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MAXIMUM INTRA-THORACIC PRESSURE WITH ANTI-G STRAINING MANEUVERS AND POSITIVE PRESSURE BREATHING DURING +Gz

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Maximum Intra-Thoracic Pressure with Anti-G Straining Maneuvers and Positive Pressure Breathing During $+G_z$

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Positive pressure breathing during $+G_z$ (PBG) and anti-G straining maneuvers (AGSM) each improve $+G_z$ tolerance by increasing blood pressure through increases in intra-thoracic pressure, but the maximal intra-thoracic pressure from their combined effect is not known. Six subjects performed the following: 1) maximal AGSM at +1 G_z; 2) assisted PBG (constant 60 mm Hg) at $+G_z$; 3) submaximal AGSM at $+G_z$ (enough to maintain peripheral vision); 4) maximal AGSM at $+G_z$; and 5) combined PBG and maximal AGSM at $+G_z$. They wore TLSS mask/helmet ensemble, CSU-15/P G-suit, and TLSS-style jerkin. Intra-thoracic pressure was measured with a catheter-tip pressure transducer in the esophagus (P_{es}). The change in gastric pressure was also measured (ΔP_{ga}). For both P_{es} and ΔP_{ga}, there were no significant differences among experimental conditions (1), (4) and (5), as above. Group mean P_{es} and ΔP_{ga} in these three conditions were 139 and 197 mm Hg, respectively. The similar results between maximal AGSM, and maximal AGSM and PBG are explained by limited support from the thoracic counter-pressure garment, and the characteristics of the respiratory system.

EXPOSURE TO SUSTAINED, headward acceleration ($+G_z$) decreases arterial blood pressure at head level by approximately 22 mm Hg per unit $+G_z$ increase in upright man. Near +5 G_z, compromised cerebral perfusion produces unconsciousness in a relaxed and unprotected individual. $+G_z$ tolerance can be improved by increasing blood pressure. Increases in intra-thoracic pressure act directly on the heart and great vessels producing an almost one-for-one increase in blood pressure (10). (Intra-thoracic pressure is loosely defined as the pressure around the heart; i.e., intrapleural pressure.) An anti-G straining maneuver (AGSM), a vigorous expiratory effort against a closed or partially-open glottis coupled with peripheral skeletal muscle tensing, can increase intra-thoracic pressure up to 100 mm Hg. When combined with a pressurized anti-G suit, AGSM can increase $+G_z$-intensity tolerance up to the level of +8–9 G_z (17).

Performing AGSMs requires concentration and is physically demanding. By increasing intra-thoracic pressure with positive pressure breathing using a breathing regulator, the requirement for AGSM is reduced. The maximal pressure delivered by pressure breathing during $+G_z$ (PBG) systems such as the USAF's Combat Edge, is currently set at 60 mm Hg. This pressure should increase relaxed $+G_z$-intensity tolerance by approximately +2.5 G_z producing a +7–8 G_z protection system. If pilots are to withstand exposure to higher $+G_z$ levels, as may occur during aerial combat or flight emergency, PBG must be supplemented with AGSM. The degree of $+G_z$-intensity protection from the combination of PBG and a maximal AGSM is not known. Several investigators have reported experimental subjects requiring moderate AGSM in order to complete PBG studies in the centrifuge (4,13,20), but the effect of maximal AGSM does not appear to have been researched. The intra-thoracic pressure is a critical issue. What is the maximal intra-thoracic pressure produced by the combination of assisted PBG (PBG with thoracic counter-pressure from a jerkin) and maximal AGSM? The study reported here addresses this question.

METHODS

Experimental Subjects

Six medically-screened volunteers participated as subjects after giving informed consent. They were ex-

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perienced in riding the centrifuge with a mean $+G_z$ tolerance of $+8.3$ G_z in a seat reclined 22° from vertical. They received additional training in positive pressure breathing at $+1$ G_z and in the centrifuge, and then in supplementing PBG with maximal AGSM.

Measurements

Mask cavity pressure (P_m) and G-suit pressure ($P_{g\text{-suit}}$) were measured with variable reluctance pressure transducers (model DP15 Validyne, Northridge, CA). P_m was obtained via a fitting fixed through the shell and facepiece of the oronasal mask. $P_{g\text{-suit}}$ was measured through a bayonet-style (Luer-Lok, Becton-Dickinson, Mississauga, Ont.) fitting in the valve connector of the G-suit hose. All transducers were calibrated.

Intra-thoracic pressure was estimated by measuring pressure in the esophagus (P_{es}). Because abdominal pressure is important in venous return and in supporting intra-thoracic pressure, gastric pressure (P_{ga}) was also measured. P_{es} and P_{ga} were measured with miniature catheter-tip pressure transducers (Medical Measurements Inc, model 16CT, Hackensack, NJ). A custom brass fitting replaced the anti-suffocation valve of the mask. With the mask hanging by one bayonet from the mounted helmet, the P_{es} and P_{ga} catheters were passed 40 and 65 cm, respectively, through two small ports in this fitting. The catheters were taped to the sleeves of this fitting to prevent sliding. A small amount of Xylocaine ointment was applied to the back of the nares. With the tip dipped in a water-soluble lubricant, the P_{ga} catheter was inserted into the nose and moved to the glottis. The subject swallowed a small amount of water as the catheter was pushed past the glottis. It was then advanced to the stomach. The procedure was repeated with the P_{es} catheter which ultimately rested in the lower third of the esophagus. The mask was lifted to the face, ensuring that neither catheter became looped in the mask cavity. The second bayonet was then fastened. Catheter positions were checked and considered correct when, during inspiration to total lung capacity, P_{es} became more negative and P_{ga} became more positive. The catheter-tip pressure transducers were pneumatically calibrated before insertion.

Cardiac function during all $+G_z$ exposures was monitored by six-lead ECG. The centrifuge $+G_z$ level was controlled by a computer using tachometer verification. An accelerometer mounted at heart level behind the seat provided the $+G_z$ analogue signal. All measurements were recorded on a multi-channel strip-chart recorder (model ES-1000 Gould, Cleveland, OH).

Man-Mounted and Pressure Equipment

The subjects wore a jerkin similar in design to the Tactical Life Support System (TLSS, Gentex Corp, Carbondale, PA) jerkin (7) which evolved from the Canadian Forces jerkin (14). It is a full trunk garment with a bladder over the anterior and lateral rib-cage, and in the inter-scapular space. There is no bladder over the abdomen or back. It was worn over the CSU-15/P G-suit (Irvin Industries, Fort Erie, Ont.). The G-suit was pressurized by an anti-G valve (Alar Products, Cleveland, OH). The TLSS oronasal mask/helmet ensemble was used. An oxygen regulator (BF2400, ARO, Buffalo, NY), designed to provide positive pressure breathing on exposure to high altitude, was used to deliver PBG and pressurize the jerkin to the same level as the mask pressure. With a needle valve on the bleed mechanism, the regulator was set to deliver a constant level of 60 mm Hg PBG. PBG to the mask was controlled using two one-way solenoids (Ascolectric, Brantford, Ont.).

Experimental Design

The experiment consisted of the following five conditions:

Experimental condition no. 1: (C-1G)—maximal Valsalva/AGSM at $+1$ G_z;
Experimental condition no. 2: (C-PBG)—assisted PBG at high $+G_z$;
Experimental condition no. 3: (C-sAGSM)—submaximal AGSM at high $+G_z$;
Experimental condition no. 4: (C-mAGSM)—maximal AGSM at high $+G_z$;
Experimental condition no. 5: (C-PBG + mAGSM)—assisted PBG and maximal AGSM at high $+G_z$.

Experimental Procedures

The subject arrived at the laboratory with flight suit and ECG electrodes on. After the P_{es} and P_{ga} catheters were inserted, the subject donned the jerkin and G-suit. The subject entered the centrifuge gondola and all the pneumatic and electrical connections were made. The briefing session reminded the subject of the well-practiced procedures. In particular, when full AGSM effort was instructed, he was to produce his maximal intra-thoracic pressure and to maintain the normal AGSM rhythm. Maximal efforts were encouraged by showing an LED display of the intra-thoracic pressure level to the subject.

In the first experiment condition (G-1G), three maximal straining efforts were performed separated by brief rests. Preparatory $+G_z$ exposures were then made. The relaxed subject was exposed to a gradual $+G_z$ onset rate centrifuge profile (0.1 G/s) until he reached 100% peripheral light loss and/or 50% central light loss. Visual light loss was measured subjectively using a light bar similar in construction to that used by the U.S. Navy (12). During this centrifuge profile, PBG of 60 mm Hg was delivered at $+4$ G_z and maintained at that level until the visual end-point criterion was reached. The subject then released an enable switch which automatically stopped the centrifuge. For all subsequent $+G_z$ exposures for that subject, that same peak $+G_z$ level was used. The $+G_z$ plateau was maintained for 20 s.

Experimental conditions 2–5 were then presented to the subject in pre-assigned, semi-randomized order. The conditions requiring maximal AGSM were never consecutive. In condition C-PBG, the subject was relaxed and received 60 mm Hg PBG at $+4$ G_z and for the remainder of the profile. No PBG was provided in C-sAGSM. Submaximal straining was used but only as necessary to avoid reaching the visual end-point. In

C-mAGSM, moderate straining was performed as required during the $+G_z$ onset, and then on reaching the $+G_z$ plateau, maximal AGSM was instructed. (In C-sAGSM and C-mAGSM, the jerkin was worn but was not pressurized.) In C-PBG + mAGSM, PBG was provided at +4 G_z, and was then combined with maximal AGSM on reaching the $+G_z$ plateau. At these plateau $+G_z$ levels, subjects could concentrate on performing maximal AGSM without fear of losing consciousness.

Data Analysis

All pressures and $+G_z$ levels were analyzed on the strip chart record. Measurements of P_{es}, P_{mask}, $P_{g\text{-}suit}$, and $+G_z$ were referenced to zero. Values for P_{ga} were taken as displacement above baseline (ΔP_{ga}). The "maximal" P_{es} in an experimental condition was defined as the greatest pressure over a 0.5-s period. All other P_{es} levels were measured as the greatest pressure over a 1-s period. Cardiac artifacts complicate analysis of the P_{es} waveform, but the effects are negligible at these high P_{es} levels. All other variables were analyzed over the same time interval as the respective P_{es} measurement.

The data were analyzed by repeated measures analysis of variance (alpha level at 0.05). Scheffe post-hoc tests followed significant F-ratio results. Variability about mean values are reported as standard error of the mean (±S.E.M.).

RESULTS

With jerkin and G-suit on, group mean P_{es} at the end-expiratory lung volume position while sitting in the gondola at +1 G_z was −10 (±2.9) mm Hg. At end-tidal volume, mean P_{es} was −19.2 (±3.4) mm Hg. Because PBG tends to increase lung volume, the increase in P_{es} with PBG was calculated as the difference between P_{es} at mid-inspiration before PBG and P_{es} at mid-inspiration with PBG. During C-PBG when group mean P_m was 57.7 (±0.6) mm Hg, P_{es} had increased by 55.0 (±1.6) mm Hg (Fig. 1) producing a mean P_{es}-increase ratio of 0.95 (±0.03).

Secondary parameters were uniform for comparison of P_{es} between C-mAGSM and C-PBG + mAGSM. The $+G_z$ level (mean = +7 G_z) and $P_{g\text{-}suit}$ (mean = 394 mm Hg) were constant for individual subjects.

P_{es} for all parts of the various experimental conditions are shown in Fig. 2. P_{es} was significantly greater when maximal straining was used (C-1G, C-mAGSM, C-PBG + mAGSM), compared to submaximal efforts (C-sAGSM) or PBG alone (C-PBG). P_{es} in C-sAGSM was slightly greater compared to the levels in C-PBG. P_{es} before AGSM started in C-PBG + mAGSM was not statistically different from P_{es} during C-PBG. Within each 20-s period in all experimental conditions, the variation in P_{es} with different breaths or AGSMs was not statistically significant.

The bars marked "max" in C-1G, C-mAGSM, and C-PBG + mAGSM of Fig. 2 show maximal P_{es} over 0.5 s in their respective conditions. There was no statistical difference among these values. Their average value was 138.9 (±1.9) mm Hg.

Fig. 3 shows ΔP_{ga} corresponding to each measurement of P_{es} in Fig. 2. Similar to P_{es}, ΔP_{ga} was greatest when maximal straining was performed. ΔP_{ga} was similar in C-sAGSM and C-PBG. At the time of maximal P_{es}, the ΔP_{ga} levels in C-1G, C-mAGSM, and C-PBG + mAGSM were not statistically different. The average ΔP_{ga} at maximal P_{es} was 197.2 (±3.9) mm Hg, but there were no instructions to the subjects to increase P_{ga} specifically during maximal straining.

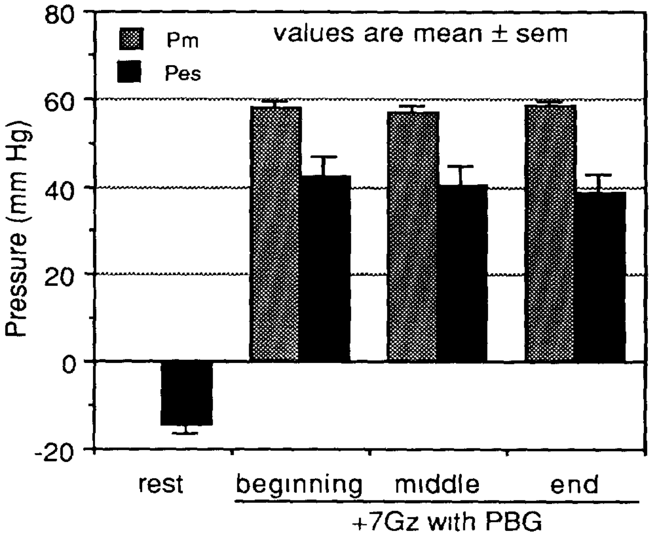

Fig. 1. Comparison of mask pressure (P_m) and esophageal pressure (P_{es}) from three breaths during condition C-PBG at beginning, middle, and end of +7 G_z plateau.

DISCUSSION

PBG, both without and with the aid of thoracic counter-pressure, provides substantial increases in $+G_z$-duration tolerance compared to AGSM tests (4,18,20). However, increases in $+G_z$-intensity toler-

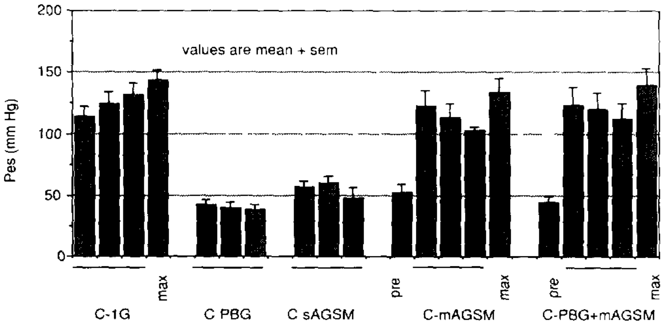

Fig. 2. Esophageal pressure (P_{es}) in all experimental conditions.

Legend

C-1G: maximal valsalva/AGSM at +1 G_z;

C-PBG: PBG at high $+G_z$;

C-sAGSM: submaximal AGSM at high $+G_z$;

C-mAGSM: maximal AGSM at high $+G_z$;

C-PBG+mAGSM: PBG and maximal AGSM at high $+G_z$;

———: 3 bars underlined are pressures measured over 1 s and represent pressures at beginning, middle, and end of high $+G_z$ plateau;

pre: pressure measured before start of maximal AGSM;

max: greatest pressure over 0.5 s in that experimental condition.

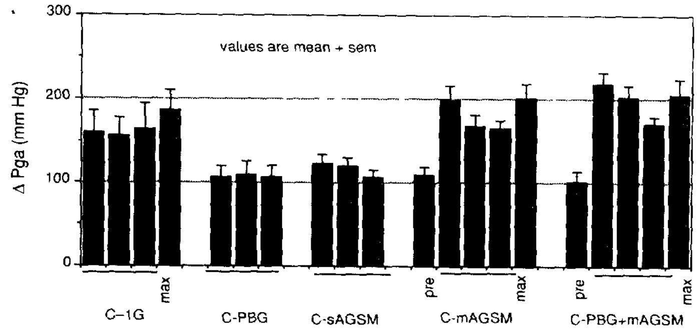

Fig. 3. Change in gastric pressure (ΔP_{ga}) in all experimental conditions. Legend same as for Fig. 2.

ance with PBG have not been documented. Due to increases in blood pressure from the potential extra increases in intra-thoracic pressure from the combination of PBG and straining maneuvers, improvements in $+G_z$-intensity tolerance might be expected. If the combination of assisted PBG and maximal AGSM had produced an additive effect on intra-thoracic pressure, maximal P_{es} would have reached levels approximately 60 mm Hg greater than the observed values. Instead, P_{es} from straining and PBG combined was not different from P_{es} produced by maximal AGSM alone at $+7\ G_z$, or by a maximal strain at $+1\ G_z$.

It is unlikely that the difference between the perfect additive effect on maximal P_{es} and the findings presented here was due to methodological or experimental subject limitations. Reasons for this are as follows:

1. Methodological. a) P_{es} was measured as an index of intra-thoracic pressure. Although it does not record the absolute pressure around the heart (21), changes in P_{es} agree well with changes in pleural pressure (5). b) The miniature esophageal pressure transducer performs satisfactorily when compared to the standard esophageal balloon system (9).
2. Experimental subjects. a) The maximal P_{es} recorded at $+1\ G_z$ agrees with the observations of others (6,15). b) The subjects were highly motivated and performed consistently. Maximal P_{es} values during $+G_z$ exposure were as high as at $+1\ G_z$.

We believe the observations are explained by inadequate support from thoracic counter-pressure during PBG, and the characteristics of the expiratory musculature.

Inadequate Support from Thoracic Counter-Pressure

We view the thorax during AGSM to behave as the piston model shown in Fig. 4. Part of the thorax is represented by the rigid walls. The piston surface represents all the compliant regions of the thoracic wall. All the muscles participating in AGSM, primarily expiratory muscles, are represented by the contractile unit pulling the piston. The inspiratory muscles are ignored. (The effect of $+G_z$ on the chest wall is also omitted. $+G_z$ impedes normal elevation of the chest wall but PBG dampens that effect by assisting to lift the chest.) The model's recoil characteristics are represented by the spring. The spring ensures that the piston returns to the same position when there is no muscular contraction and no pressure differential across the piston surfaces as in the resting condition shown in Fig. 4a.

Fig. 4b simulates the situation during AGSM alone. The glottis closes. Concentric contraction pulls the piston inward causing gas compression and an increase in intra-thoracic pressure of 130 mm Hg relative to outside. Boyle's Law describes the proportional relationship between volume reduction and pressure increase.

In Fig. 4c, PBG delivers pressurized gas to the airway, as would occur with an oronasal mask with a reflected seal, and directly to the compliant part(s) of the thorax, in this case most effectively performed by a device similar to an iron lung in which equal pressure is applied to all parts of the thorax. In this figure, the intra-thoracic pressure increase is similar to the elevation in mask cavity pressure and is perfectly balanced by pressure on the piston exterior.

An AGSM is added to perfectly-balanced PBG in Fig. 4d. First the muscle is relaxed and intra-thoracic pressure is increased 60 mm Hg by PBG. Then the glottis is closed and AGSM is performed. The straining muscles generate the same transmural pressure difference across the two surfaces of the piston as in Fig. 4b. This increment in pressure then adds to the already-elevated intra-thoracic pressure producing 190 mm Hg.

Fig. 4e represents PBG with mask and jerkin. This situation differs from the previous figure by the presence of a bladder interface between the body, or piston surface, and external pressure. This type of counter-pressure would reproduce the counter-pressure effect of Fig. 4c and 4d, provided the interface is highly compliant and covers completely, and is supported by a reliable pressure source. This is not the case, and the increased intra-pulmonary pressure becomes only partially-balanced at the body surface. Although the jerkin limits chest wall displacement outward, counter-pressure acting in the inward direction is not widely distributed.

There are several indications that the type of counter-pressure used was less than optimal.

1. The physiological consequences of pressure breathing are minimized when counter-pressure garments maintain the subdivisions of vital capacity near the normal levels, particularly that of the end-expiratory position (16). Only complete trunk coverage with a bladder was successful in this regard. A capstan suit and chest-only counter-pressure with a vest were just slightly better than no counter-pressure at all (16). The TLSS-style jerkin used here does not maintain the normal end-expiratory position during PBG. Chest wall shape studies during pressure breathing with 70 mm Hg at $+1\ G_z$ indicated that the rib-cage component of lung volume was markedly inflated. The rib-cage had a configuration similar to that at 2 L above the end-expiratory position without pressure breathing. Only by abdominal compression through pressurization of the G-suit (at $4\times\ P_m$) was resting lung volume during pressure breathing brought close to pre-pressure breathing levels (3).

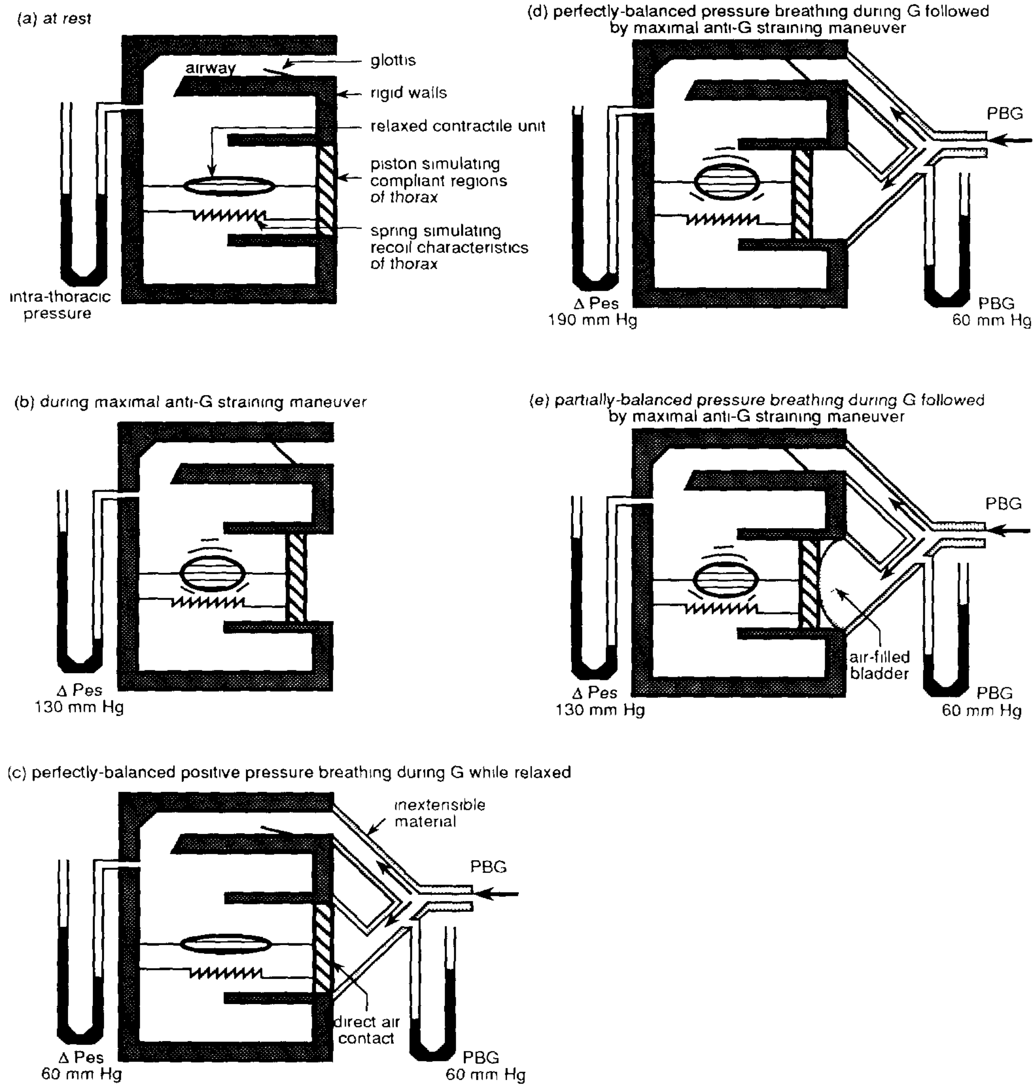

Fig. 4. Mechanical model of some respiratory system components and interaction of anti-G straining maneuvers with positive pressure breathing during +Gz.

2. Although the outer shell of the TLSS-style jerkin covers the entire trunk, the bladder only covers the inter-scapular space and the anterior to mid-lateral portion of the rib-cage. (Some lower trunk support is provided by the abdominal bladder of the G-suit). This is significantly less than the all-encompassing bladder of the RAF jerkin which, from the view of respiratory and cardiovascular support, successfully balances pressure breathing at +1 Gz. Fig. 4e illustrates the problem with a bladder which does not provide complete coverage. Counter-pressure only occurs between surfaces in contact. Small bladders or ballooning of bladders reduce the contact area and the effectiveness of the counter-pressure. Unsupported body regions are compliant structures which waste the potential rise in intra-thoracic pressure. With the TLSS-style jerkin, two candidate regions for added support are the anterior and lateral aspects of the costal margin. Here chest wall movement is possible due to displacement of the diaphragm by changes in either intra-thoracic or intra-abdominal pressure.
3. Full trunk counter-pressure compared to chest-only coverage increased the blood pressure elevation with pressure breathing (8). The closeness-of-fit of the jerkin is also important. During 70 mm Hg pressure breathing, blood pressure was 22 mm Hg greater with a tightly-fitted TLSS-style jerkin compared to a jerkin fitted more loosely (2). The tightly-fitted jerkin reduced vital capacity by 0.5 L before pressure breathing.

It is also possible that contact between the inner jerkin liner and the thorax is not constant. To compress gas at the start of AGSM, muscle contraction reduces the size of the chest, causing the chest wall to move inward away from the jerkin. Until pressure in the bladder and surface contact are restored, counter-pressure is incomplete.

Characteristics of Expiratory Musculature

From the preceding analysis, inadequate thoracic counter-pressure can account for the failure of combined PBG and maximal AGSM to increase intra-thoracic pressure to the level determined by the sum of their individual effects. That the maximal intra-thoracic pressure with PBG, jerkin, and maximal AGSM is not different from maximal AGSM alone suggests this counter-pressure is very ineffective. It is so ineffective that the assisted PBG more closely resembles unassisted PBG (PBG without a jerkin) than perfectly-balanced PBG. In unassisted PBG, the characteristics of the expiratory musculature can predict the ceiling of P_{es} when maximal AGSM is combined with PBG.

The ability of the expiratory muscles to generate intra-pulmonary pressure (a good indicator of P_{es} in this situation) is described by the maximal pressure-lung volume (PV) diagram (Fig. 5). Maximal Valsalva-type maneuvers were used in the development of the original PV diagram (15). These findings were confirmed using AGSM (6). The horizontal distance from the ordinate to the heavy dashed curve in the PV diagram shows the maximal intra-pulmonary pressure that can be produced when the expiratory/AGSM muscles contract against a closed airway as measured at different lung volumes. The expiratory muscles produce the greatest intra-pulmonary pressure (approximately 172 mm Hg in this example) when lung volume is near full vital capacity at the start of the effort. The maximal pressure that can be generated decreases somewhat exponentially when lung volume decreases. This explains the success of maximal AGSM to increase blood pressure after a rapid inspiration to a high lung volume. The hyperinflation produced by pressure breathing may confer a similar benefit. It places the expiratory muscles at a more advantageous position to generate force.

During expiratory efforts against a closed glottis, the forced decrease in lung volume causes compression of gas. The lung volume decrease for a maneuver performed at 100% vital capacity is represented by the solid sloping line with a single arrow in Fig. 5. This line joins the top of the ordinate, at a time just before the strain, with the maximal pressure produced during the strain at that lung volume. At maximal pressure, the maximal forces of the expiratory muscles attempting to further reduce lung volume are equally opposed by the elevated intra-pulmonary and intra-thoracic pressures. A submaximal AGSM effort at any lung volume would be represented by a pressure point located within the boundaries defined by the maximal pressure curve, the volume reduction line, and the ordinate.

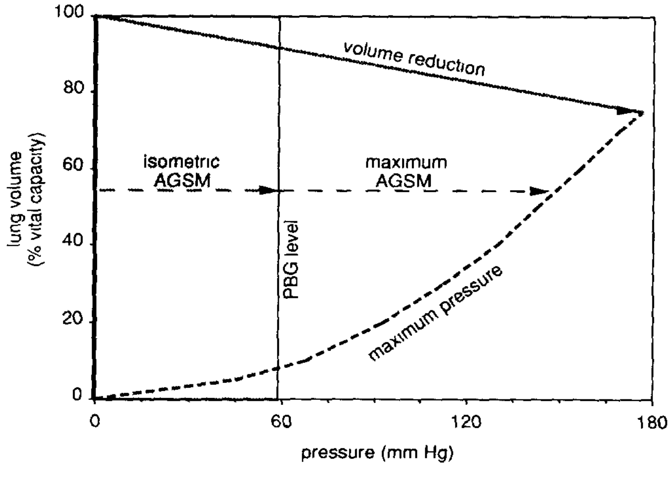

Fig. 5. Pressure-volume diagram. Heavy dashed curve (– – – –) represents maximal expiratory intra-pulmonary pressure at different lung volumes (after several sources). Solid line arrow (—▶) represents reduction in lung volume due to gas compression when maximal pressure is exerted at 100% of vital capacity. Shaded area represents intra-pulmonary pressure produced with PBG 60 mm Hg; when AGSM is added to PBG, the left dashed line arrow (– –▶) represents the potential intra-pulmonary pressure resulting from the submaximal isometric AGSM. The right dashed line arrow (– –▶) shows the added pressure resulting from the maximal AGSM.

The heavy dashed curve in Fig. 5 indicates typical pressures achievable during maximal voluntary expiratory efforts. They do not indicate the overall maximal pressure that can be generated by the muscles. Intra-thoracic pressure as high as 300 mm Hg can be produced transiently during cough (19). Reflexive inhibition of muscle may limit the maximal pressure that can be generated voluntarily.

The shaded area in Fig. 5 represents the pressure supplied by PBG. A breathing regulator can provide the work for the first 60 mm Hg of pressure. For intra-pulmonary pressure to exceed 60 mm Hg, the muscles first generate isometric tension equivalent to producing 60 mm Hg pressure without PBG (i.e., to the rightward limit of the shaded area of Fig. 5). This amount of tension does not change lung volume. When additional tension from maximal AGSM compresses gas further, intra-thoracic pressure increases. The total pressure, however, would not exceed that defined by the maximal pressure curve. This would explain our observations.

Since muscular contraction is used to reach any pressure beyond the PBG level, it follows that the sense of AGSM effort would be in parallel with the total pressure rather than the pressure change from 60 mm Hg to the final level. In other words, an AGSM effort which adds 2 $+G_z$ of $+G_z$-intensity tolerance to 2 $+G_z$ of tolerance already provided by PBG, will feel like a 4 $+G_z$ strain and not like 2. This requires experimental verification. It contrasts an earlier analysis which cites pilots' reports of reduced AGSM effort with PBG at $+9$ G_z (11). Perhaps part of the difference is due to the greater lung volume during PBG which optimizes the position for the chest wall to generate positive pressure, and/or the lifting of the chest wall by PBG which assists inspiration. The analysis would also predict that when thoracic partial pressure garments evolve from minimal coverage to more complete counter-pressure, AGSM adding 2 $+G_z$ of protection to PBG will feel like a 2 $+G_z$ AGSM; and, the effect of PBG and maximal AGSM on P_{es} will be additive.

Other Observations of Performing AGSM with PBG

PBG requires a reliable pressure source. The experimental records of PBG with AGSM show that P_m is reduced immediately after the rapid inspiration and during the first portion of the strain compared to the normal PBG level. An extreme example from our experiments is shown in Fig. 6. Therefore, both PBG level and counter-pressure from the jerkin can be less than expected. A breathing regulator with insufficient capacity to meet the flow demands from inspiration and the vol-

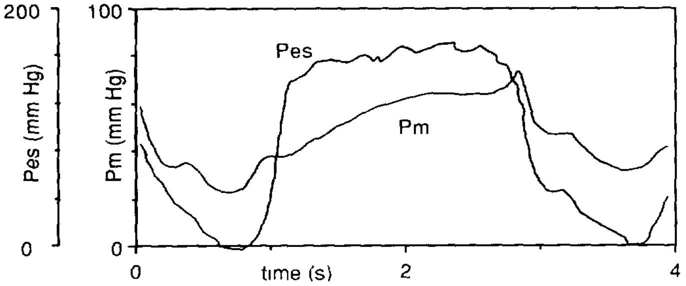

Fig. 6. Tracing of a record of mask cavity pressure (P_m) and esophageal pressure (P_{es}) during assisted PBG (approximately 60 mm Hg) and maximum AGSM at $+7\ G_z$.

ume demands for jerkin pressurization could explain these results.

During preliminary experiments, one subject could not increase P_{es} with PBG and AGSM much above his level with PBG alone, even though his maximal P_{es} with only AGSM was substantially greater. When his straining technique incorporated a more pronounced "hook" sound (22), P_{es} increased. PBG probably made closure of the glottis more difficult. Positive pressure breathing distends the upper respiratory passages (8) and the glottis may have to be moved farther to obtain complete closure. If the glottis is not completely closed during AGSM, intra-pulmonary gas compression forces air out through the mask leading to loss of pressure.

Conclusions

1. At high $+G_z$, maximal intra-thoracic pressure generated by the combination of maximal AGSM and PBG with small-bladder thoracic counter-pressure garments is not greater than pressure produced by maximal AGSM alone. Therefore, the $+G_z$-intensity protection obtained separately from PBG and AGSM is not additive.
2. Assisted (or balanced) PBG using thoracic garments which provide less-than-full trunk counter-pressure should be regarded as only partially-balanced PBG.

Implications of Findings

1. Jerkins were originally designed to limit hyperinflation of the lungs and assist expiration during positive pressure breathing for hypoxia protection. Even jerkins with smaller bladders fulfill this role. With only slight modifications, similar jerkins are being used with PBG, but the present analyses suggest that their value during PBG may have been underestimated. Greater increases in intra-thoracic pressure might be produced with larger jerkins, or with greater pressure in the jerkin compared to the mask in those jerkins with smaller bladders. Designs of thoracic counter-pressure garments should consider both hypoxia and $+G_z$ protection roles, but expanded coverage for physiological protection must be reconciled with minimal coverage for flying comfort.
2. Breathing regulators must provide high gas flow to meet the most demanding respiratory requirements in the cockpit (23). Inspiratory flow during vigorous AGSM can reach 4.7 L/s BTPS (1). Design specifications must also consider frequent pressurization of high-volume thoracic counter-pressure garments during PBG and AGSM.
3. The AGSM will likely remain a vital component of any $+G_z$-protection system for the upright aviator. Even with PBG, straining training in the centrifuge will be necessary.

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