parameters. Significant interactions were further evaluated by planned comparison. ND/D ratios and linear regression slopes during 1-G and 3-G conditions were compared for each posture separately by using a paired two-tailed Student’s $t$-test. Results were considered statistically significant if $P < 0.05$; all tests were two sided.

**RESULTS**

Physiological measurements are presented in Table 1. Hemoglobin oxygen saturation measured by pulse oximetry decreased in all subjects during the exposure to hypergravity ($P = 0.049$). The mean decrease was 4% (range 1–7%) when supine and 1% (range 0–3%) when prone. In three of the subjects there was a modest decrease in the tidal volume during hypergravity, corresponding to 9–22% of the tidal volume at normal gravity. Minute ventilation decreased to a lesser extent because there was also a small increase in respiratory rate. SPECT images representing blood flow distribution within the lung section for all conditions in one subject are presented in Fig. 2. Vertical blood flow distribution in each situation for all subjects is presented in Table 1.

**Table 1. Physiological measurements**

<table>
<thead>
<tr>
<th></th>
<th>Supine</th>
<th>Prone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 G</td>
<td>3 G</td>
</tr>
<tr>
<td>Pulse oximetry, %</td>
<td>97±1.0</td>
<td>93±2.7*</td>
</tr>
<tr>
<td>Respiratory rate, breaths/min</td>
<td>12±2.5</td>
<td>14±4.7</td>
</tr>
<tr>
<td>Tidal volume, ml</td>
<td>700±180</td>
<td>650±215</td>
</tr>
<tr>
<td>Minute ventilation, l/min</td>
<td>8.5±1.9</td>
<td>8.1±1.7</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>70±3</td>
<td>62±6</td>
</tr>
</tbody>
</table>

Values are means and SD. Ventilatory volumes as BTPS. 3 G, 3 times normal gravity. *Significantly different from normal gravity (1 G), $P = 0.049$, with no difference between postures. †Significantly different from 1-G supine posture, $P = 0.018$. 

\[\text{Downloaded from http://jap.physiology.org by 10220.33.02 on April 19, 2017} \]
ble 2), $P < 0.05$. Similarly, in both postures the linear regression slope was significantly more positive during 3-G than 1-G conditions (Table 2), $P < 0.05$. The amount of redistribution varied between subjects, being more obvious in subjects 2 and 4 (Fig. 3), but the direction of the redistribution was consistent in all subjects in both postures. A comparison of the vertical distribution of blood flow for the lung section and for the whole lung of one subject is presented in Fig. 4. The ND/D ratio for the right and left lung during 3-G conditions in the supine posture was not significantly different (Table 3).

**DISCUSSION**

The main result of the present study is that when healthy volunteers are exposed to 3 G in the prone and supine postures, pulmonary blood flow is redistributed from dependent to non-dependent lung regions. The results contradict our original hypothesis that exposure to hypergravity causes a redistribution of pulmonary blood flow to dependent lung regions. The results are surprising because they mean that an increased gravitational gradient does not explain our prior observations of increased blood flow heterogeneity during exposure to hypergravity in the prone and supine postures (36–38). The circulatory and respiratory effects of an exposure to hypergravity have been discussed in earlier publications from our group (36–38). We have also previously discussed the characteristics and limitations of the SPECT method (32, 41). In the following discussion we comment on some methodological issues pertinent to this study and discuss potential explanations of the results.

**Methodological Issues**

With SPECT, imaging of regional blood flow is accomplished by microembolization of radionuclide-labeled particles in the arterial pulmonary microcirculation. The number of particles trapped in a lung volume is proportional to regional blood flow, which has been verified with other measurement methods (24). Quantitative SPECT measurements are hampered by attenuation and scatter of the radioactivity emitted from the radiotracer within the body. The SPECT method used in this study incorporates new methods of correcting for attenuation and scatter. In phantom studies, these methods have been shown to produce corrected values with a mean deviation from the true value of $-1.9\%$ (41). Moreover, in the present study we compared images obtained in identical subjects in identical postures, which means that differences between images cannot be caused by the influence of scatter or attenuation. After administration and entrapment, the macroaggregates remain at the same location within the pulmonary vasculature. Therefore, even if imaging is performed during normal gravity, the obtained images correspond to the distribution of blood flow at the time of radiotracer administration. Even at normal gravity alveoli in nondependent regions are more expanded than alveoli in dependent regions (10, 21, 26). Dependent lung regions therefore contain a greater number of alveoli and capillaries per unit lung volume. The imaged activity distribution corresponds to the sum of the distribution of macroaggregates within the vasculature and the distribution of tissue within the thorax. During exposure to hypergravity the gravitational gradient in tissue distribution is increased (8, 9, 40). Although the distribution of macroaggregates within the vasculature does not change with the transition from hypergravity to normal gravity, the distribution of lung tissue changes. It is therefore not possible for us to describe blood flow distribution per unit lung volume during hypergravity, which would require imaging during hypergravity. In contrast, evaluation of the effect of hypergravity on the distribution of blood flow within the lung vasculature requires images to be obtained with identical lung tissue distribution. Distribution of tissue being unchanged, differences in activity distribution reflect redistribution of blood flow within the vasculature.

Lung tissue distribution also changes with posture, the gravitational gradient in tissue distribution being reduced in the prone posture (14, 17, 23). Therefore our methods do not allow us to compare the effect of hypergravity on blood flow distribution in the supine and prone posture because images were obtained in different postures.
In this study the time interval between macroaggregate administration and SPECT imaging was longer for the images of blood flow distribution during hypergravity than the images of flow distribution during normal gravity. Hosono et al. (16) recently reported that 20% of the radioactivity was lost from the lung during the first hour after macroaggregate administration. Different time intervals in combination with a great loss of activity during the first hour after macroaggregate adminis-

Fig. 3. Blood flow per voxel as a function of height up the lung for all subjects during all conditions. Values are mean flow per voxel within each isogravitational plane. Independent and dependent axes have been exchanged for presentation. Plots demonstrate mean flow per voxel at each height. G, gravity.
Redistribution of Blood Flow

Redistribution of blood flow from dependent to nondependent lung regions during hypergravity implies an increase in vascular resistance in dependent regions either through an increase in vascular tone, e.g., hypoxic vasoconstriction, or through mechanical factors. We speculate that the effect of an increased gravitational force on lung parenchyma might cause both mechanisms to contribute to blood flow redistribution. Exposure to hypergravity in recumbent postures reduces overall end-expiratory lung volume (FRC) and increases the gravitational gradient in alveolar size, i.e., regional FRC (3, 7, 37). Atelectasis in dependent lung regions has been demonstrated radiographically after exposure to hypergravity in the seated and supine postures (9), but only when subjects were breathing 100% oxygen during the exposure (8, 9, 30). Alveolar collapse was therefore proposed to be the result of absorption of alveolar gas and not a direct effect of parenchymal compression (8, 9). Because our subjects were breathing air, it is less likely that the observed redistribution of blood flow was caused by a development of true atelectasis.

Development of absorption atelectasis in dependent lung regions while breathing pure oxygen is an indirect proof of airway closure. During hypergravity, FRC is reduced in both the supine and prone postures (36, 38). With increasing levels of hypergravity, airway closure occurs at progressively larger lung volumes (3, 20), which reduces the ventilation of dependent regions (8). Entrapped airway gas has been demonstrated in human subjects breathing air during 3G in the sitting posture (9). In contrast, no unventilated gas-containing airways could be demonstrated when subjects breathed 100% oxygen, which was explained as absorption of all entrapped gas. Breathing at an unnaturally large lung volume has been demonstrated to prevent the development of atelectasis during hypergravity (9). Together these observations suggest that

**Table 2. Nondependent to dependent blood flow ratios and vertical gradients**

<table>
<thead>
<tr>
<th></th>
<th>ND/D ratios</th>
<th>Vertical gradients</th>
</tr>
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<tbody>
<tr>
<td>Supine</td>
<td>1 G</td>
<td>3 G</td>
</tr>
<tr>
<td></td>
<td>0.86 ± 0.07</td>
<td>1.19 ± 0.22*</td>
</tr>
<tr>
<td></td>
<td>1.04 ± 0.02*</td>
<td></td>
</tr>
<tr>
<td>Prone</td>
<td>1 G</td>
<td>3 G</td>
</tr>
<tr>
<td></td>
<td>0.88 ± 0.13</td>
<td>1.55 ± 0.24*</td>
</tr>
<tr>
<td></td>
<td>−0.02 ± 0.03</td>
<td></td>
</tr>
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</table>

Values are means and SD. ND/D ratio, ratio between blood flow to the nondependent and dependent halves of the lung. ND/D ratios are the ratios between mean perfusion per voxel for the nondependent and dependent halves of the analyzed lung section. Vertical gradients are the slope for linear regression of blood flow as a function of vertical distance up the lung, relative flow per voxel per centimeter. Increasing ratios and gradients (more positive) signifies redistribution of flow from dependent to nondependent lung. *Significantly different from 1 G, P < 0.05.
owing to the simultaneous increase in the extravascular pressure distending the blood vessels is much less increased. The vascular pressure is increased in dependent lung regions but the flow (45). In comparison, during hypergravity the hydrostatic pulmonary vascular pressures and increased pulmonary blood flow have been documented during conditions of increased distending pressure. However, as we have discussed in previous publications (35, 37, 38), we consider edema formation unlikely to be a cause of impaired lung function during hypergravity. However, if that occurred, redistribution of blood flow per alveoli from the nondependent lung to the dependent regions. A potential explanation of the different results is that although the SPECT and microsphere methods both measure regional blood flow per unit lung volume the measurements are done at different overall lung volumes and with different regional distributions of lung tissue. In agreement with our results, they demonstrated an overall redistribution of blood flow per alveoli from the nondependent lung to dependent regions. A potential explanation of the different results is that although the SPECT and microsphere methods both measure regional blood flow per unit lung volume the measurements are done at different overall lung volumes and with different regional distributions of lung tissue. In agreement with our results, they showed that blood flow through the most dependent lung regions progressively decreased with increasing gravitational force. In a second study (5), the same research group studied awake pigs exposed to hypergravity in the head-to-foot direction. At 3 G lung blood flow was redistributed in the direction of gravity. In contrast, at 6 G blood flow to the caudal regions was reduced, which was attributed to the increased inflation of the anti-G suit. High inflation pressure displaces the diaphragm in the cranial direction, which reduces the volume of caudal lung regions. Thus the change in the direction of blood flow redistribution at different G levels might be contributed to the same mechanisms that we propose explain the results of the present study.

Chevalier et al. (4) used radioactive microspheres to study pulmonary blood flow in dogs exposed to 1, 2, 4, and 6 G in the right lateral posture. Increasing levels of hypergravity caused a redistribution of blood flow from the upper region of the nondependent lung to the dependent lung, but there was only a minimal increase in flow to the most dependent regions of this lung. The time sequence of blood flow redistribution was studied in one dog. After 60 s of exposure to 7 G, blood flow had shifted toward the dependent lung, but after 120 s blood flow was redistributed to the upper lung. Also, arterial oxygenation was better at 120 s than at 60 s. These results are consistent with hypoxic vasoconstriction as a major determinant of blood flow redistribution during hypergravity, and they also suggest that the duration of hypergravity must be taken into account when results from different studies are compared. In our study the duration of hypergravity before the administration of the macroaggregates approximated 7.5 min, which is considerably longer than in the previous studies of human volunteers.

### Table 3. Nondependent to dependent blood flow ratios in right and left lung separately during 3 G supine

<table>
<thead>
<tr>
<th>Subject</th>
<th>Left Lung</th>
<th>Right Lung</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.18</td>
<td>1.20</td>
</tr>
<tr>
<td>2</td>
<td>1.22</td>
<td>1.26</td>
</tr>
<tr>
<td>3</td>
<td>0.85</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>1.41</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Values are the ratios between the mean perfusion per voxel for the nondependent and dependent halves of the left and right lung during 3 G supine. Increasing ratios signifies redistribution of flow from dependent to nondependent lung.

During hypergravity a reduced FRC and increased airway closure reduce regional ventilation in dependent regions and that some regions might remain unventilated although not necessarily atelectatic. In closed-off airways the partial pressure of oxygen rapidly decreases to a level below the threshold for hypoxic vasoconstriction (19, 28, 29). Hypoxic vasoconstriction might thus explain the redistribution of blood flow in the present study.

Several studies have demonstrated a reduction of regional blood flow with vertical distance down the lung in the most dependent lung regions (18, 34), zone 4 according to the zonal model. The decrease in flow is accentuated at lung volumes below FRC and abolished at total lung capacity. Hughes et al. (18) proposed that zone 4 is a result of decreased tethering of extra-alveolar vessels owing to less alveolar expansion in dependent regions. A further decrease in alveolar expansion, increasing local vascular resistance, is therefore a second possible cause of increased vascular resistance in dependent lung regions during exposure to hypergravity. The relationship between regional lung expansion and regional vascular resistance is, however, unclear. If a decreased lung expansion causes zone 4, then mechanical factors would be expected to contribute to the diversion of blood flow from atelectatic lung regions. In contrast, several studies have been unable to demonstrate any contribution of mechanical factors to the reduction of blood flow through atelectatic lung regions (6, 27, 33).

In summary, both an active increase in vascular tone and passive distortion of the lung parenchyma could be hypothesized to contribute to the observed redistribution of blood flow. We cannot exclude the development of true atelectasis in our subjects. However, if that occurred, redistribution of blood flow could be contributed to the same mechanisms as suggested above. That is also true for any formation of parenchymal edema in dependent lung regions, which has been suggested to be a cause of impaired lung function during hypergravity. However, as we have discussed in previous publications (35, 37, 38), we consider edema formation unlikely during a short exposure to hypergravity.

Blood flow through intrapulmonary arteriovenous shunts is a further, potential cause of different distributions of macroaggregates at normal and increased gravity. Such shunts have been documented during conditions of increased distending pulmonary vascular pressures and increased pulmonary blood flow (45). In comparison, during hypergravity the hydrostatic vascular pressure is increased in dependent lung regions but the pressure distending the blood vessels is much less increased owing to the simultaneous increase in the extravascular pressure. In addition, during hypergravity pulmonary blood flow is decreased. Although we cannot exclude it, we believe that it is unlikely that intrapulmonary shunting occurred in our study.

### Previous Studies

Glaister (7) studied supine human subjects using intravenous injection of radioactive xenon and an external scintillation counter. Similar to our result, he found that blood flow per alveoli decreased in dependent regions during ventral-to-dorsal hypergravity. In this study it was also demonstrated that during hypergravity blood flow per unit lung volume increased in dependent regions, but this resulted from a decrease in regional alveolar size. In contrast, Hoppin et al. (15) compared regional lung blood flow in two supine subjects during normal and increased gravitational force and found no redistribution of flow per alveoli during hypergravity. The greater level of hypergravity, eight times normal gravity, might explain the discrepancy between these results and the results of the present study. Hlasta et al. (13) studied the redistribution of lung blood flow in spontaneously breathing pigs exposed to 2 and 3 G in the prone posture (dorsal-to-ventral hypergravity). In contrast with our results, they demonstrated an overall redistribution of blood flow per alveoli from the nondependent lung to dependent regions. A potential explanation of the different results is that although the SPECT and microsphere methods both measure regional blood flow per unit lung volume the measurements are done at different overall lung volumes and with different regional distributions of lung tissue. In agreement with our results, they showed that blood flow through the most dependent lung regions progressively decreased with increasing gravitational force. In a second study (5), the same research group studied awake pigs exposed to hypergravity in the head-to-feet direction. At 3 G lung blood flow was redistributed in the direction of gravity. In contrast, at 6 G blood flow to the caudal regions was reduced, which was attributed to the increased inflation of the anti-G suit. High inflation pressure displaces the diaphragm in the cranial direction, which reduces the volume of caudal lung regions. Thus the change in the direction of blood flow redistribution at different G levels might be contributed to the same mechanisms that we propose explain the results of the present study.
Compression by the Heart

The position of the heart in relation to the lung has been suggested as one potential explanation for the difference in arterial desaturation during 5-G exposure in the prone and supine postures (37). In the supine posture the increased weight of the heart during hypergravity might cause compression of the underlying lung, whereas in prone the heart is supported by the sternum. If compression of the lung by the heart contributed to redistribution of lung blood flow in the supine posture, redistribution should be greater for the left lung than for the right lung because a much greater part of the left lung is located under the heart (1, 22). In this study the redistribution of blood flow was similar for the left and right lung, which suggests that direct compression of the lung by the heart was not a major cause of flow redistribution. However, this does not exclude that the weight of the heart contributed to the greater pleural pressure gradient in supine.

Cause of Arterial Desaturation

Because we studied only the redistribution of perfusion, it is not possible for us to provide a full explanation to the arterial desaturation observed during hypergravity. However, decreased ventilation of dependent lung regions has previously been demonstrated in healthy volunteers during exposure to 3 G (7). We therefore consider it unlikely that the redistribution of blood flow contributed to the impairment of gas exchange. Arterial desaturation is probably caused by a reduction in ventilation of dependent lung regions that is only partly compensated for by the redistribution of perfusion. Decreased cardiac output and mixed venous oxygen saturation during hypergravity might further increase the effect of regions with low ventilation-to-perfusion ratios on arterial oxygenation.

In conclusion, this study has demonstrated that during exposure to 3 G in the supine and prone postures, lung blood flow is not redistributed by the effect of gravity on vascular pressures and blood flow per se but rather as a consequence of the effect of the gravitational force on lung parenchyma. This results in decreased blood flow to dependent regions and increased flow to nondependent regions. It is unlikely that the redistribution of blood flow during hypergravity contributes to the impairment of gas exchange; the redistribution rather serves to reduce the arterial desaturation caused by hypergravity. Further studies simultaneously exploring regional ventilation and perfusion during hypergravity are needed to confirm this.

ACKNOWLEDGMENTS

We gratefully acknowledge the dedication of our subjects and the excellent technical support from Ann-Marie Danielsson, Annette Ebberyd, Marie Finnbogason, Gunilla Fyhr, Ingeborg Gottlieb-Inacio, Bertil Lindborg, and Jan-Olov Thorell.

GRANTS

This research was supported by Swedish Medical Research Council Grant K2003-74X-10401-11A, the Swedish Heart and Lung Foundation Grant 200141470, and Linde Healthcare AGA AB.

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J Appl Physiol • VOL 100 • JANUARY 2006 • www.jap.org


