Gravity effects on upper airway area and lung volumes during parabolic flight

Maurice Beaumont, Redouane Fodil, Daniel Isabey, Frederic Lofaso, Dominique Touchard, Alain Harf, and Bruno Louis. Gravity effects on upper airway area and lung volumes in six normal subjects in the sitting and supine positions during 20-s periods in normogravity, hypergravity ([1.8 + head-to-foot acceleration (Gz)]), and microgravity (−0 Gz) induced by parabolic flights. Airway caliber and lung volumes were inferred by the acoustic reflection method and inductance plethysmography, respectively. In subjects in the sitting position, an increase in gravity from 0 to 1.8 +Gz was associated with increases in the calibers of the retrobasi-tongue and palatopharyngeal regions (+20 and +30%, respectively) and with a concomitant 0.5-liter increase in end-expiratory lung volume (functional residual capacity, FRC). In subjects in the supine position, no changes in the areas of these regions were observed, despite significant decreases in FRC from microgravity to normogravity (−0.6 liter) and from microgravity to hypergravity (−0.5 liter). Laryngeal narrowing also occurred in both positions (about −15%) when gravity increased from 0 to 1.8 +Gz. We concluded that variation in lung volume is insufficient to explain all upper airway caliber variation but that direct gravity effects on tissues surrounding the upper airway should be taken into account.

MATERIALS AND METHODS

Setup

Acoustic reflection method. Longitudinal airway area profile was inferred by the two-microphone acoustic reflection method as previously described (19, 20). Briefly, a tube (30 cm in length, 1.9 cm in diameter) was prepared to accommodate two flush-mounted piezo-resistive pressure transducers (Endevco model 8510 B-2, Le Pré, Saint Gervais, France) and a horn driver. The transducers were located 7 cm apart. A mouthpiece was connected to the end of the wave tube in such way that the distance from the second microphone to the incisors was 10 cm. The other end of the wave tube was open to the atmosphere, permitting the subject to breathe spontaneously. Acoustic impulse was generated by the horn driver, which was driven via a digital-to-analog converter by a computer-generated signal. Transducer outputs were fed to an analog-to-digital converter (14 bits) with a sampling period of 24 µs. Each acoustic pressure acquisition took ~6 ms. A microcomputer inferred the area-distance function from the digitized pressure data (Benson Hood Laboratories, Pembroke, MA).

Airflow. Airflow was measured using a no. 2 Fleisch pneumotachograph connected to the wave tube and a differential pressure transducer (Validyne model DP 45, Northridge, CA). The transducer was placed in an assembly screwed on the rack holding all of the apparatus to ensure constant position during flight. Flow signal was electrically zeroed before and after a series of measurements. Recording of this signal during a complete parabola revealed no consistent change in transducer output at zero flow as gravity varied.

Lung volume. Tidal volume (VT) was calculated by integration of the flow signal. The flow calibration was obtained before takeoff by passing the volume of a 1-liter syringe through the pneumotachograph at different speeds. The gain was then adjusted (offline) to match the volume of the integrated flow signal to the known volume of the syringe. Thoracic and abdominal movements were measured using an inductance plethysmography (Respiracé Ambulatory Monitoring, Ardsley, NY). Before takeoff, the bands were positioned around the thorax at the level of the nipples and around the abdomen at the level of the umbilicus. The bands were firmly secured to the skin by tape. The plethysmograph was calibrated against the integrated pneumotachograph signal at 1 +Gz with subjects in the sitting position as described by Zacker et al. (26) during an ~5-min period of natural breathing. The volumetric sums of thoracic and abdominal
displacements were matched to obtain changes in end-expiratory lung volume (functional residual capacity, FRC).

Gravity acceleration. Gz acceleration was continuously measured using the Gz accelerometer (±20 m/s² accelerometer JT21–46, SFIM, Massy-Palaiseau, France) currently used in French Flight Test Centers.

Protocol

Subjects. Six healthy adults [5 men and 1 woman, age 38 ± 6 (SD) yr, height 174 ± 5 cm, and weight 71 ± 11 kg] volunteered for this study. The experimental protocol was approved by the human ethics committee of our institution. All subjects underwent preliminary medical examinations before participation, according to National Aeronautics and Space Administration (NASA) class III specifications (13). They had become familiarized with functional respiratory tests. Furthermore, five of them had prior experience with parabolic flights.

Parabola. Periods of weightlessness of 20–25 s were obtained by flying a NASA KC135 aircraft along parabolic trajectories. The flight lasted ~2.5 h and included six series of five parabolas. Each parabola included the following steps: 1) steady 1 +Gz, in horizontal trajectory at ~8,000 m; 2) ~20-s period of hypergravity (~1.8 +Gz, pull-up at ~45° of incidence in an ascendant trajectory); 3) parabolic trajectory (20- to 25-s period of weightlessness, ~0 Gz); and 4) ~20-s period with an acceleration of ~1.8 +Gz (recovery trajectory; Fig. 1). In parabolic flight, whatever the gravity (1 or 1.8 +Gz), the gravitational force is applied perpendicularly to the longitudinal axis of the plane in a top-to-deck direction (Fig. 1). The five parabolas within a series were separated by steady-state periods of 90 s at normogravity. Between two consecutive series of parabolas, duration of the 1 +Gz period was ~5 min.

Our study was performed during two flights on 2 consecutive days. Three subjects were studied per flight. Each subject was studied during two series of five parabolas, one series in supine position with the back against the floor and another in the sitting position with the back and shoulders against a flat area. The two series were attributed randomly. Special care was taken to stabilize body position and to minimize changes in spinal posture induced by the gravity changes. In each position, the legs, thighs, and pelvis were strapped to the aisle, and the shoulders were maintained manually by an investigator so that the subjects did not have to exert themselves to maintain their position constant. Before the first series of parabolas, the calibration of the plethysmograph was done in steady normogravity in sitting postures. Data measurements were done throughout the two series of five parabolas with subjects in the supine and sitting positions. During all measurements, subjects wore a nosedip and were asked to breathe quietly through the mouth via the wave tube. It is important to point out that, for an observer attached to the plane, the deck always appears horizontal when gravity remains constant. Gravity forces are applied from the head to the buttocks in the sitting position and from the anterior thorax to the back in the supine position.

Data recording and data analysis. While acoustic pressure data were being recorded on one microcomputer, flow, rib cage and abdominal displacements, acoustic pulse, and Gz acceleration signals were simultaneously sampled at a rate of 128 Hz and stored in the hard drive of another microcomputer by use of Acknowledge software and device (Biopac Systems, Santa Barbara, CA; Fig. 2). Data recordings were composed of consecutive periods of 105 s, including the duration of the entire parabola (~65 s) plus periods of ~20 s before and after the parabola. During these 105-s periods, acoustic pulses were run at a rate of ~1 Hz.

To obtain volume-motion coefficients, we developed a software to analyze the data recorded during the normogravity periods at the beginning and end of the parabolas, i.e., during an ~5 min-period. The sampling frequency of measurements from Respitrace signals was 128 Hz; so we have ~400 points of measurements per respiratory cycle. In fact, the relative gains for the rib cage and abdominal signals were computed retrospectively from the recording. In addition, during an experimental session, accuracy of the respiratory inductive plethysmographic calibration was verified in each situation (posture and gravity) by comparison of respiratory inductive plethysmographic signal with spirometer signal (integrated flow signal). We found a discrepancy between Respitrace and spirometer method <10%, which confirmed our calibration of the inductance plethysmograph.

By averaging the area-distance curves obtained by the acoustic method, we assessed the mean area of three regions of the upper airways, i.e., the palatopharyngeal, retrostobasal, and laryngeal regions, for each subject at each gravity level and in each position (Fig. 3).

The cephalometric method allowed definition of each of these three regions with good accuracy. In each subject in the supine and sitting positions, distances between the limits of these different regions and the incisors were measured. In terms of these distances, we did not find any differences between the two positions. Figure 4 presents a tracing
showing variations in the mean area of these regions induced by gravity changes in a representative subject in the sitting position. We also computed, for both positions and gravity levels, the mean total area of the upper airways as the sum of the mean areas of the three regions.

Because we found that the area-distance inferred by the acoustic method was not substantially modified during an entire breathing cycle under constant conditions of both gravity and position, we analyzed acoustic data without taking into account the direction or the magnitude of the breathing flow when acoustic measurements were processed. Aberrant acoustic results, due to velum opening, for example, were easily discarded as previously described (25). Data recorded during periods of unstable gravity were also discarded. Only respiratory cycles that matched the considered acoustic data were used to obtain VT and FRC variations. Data obtained at 1.8 \( \pm \) G\(_z\) before and after weightlessness periods were not significantly different and were consequently averaged and taken into account for the analysis.

Cabin pressure was set at 850 mmHg during the flight. However, this pressure tended to decrease slightly (by \( \sim 5 \) mmHg) when the aircraft climbed from the steady altitude level (8,000 m) to the altitude of the top of the parabola (11,500 m). Because of their small magnitude, these pressure variations were ignored and the associated changes in lung volume were neglected as in previous studies done using the same aircraft (22).

For simplicity, the microgravity, normogravity, and hypergravity periods will be referred to as 0, 1, and 2 \( +G_z\), respectively.

Statistics

Data were analyzed using a one-way ANOVA [supine position at 0, 1, and 2 \( +G_z\) (SU0G, SU1G, and SU2G, respectively), and sitting position at 0, 1, and 2 \( +G_z\) (SI0G, SI1G, and SI2G, respectively)]. Because gravity and posture are not independent variables (modifying posture results in a 90° change in inertial force exerted on the body), use of two-way ANOVA would not have been appropriate. The significance level was set at \( P = 0.05 \). Post hoc comparisons were performed using a Newman-Keuls test to look for statistically significant differences in physiological responses to the changes in situations.

RESULTS

**VT**

Significant changes in VT occurred in subjects in the sitting position between 0 \( G_z\) and the other gravity levels (\( \pm 0.12 \) liter between SI0G and SI1G, \( P < 0.05 \); \( \pm 0.1 \) liter between SI0G and SI2G, \( P < 0.05 \)). Changing in normogravity from the sitting to supine position did not produce significant variation of VT (\( P > 0.05 \)). In the supine position, significant changes were observed only between 0 and 2 \( +G_z\) (0.08 liter, \( P < 0.05 \); Fig. 5A). However, the 0.17-liter variation observed between SI0G and SU0G, which cannot be explained inasmuch

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**Fig. 3.** Schematic illustration of upper airways. 1, Palatopharyngeal region; 2, retrobasitongue region; 3, laryngeal region.

**Fig. 4.** Tracing of variations in upper airway areas (pharyngeal, retrobasitongue, and laryngeal regions) during a parabola in a representative subject in sitting position. SI0G, SI1G, and SI2G, sitting position at 0, 1, and 2 \( +G_z\), respectively.

**Fig. 5.** Variations in tidal volume (VT; A) and changes in end-expiratory lung volume (functional residual capacity, FRC; B) as functions of gravity and position. SI0G, SI1G, and SI2G, sitting position in microgravity, normogravity, and hypergravity, respectively. SU0G, SU1G, and SU2G, supine position in microgravity, normogravity, and hypergravity, respectively. Values are means \( \pm SE\). For VT, significant differences (\( P < 0.05 \)) occurred only between 0 and 1 or 2 \( +G_z\), in sitting position and between 0 and 2 \( +G_z\), in supine position. For FRC, there are significant differences (\( P < 0.05 \)) between all position and gravity conditions. * Situation significantly different from baseline value (SI1G).
as these two situations are equivalent in terms of gravity, suggests that no relevant change in Vr was observed in our study.

FRC

For each subject, the mean values obtained in sitting positions in normogravity (SI1G) were chosen as the baseline values (Fig. 5B). In the sitting position, FRC increased by 0.5 liter (P < 0.05) from microgravity to hypergravity (−0.2 liter SI0G and 0.3 liter SI2G). Changing from the sitting to supine position at 1 + Gz produced a decrease in FRC of ~1.1 liter (P < 0.05). In the supine position, the value increased at 0 and 2 + Gz (0.64 and 0.17 liter, respectively; P < 0.05). The 0.26-liter variation observed between the two equivalent situations of microgravity (SI0G and SU0G) is not explainable. It suggests that differences between SU1G and SU2G (0.17 liter) are meaningless.

Mean Area of Palatopharyngeal Region

Relative changes in mean area of the palatopharyngeal are shown in Fig. 6A. For all subjects, the value obtained in the sitting position in normogravity (SI1G) was chosen as the baseline. The values obtained in SI0G, SU0G, and SU2G were statistically similar. These three situations resulted in a 15% (P < 0.05) decrease in the mean area of the palatopharyngeal region compared with baseline. SU1G also induced an ~20% (P < 0.05) decrease in the mean area of the palatopharyngeal region. By contrast, hypergravity in the sitting posture induced a 15% expansion of the mean palatopharyngeal area. Interestingly, changes in FRC and the palatopharyngeal region mean area occurred in the same direction.

Mean Area of Retrobasitongue Region

Relative changes in mean area of the retrobasitongue region are shown in Fig. 6B. In the sitting position, the mean area of the retrobasitongue region increased with Gz, and a concomitant increase in FRC was also seen. Compared with SI1G (baseline), lying down induced a significant decrease of ~2–5% (P < 0.05) in the area in all gravity conditions. In the supine position, the evolution vs. gravity of this area seemed to be in opposition with the evolution of the FRC; an increase in FRC corresponded to a decrease in the area of the retrobasitongue region and vice versa. Differences between SU1G and SU2G and between SU0G and SU2G were not significant, and there was a slight difference between SU0G and SU1G (2.5% of baseline value).

Mean Area of Laryngeal Region

Relative changes in mean area of the laryngeal region are shown in Fig. 6C. In the supine and sitting positions, the mean area of the laryngeal region decreased as Gz increased. This decrease was more marked in the supine posture, reaching 17% at 2 + Gz vs. baseline (SI1G). Changes in laryngeal region area occurred in the opposite direction from changes in FRC in the sitting position and also in the supine position at 0 Gz (SU0G) only.

Mean Total Area of Upper Airways

Relative changes in mean area of the total area of upper airways are shown in Fig. 6D. Compared with the baseline situation (SI1G), this total area decreased by 4% (P < 0.05) in microgravity (SI0G) and increased by 2% (P < 0.05) in hypergravity (SI2G). Changing from the sitting to supine position in normogravity (SU1G) induced an 11% decrease in mean total upper airway area (P < 0.05). In the supine position compared with normogravity, the mean total area was higher by 5.5% (P < 0.05) in microgravity (SU0G) and lower by 4% (P < 0.05) in hypergravity (SU2G).

DISCUSSION

We found two main effects of gravity on upper airway configuration. First, mean laryngeal region area increased as gravity decreased in both positions. Second, when gravity increased, mean areas of the palatopharyngeal and retrobasitongue regions increased in the
sitting position but exhibited only minor variations in the supine position.

Palatopharyngeal Region, Retrobasitongue Region, and Laryngeal Region Mean Areas

Supine posture. In the supine position, the decrease in the mean total area of the upper airways seen as gravity increased was entirely due to a decrease in the mean area of the laryngeal region, since the mean areas of the palatopharyngeal and retrobasitongue regions remained virtually unchanged (Fig. 6). Moreover, the decrease in the area of the laryngeal region that occurred as gravity increased was more pronounced in the supine than in the sitting position, suggesting that it may contribute to the increase in upper airway resistance known to occur when body position changes from sitting to lying down (18). Because this decrease in laryngeal area between normogravity and hypergravity occurred in the absence of any decrease in FRC, it can be concluded that it was dependent primarily on gravity. Indeed, in terms of upper airway narrowing due to lying down, position effects have been shown to be more important than lung volume effects (11, 16). In normal subjects, gravity effects are known to make a much larger contribution to the increase in upper airway resistance seen during sleep than the relative atonia of upper airway muscle (30). Similarly, at sea level, gravity forces that cause the soft palate and tongue to fall back in the supine posture would narrow upper airways in all its length. For instance, some studies (11, 16) reported that passage from the sitting to supine position resulted in a pharyngeal area decrease of ~20%. In exploring the hypothesis that upper airway area decreases in the supine position, we were surprised that only small changes occurred in the retrobasitongue region compared with the changes in palatopharyngeal region. The contrast between the decrease in the mean laryngeal region area and the absence of any noticeable change in the retrobasitongue region may be ascribable to a difference in the amount of upper airway dilator muscles between these two regions. Almost all of the muscles in the retrobasitongue region are dilators, and the mean area of the retrobasitongue region depends on the activity of the dilator muscles of the tongue. Contrary to others (30), we studied our subjects during wakefulness, a state in which subtle neuromuscular mechanisms may maintain the retrobasitongue region open (4), thus potentially counteracting the effects of gravity. This assumption is supported by the fact that dilator muscle activity increases significantly when position is changed from upright to supine (27). In contrast, the larynx is semi-rigid due to its cartilaginous components, and there is only one dilator muscle in the laryngeal region (cricothyroid muscle). Reflex regulation of caliber is less important than in the retrobasitongue region. In our study, a decrease in laryngeal section with the increase in gravity was observed. We can assume that the anterior wall of the larynx moved downward to the posterior wall, thus reducing the laryngeal airway section. In the supine position, FRC changes were of little relevance to variations in upper airway patency, since the palatopharyngeal and retrobasitongue region areas remained constant despite FRC changes, and the laryngeal region area failed to mirror variations in FRC (Figs. 5 and 6).

Sitting posture. In the sitting position, increasing gravity was associated with increases in FRC and retrobasitongue and palatopharyngeal mean areas and with a decrease in laryngeal region mean area. Mean total upper airway area increased with gravity. The dilating effect of gravity on the retrobasitongue and palatopharyngeal regions may be ascribable to the FRC changes seen in our study in agreement with previous studies (9, 10, 22). Also, many studies in humans subjected to hypergravity found that blood volume decreased in the upper part of the body and increased in the lower part (6–8, 14). Thus blood volume in the palatopharyngeal and retrobasitongue regions probably decreases with increasing gravity. In the sitting position, an increase in gravity from 0 to +Gz may significantly increase the size of the upper airways as a result of substantial reductions in the volume of blood surrounding the upper airways. Shepard et al. (29) have reported that a decrease in blood volume may increase upper airway size. Because the tongue is a well-vascularized region, this mechanism would explain size increases in the palatopharyngeal and retrobasitongue regions but not in the laryngeal region. We found that laryngeal region area decreased as gravity increased (+10% of baseline at 0 Gz, to ~10% of baseline at 2 Gz). In a previous study of subjects in the sitting position, Beydon et al. (2) found that, after topical anesthesia, the epiglottis could drop onto the vocal cords, resulting in complete airway obstruction. A similar phenomenon may be part of the explanation of our observation. Further studies are required to confirm this assumption. Indeed, in our study, the subjects were not anesthetized, and the tone of the cricoarytenoid muscle would be able to limit the obstruction in hypergravity.

End-Expiratory Lung Volume

Sitting posture. When normogravity was used as the reference, a decrease in FRC has been reported in microgravity in the sitting (9, 22) and standing positions (10). By contrast, an increase in FRC in microgravity has been observed compared with supine position in normogravity (10). Our results are in agreement with these findings. When subjects assumed the sitting position, we found a decrease in FRC by ~0.17 liter, which is close to the decrease in FRC (~0.25 ± 0.03 liter) reported by Edyvean et al. (9) in microgravity during parabolic flight. Paiava et al. (22) reported a more pronounced decrease in FRC (~0.4 ± 0.07 liter), which could be explained by the fact that their subjects’ shoulders were securely taped to the back support, tending to reduce inspiratory capacity maneuvers and possibly the expansion of the rib cage during normal tidal breathing. The reduction in FRC reported by these studies and ours can be attributed to changes in respiratory mechanics, i.e., to a cranial shift of the
diaphragm-abdominal compartment related to the gravitational unloading of the abdomen. On the other hand, it is known that changes in thoracic volumes measured by Respitrace include trunk blood volume modifications. We were unable to assess the possible microgravity-related increase in intrathoracic blood volume. However, by measuring FRC and thoracoabdominal volume (Vw), Paiva et al. (22) could detect whether any changes in intrathoracic blood volume occurred during the brief periods of microgravity. Because the decrease in Vw did not differ from that in FRC, these data suggest that there was no increase in intrathoracic blood volume. Moreover, because, in studies in parabolic flight such as ours, measurements are made during very brief periods of microgravity, which are bracketed by 2-G exposures, there may not have been time for blood volume shifts, since it has been shown that the increase in thoracic blood volume is time dependent (10, 31). We can therefore assume that, in our study, the decrease in FRC at microgravity is purely due to changes in respiratory mechanics.

Supine posture. We found that FRC at normogravity or hypergravity is lower than FRC measured in microgravity. This finding is consistent with a previous observation (32) showing that, in normogravity, changing from sitting to supine posture, i.e., introducing the gravity component oriented from belly to back, induces a decrease in cross-sectional area of the abdomen and thus a shift of the diaphragm in the cranial direction and a decrease in FRC.

The 0.17-liter increase in FRC observed from SU1G to SU2G appears irrelevant, since this variation is lower than the variation observed between the two equivalent situations of microgravity (S10G and SU0G). Such an increase is probably due to the extreme conditions of the parabolic flights. In addition, a 0.17-liter variation in FRC represents ~5% of the FRC normal value (24). This suggests that such a variation is relatively irrelevant from the clinical point of view.

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\text{Vt}
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No relevant changes in Vt were observed in the study (Fig. 5) regardless of gravity or posture. Stability of Vt values with changes in gravity has previously been reported for the sitting (22) and standing (9) positions during parabolic flight. Here, we extended these results to the supine position. This finding was expected, since Vt is known to remain constant from the upright to the supine position in normogravity and to be controlled by a reflex originating in muscular mechanoreceptors (17).

We were surprised that no changes in upper airway cross-sectional area occurred during the breathing cycle. However, stability of upper airway geometry throughout the breathing cycle has been reported in previous studies using the acoustic reflective method (3, 12, 15, 25). One possible explanation for this phenomenon may be the small variations in lung volume observed during quiet breathing in comparison to total lung volume. If total lung volume is assumed to 5–6 liters in an adult, the variations observed in our study were never higher than 15% of the total lung volume.

In summary, we observed an increase in palatopharyngeal and retrobasitongue areas with increasing gravity in the sitting position only, whereas the laryngeal region area decreased in both positions. In the sitting position, the increase in mean area of the palatopharyngeal and retrobasitongue regions may be related to 1) increases in end-expiratory lung volume and 2) decreases in blood volume due to a mechanical hydrostatic effect of gravity. In the supine position, the area of the palatopharyngeal and retrobasitongue regions remained unchanged; a dilator muscle reflex probably inhibits the narrowing effect of gravity in these regions. In the sitting position, narrowing of the larynx with gravity could be linked to downward displacement of the epiglottis. In the supine position, the laryngeal section decreased with increasing gravity, probably as a result of direct mechanical effects of gravity on this semirigid structure.

The variations observed in all of the upper airway regions in the supine position and in the laryngeal region in the sitting position were apparently independent from lung volume variations. Variations in lung volume were clearly insufficient to explain most of the variations in upper airway areas observed in this study. Other mechanisms, such as gravity effects on tissues surrounding the upper airways and/or on the blood volume in these tissues, must have been operative.

We are grateful to A. Bacchi and B. Malbec, Flight Test Center, Brétigny-sur-Orge, France, for their assistance with this study. This work was supported by Centre National d’Etudes Spatiales, Toulouse, France.

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Received 19 May 1997; accepted in final form 26 Januay 1998.

REFERENCES


