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Determination of a Pressure Breathing Schedule for Improving $+G_z$ Tolerance

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A base of empirical data for developing optimal pressure breathing during $+G_z$ (PBG) schedules is lacking. Relaxed $+G_z$-intensity tolerance with PBG was measured during gradual $+G_z$-onset rate centrifuge profiles using standard lightbar criteria. Constant PBG levels ranging from 18–73 mm Hg were randomly assigned. G-suit pressure followed the standard or an increased inflation schedule. Nine subjects wore a jerkin, CSU-15/P G-suit, and TLSS helmet and mask. With mean mask cavity pressures of 0, 18, 38, 60, and 73 mm Hg, corresponding $+G_z$-tolerances (mean ± S.E.M.) were: 5.3 ± 0.2, 5.8 ± 0.1, 6.6 ± 0.2, 7.3 ± 0.3, and 7.5 ± 0.3 G_z (linear correlation, $r = 0.994$). Increased G-suit pressure did not change the $+G_z$-tolerance improvement with PBG. The inverse of individual subject regression slopes ranged from 22.6 to 58.1 mm Hg/$+G_z$. Considering additional factors and adequate $+G_z$ protection for all subjects while relaxed, the proposed schedule would apply 42 mm Hg PBG/$+G_z$ beginning at $+3.3$ G_z with a maximum pressure of at least 73 mm Hg.

THE PHYSIOLOGICAL capacity of pilots to tolerate high gravito-inertial forces can be a limiting factor in air combat situations. Aircraft are able to apply high positive gravitational forces ($+G_z$) rapidly and sustain them for prolonged periods. When such forces exceed the physiological tolerance level, impaired performance and even unconsciousness may result.

Tolerance to $+G_z$ can be improved by increasing blood pressure. Pilots perform anti-G straining maneuvers (AGSMs), intense muscular contractions which increase intra-thoracic and intra-abdominal pressures, and elevate blood pressure (11,16,18,19). Part of this increase in blood pressure is probably due to increases in peripheral vascular resistance as is believed to occur during high-intensity resistance exercise (10). AGSMs require concentration, are fatiguing, and may detract from flight duties. These limitations may be reduced if intra-thoracic pressure is increased via positive pressure from specialized breathing regulators. Positive pressure breathing also sustains the pressure throughout the respiratory cycle. Pressure breathing during $+G_z$ (PBG) increases $+G_z$-intensity tolerance compared to the unprotected condition (3,4,9) and reduces the level of fatigue associated with a straining maneuver (2,15).

The intensity of AGSM must be increased at increased $+G_z$ levels, but the optimal amount of pressure to be delivered by PBG systems has not been determined. One schedule applies 12 mm Hg PBG/$+G_z$ beginning at $+4$ G_z (1). The maximum pressure of 60 mm Hg is attained at $+9$ G_z. Since blood pressure at head level decreases by approximately 22 mm Hg/$+G_z$, this schedule must be supplemented with AGSM. Experimental determination of the pressure breathing requirements is necessary to produce a PBG schedule which would eliminate the need for, or at least reduce the effort in, performing the AGSM.

The work presented describes the amount of PBG required by relaxed subjects to reach high sustained $+G_z$ levels. Since high intra-thoracic pressures can impede venous return, the possible influence of an increased G-suit pressure on the protection afforded by PBG was also examined. The effect of PBG level on $+G_z$-intensity tolerance was investigated using gradual $+G_z$-onset rate centrifuge profiles. Compared to profiles using higher $+G_z$-onset rates, gradual onset rate profiles optimize the consistency of subjective visual endpoints and reduce the risk of the subject losing consciousness. The results can then be used to help predict PBG requirements at $+G_z$ levels reached more rapidly.

METHODS

Experimental Design

The experiment consisted of two sessions (Day 1 and Day 2), separated by 1 to 4 d. Day 1 assessed the re-

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producibility of the subjects' relaxed $+G_z$-intensity tolerance. It consisted of four gradual $+G_z$-onset rate exposures to visual endpoint criteria, with the first exposure designated a "warm up" and the final three exposures analyzed. Subjects wore a G-suit inflated according to the standard inflation schedule.

Day 2 sessions investigated the effect of pressure breathing and G-suit pressurization. Four PBG pressure levels ranging from 18–73 mm Hg were applied with either the standard G-suit inflation schedule or a modified (higher) schedule. The design was completely randomized. An additional condition (0 mm Hg PBG and standard G-suit pressure schedule) was performed three times: at the beginning of the session (pretest), at the end of the session (posttest), and once (control) randomized among the eight PBG/G-suit schedule combinations. The subjects could not relax with the higher G-suit pressure schedule without PBG, therefore this condition was omitted. A 2-min rest interval separated the 11 $+G_z$ exposures.

Subjects and Subject Preparation

The experiment was conducted in accordance with local regulations for human experimentation. Eight males and one female volunteer, ranging in age from 24 to 42 years, were recruited from personnel at DCIEM and CFB Toronto. The subjects were experienced centrifuge riders and trained in positive pressure breathing. A G-suit (CSU-15/P), thoracic counter-pressure jerkin (half front bladder, Mustang Ind., Richmond, B.C., Canada), and a pressure sealing mask and helmet (TLSS, Gentex Corp., Carbondale, PA) were used. The jerkin was pressurized to the same level as the mask. Electromyography of the rectus abdominis and the vastus lateralis muscles was recorded to ensure the subjects did not employ AGSM.

Procedure

The study was conducted in DCIEM's 20-ft arm, computer-controlled human centrifuge. The $+G_z$ level was measured (Systron Donner, Concord, CA, accelerometer, Model 4310-20-AGIM) at the subject's heart level. The seatback was reclined 22° from vertical. Subjects monitored their visual field during $+G_z$ exposure using a lightbar with a centrally located green LED and two peripheral red LEDs positioned 25° from center. The distance between subject and lightbar was 87 cm.

A 1.5 cm red LED display was located below the central green light. It presented to the subject a number that changed rapidly according to an unspecified fraction of the $+G_z$ level. In our experience, subjects who encounter central visual dimming more predominantly than peripheral light loss find it easier to monitor the changing digital display than the static LED.

Subjects were instructed to remain relaxed and at no time did the subjects know the $+G_z$ level during the profile. Criteria for termination of the $+G_z$ exposure were: 1) the inability to see the peripheral LEDs while fixated on the central LED; or 2) the reduction in the apparent intensity of the central LED by 50%; or 3) the inability to discern the digital LED display.

The Day 1 $+G_z$ profile accelerated the centrifuge at 0.1 $+G_z$/s until the subject's visual endpoint was reached. During Day 2 trials, the gondola was accelerated from $+1\ G_z$ to $+3\ G_z$ at 0.2 $+G_z$/s. The gondola remained at $+3\ G_z$ for 15 s during which a constant PBG level was applied to the mask and maintained for the duration of the $+G_z$ exposure (Fig. 1). The $+3\ G_z$ period was used to verify the mask cavity pressure, ensure commencement of PBG at the same $+G_z$ level, and decrease the time of pressure breathing required for each condition. Following completion of the $+3\ G_z$ plateau, the gondola was accelerated at 0.1 $+G_z$/s, until the subject reached one of the visual endpoint criteria. On the subject's release of the enable switch, the $+G_z$ level was reduced at a rate of 0.8 $+G_z$/s.

Fig. 2 shows the arrangement of the instrumentation. PBG was provided by a pneumatically activated BRAG valve (Breathing Regulator and Anti-G valve, Clifton Precision, Davenport, IA, P/N 3260039-0301). The G-suit pneumatic input to the breathing regulator stage of the BRAG valve had been disconnected and was simulated using a current-to-pressure (I/P) transducer (VDO, Winchester, VA, Model 22/06-15) and current control box. Pressure to the mask was controlled with two remotely actuated solenoids (Asco Electric, Brantford, Ont., Canada, Models 8210C35 and 8030B43).

The G-suit pressure was supplied by an anti-G valve (Alar, Cleveland, OH, Model 14050, high flow) or the anti-G valve portion of the BRAG valve. The Alar anti-G valve provided both the standard G-suit inflation schedule ($P = 1.5\,(+G_z\text{-}2)$ psi) or a modified schedule ($P = 2.0\,(+G_z\text{-}1.5)$ psi) via a brass weight placed on top of the "press-to-test" mechanism. Maximum G-suit pressure for both configurations was 11.0 psi. The output of the Alar and BRAG anti-G valves led to separate ports of a 3-way solenoid (Asco Electric, Model 8320A97) remotely controlled by a toggle switch. The standard G-suit pressurization schedule was applied by the Alar anti-G valve for the Day 1 and the Day 2 pretest, control, and post-test conditions. During the early

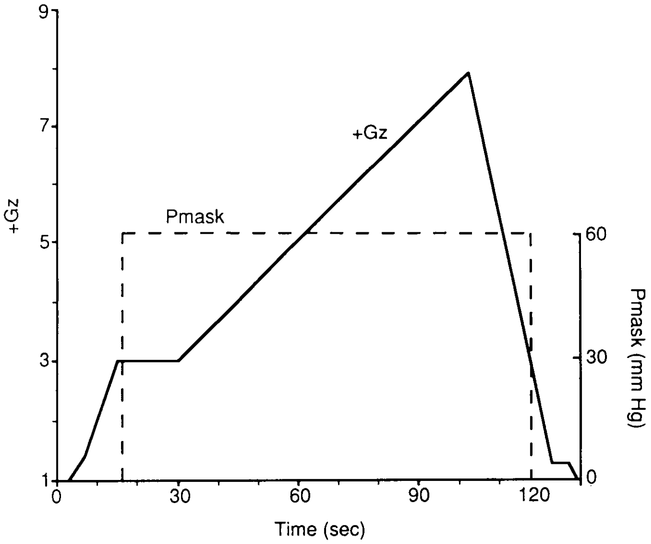

Fig. 1. $+G_z$ profile used in experiment. PBG (e.g., 60 mm Hg) applied at $+3\ G_z$ and maintained for duration of $+G_z$ exposure.

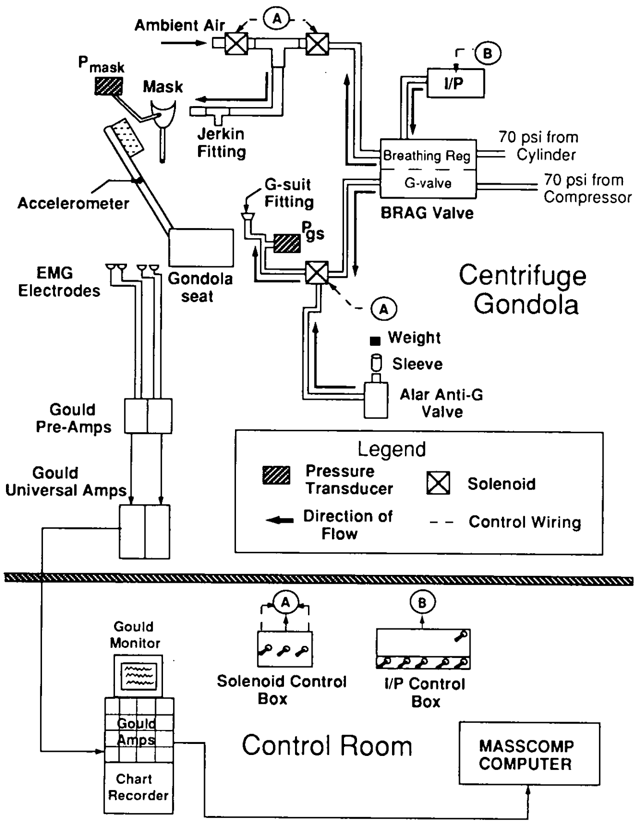

Fig. 2. Schematic of instrument setup in centrifuge gondola and control room.

portion of the PBG sessions, the G-suit was pressurized by the G-valve portion of the BRAG valve providing a 4:1 G-suit pressure: mask cavity pressure ratio at $+3\ G_z$. When a $+G_z$ level was reached where G-suit pressure for $+G_z$ protection was greater than the 4:1 ratio, the solenoid was opened for pressurization of the G-suit from the $+G_z$-dependent Alar anti-G valve.

Calibrated differential pressure transducers (Validyne, Northridge, CA, Model 1538N1S4A) were used to monitor mask cavity and G-suit pressures. Output voltages were sent through an A to D converter and stored on a computer (Concurrent Computer Corp., Westford, MA, Masscomp 5700) using an integrated data acquisition system (Creare Inc., Hanover, NH, Idars).

Analyses

Following completion of each acceleration profile, the subject reported the extent of visual light loss. The Day 2 pretest, control, and posttest data for mask cavity pressure, $+G_z$-intensity tolerance and G-suit pressure were analyzed using a one-way repeated measures analysis of variance (RM-ANOVA). The remaining eight conditions for each variable were evaluated using a 2 G-suit schedules × 4 PBG levels RM-ANOVA. Significant p values ($p \leq 0.05$) were adjusted using the Greenhouse-Geisser correction factor. Post-hoc analyses were performed using Scheffé tests with alpha = 0.1 (14). Light loss levels were compared using Friedman's two-way ANOVA of ranks. Day 2 $+G_z$-intensity tolerance values were plotted with mask cavity pressure and regression analyses were performed. Data are reported as mean ± the standard error of the mean (S.E.M.).

RESULTS

Day 1 Results and $+G_z$ Reproducibility

The EMG recordings confirmed that the subjects did not use muscular straining during any $+G_z$ exposure, and no exposure was terminated for any reason except light loss. Consistent visual endpoints were used. There were no differences in the reported light loss values among the three $+G_z$ exposures on Day 1 for either the peripheral or the central lights. The mean peripheral and central light loss values at $+G_z$-intensity tolerance across the three $+G_z$ exposures were 93.9 and 62.3%, respectively.

There was no difference in G-suit pressure during the three exposures at the greatest $+G_z$ level common to all subjects ($+4.5\ G_z$). The mean G-suit pressures were 4.23 (±0.21), 4.18 (±0.21), and 4.21 (±0.21) psi.

Measurement of relaxed $+G_z$-intensity tolerance was reliable. The coefficient of variability for individual subjects over the three exposures was less than 5% (range 0–4.31, mean 2.56%). The Day 1 overall mean relaxed $+G_z$-intensity tolerance for the three conditions was $+5.3 \pm 0.15\ G_z$. Mean $+G_z$-intensity tolerance for each of the three exposures was also $+5.3\ G_z$, with a standard error of 0.17 $+G_z$ for the first exposure, and 0.14 $+G_z$ for the second and final exposures.

Day-to-day variability on the measurement of relaxed $+G_z$-intensity tolerance was examined. The three Day 2 relaxed $+G_z$-intensity tolerance values (pretest, control, and posttest conditions) were not statistically different from those measured during the Day 1 session.

Effect of PBG on $+G_z$-Tolerance (Day 2)

All subjects remained relaxed as instructed. There was no evidence of EMG activity during Day 2 conditions. Attainment of light loss criteria was the only reason for terminating the centrifuge runs in all experimental conditions. There were no differences in the reported central and peripheral light loss percentages at $+G_z$-intensity tolerance among the 11 $+G_z$ exposures. Central light loss ranged from 0 to 100%, while peripheral light loss was consistently above 90%.

Secondary parameters were verified as being controlled. The rest period was constant between exposures. The mean interval between all experimental conditions was 122 (±1) s. (One subject was excluded from this average as one rest period was prolonged to 7 minutes due to motion sickness. His subsequent $+G_z$-intensity tolerance tests were not affected by this incident.) There was no evidence of fatigue of the subjects with repeated $+G_z$ exposure. $+G_z$-intensity tolerance values for the Day 2 pretest, control, and posttest conditions were not statistically different. The G-suit pressure was reliable. At the highest common $+G_z$ level across all experimental conditions, the G-suit pressure was the same within each pressurization schedule. The G-valve configuration significantly affected G-suit pressurization (2 × 4 RM-ANOVA ($F(1,8) = 78.988$, p =

0.0001)). At all levels of PBG, G-suit pressure was greater in the weighted configuration compared to the standard configuration.

The effectiveness of controlling mask cavity pressure was evaluated by comparing the pressures at $+G_z$-intensity tolerance. Mask cavity pressures were significantly different among the various PBG conditions ($F(3,24) = 2055.866$, $p = 0.0001$), but were not different between the two G-suit pressurization schedules. Combining across G-suit schedules, mean mask cavity pressures for the PBG conditions were 18, 38, 60, and 73 mm Hg. These values will be used for the remainder of the paper.

Among the eight experimental conditions consisting of four PBG levels and two G-suit inflation schedules, there was a significant effect of pressure breathing level ($F(3,24) = 46.732$, $p = 0.0001$) on $+G_z$-intensity tolerance. There was no effect of G-suit schedule, and no interaction between PBG level and G-suit schedule. $+G_z$-intensity tolerances were combined across G-suit schedules and a one-way RM-ANOVA compared the control condition with the PBG conditions. $+G_z$-intensity tolerance was significantly different among all PBG conditions except between the 60 and 73 mm Hg PBG levels. Group mean $+G_z$-intensity tolerance was increased from the control value of $+5.3 \pm 0.2$ G_z to $+7.5 \pm 0.3$ G_z with 73 mm Hg PBG.

Relationship Between PBG and $+G_z$-Tolerance

Correlation coefficients from linear and second order regressions of the group PBG and $+G_z$-intensity tolerance data in the 11 experimental conditions were 0.994 and 0.995, respectively. The strength of the first order correlation and the minor improvement with the second order regression suggest a linear relationship between PBG and relaxed $+G_z$-intensity tolerance (Fig. 3). The linear regression equation for the group data was: $+G_z$-intensity tolerance $= 0.314\ G_z/10$ mm Hg PBG $+ 5.34$, producing an inverse slope of 31.85 mm Hg PBG/$+G_z$.

Regression calculations for individual subjects produced the correlation coefficients, intercepts, and slopes shown in Table I. Correlation coefficients ranged from 0.846 to 0.981. The Y intercept ranged from $+4.85$ to $+5.93$ G_z. The inverse slope of the linear regression for the individual subjects ranged from 22.62 to 58.14 mm Hg PBG/$+G_z$.

DISCUSSION

Measuring $+G_z$-Intensity Tolerance

The low coefficient of variability indicated that relaxed $+G_z$-intensity tolerance and its measurement were reproducible. Mean relaxed $+G_z$-intensity tolerance of $+5.3$ G_z is consistent with previous findings (5,8). Therefore, the rating of extreme light loss was a reliable endpoint for measuring $+G_z$-intensity tolerance in our experienced subjects. There was no variation in the group $+G_z$-intensity tolerance from Day 1 to Day 2.

With guidelines, the subjects determined their own visual endpoints, but light loss reported at the conclusion of each condition was found to be consistent for each subject. The choice of the visual endpoint varied among subjects. Most chose to use the changing digital LED display.

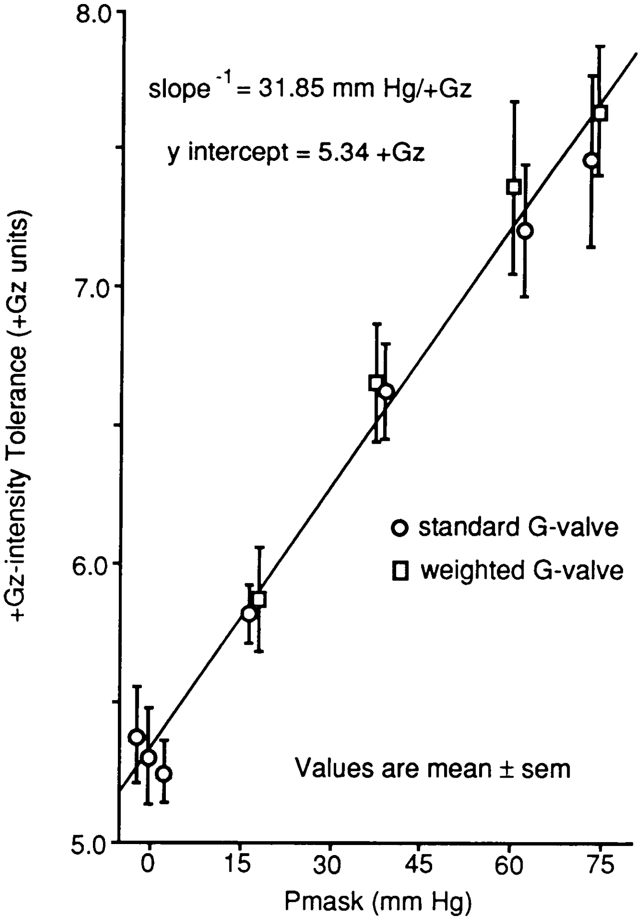

Fig. 3. Linear regression of mean relaxed $+G_z$-intensity tolerance values (with standard G-valve or weighted G-valve configuration) and mask cavity pressure.

TABLE I. INDIVIDUAL SUBJECT PBG REQUIREMENTS DETERMINED FROM LINEAR REGRESSION ANALYSIS OF $+G_z$-INTENSITY TOLERANCE ($+G_z$ UNITS) AND MASK CAVITY PRESSURE (mm Hg).

	Linear Regression			
Subject	Correlation Coefficient	Slope ($+G_z$ units/ 10 mm Hg PBG)	Y intercept ($+G_z$ units)	Inverse slope (mm Hg PBG/$+G_z$)
1	0.955	0.266	4.86	37.59
2	0.977	0.378	5.68	26.46
3	0.981	0.442	5.20	22.62
4	0.961	0.433	5.16	23.09
5	0.846	0.172	5.32	58.14
6	0.962	0.275	5.26	36.36
7	0.917	0.239	4.85	41.84
8	0.923	0.242	5.93	41.32
9	0.951	0.380	5.85	26.32

$+G_z$-Intensity Tolerance with PBG

The main independent variables, G-suit pressure and PBG level, were controlled consistently in all conditions. G-suit pressure was increased with the weighted versus the standard G-valve configuration, and consistently reached expected values. Any differences in

$+G_z$-intensity tolerance, therefore, were due to changes in mask cavity pressure. Mask cavity pressure was also reproducible.

Relaxed $+G_z$-intensity tolerance increased with PBG compared to control values in all subjects. Each step increment in PBG level further increased $+G_z$-intensity tolerance, except when 73 mm Hg mask cavity pressure was compared to the 60 mm Hg condition. In assessing the effect of 50 and 70 mm Hg pressure breathing levels, Burns and Balldin (2) found a decrease in $+G_z$-duration tolerance with the higher pressure. They suggested that the decreased tolerance may have been due to discomfort from a tightly-fit mask necessary for an effective face seal, and from increased nasopharyngeal distention. With the TLSS helmet and mask configuration used in the present study, there were no complaints of facial discomfort. The subjects perceived an increase in nasopharyngeal distension from the 60 to 73 mm Hg PBG levels, but this was not the terminating factor because the same visual endpoints were reached during both conditions. Therefore, the test with 73 mm Hg PBG is not regarded as having been terminated prematurely.

A possible explanation for the statistically ineffective change in $+G_z$-intensity tolerance with 73 mm Hg PBG was the small elevation in mask cavity pressure, only 13 mm Hg above the 60 mm Hg condition. This is substantially less than the difference in mask pressure in all other paired comparisons of PBG levels. Therefore, the small increase in PBG level would be expected to produce only a small increase in $+G_z$-intensity tolerance. Regression analyses also suggest that the small $+G_z$-intensity tolerance increase was due to the small change in the independent variable rather than attainment of a ceiling in $+G_z$-tolerance. The correlation coefficient was not improved with a second order equation. We aimed for 80 mm Hg PBG from the breathing regulator but 73 mm Hg was the maximum obtainable. It remains possible that $+G_z$-intensity tolerance can be further improved with PBG greater than 73 mm Hg.

A PBG schedule was developed by plotting mask cavity pressure as a linear function of the corresponding $+G_z$-intensity tolerance, an inversion of Fig. 3. The group data suggest the schedule should begin delivering pressure to the mask at $+5.34\ G_z$ and increase pressure by 31.85 mm Hg/$+G_z$. Linear regression analysis on data of Clère et al. (4) in which a 30° seatback angle was used, shows an inverse slope of 26.02 mm Hg/$+G_z$. The slope of a PBG schedule based on their results is twice that proposed by USAF (1), but still 18% less than the mean slope found here.

Design of PBG Schedule

Using the Y intercepts and the inverse of the slopes of the regressions, Fig. 4 shows the PBG requirements to maintain a minimum level of vision for the group and individual subjects. The pressure provided by the USAF PBG schedule is also shown. With the USAF PBG schedule, a subject would reach his or her relaxed $+G_z$-intensity tolerance limit at the $+G_z$ level where the linear regression line intersects the USAF schedule. To maintain tolerance, the average subject must supplement the USAF PBG schedule with AGSM beginning at $+6.2\ G_z$. Straining must supply additional pressure calculated by the vertical distance between the individual requirement and the PBG schedule. The USAF PBG schedule would protect most subjects at the lower $+G_z$ levels. However, in all comparisons with the regressions, the USAF schedule has a more gradual slope. It does not increase as steeply as the individual pressure breathing requirements.

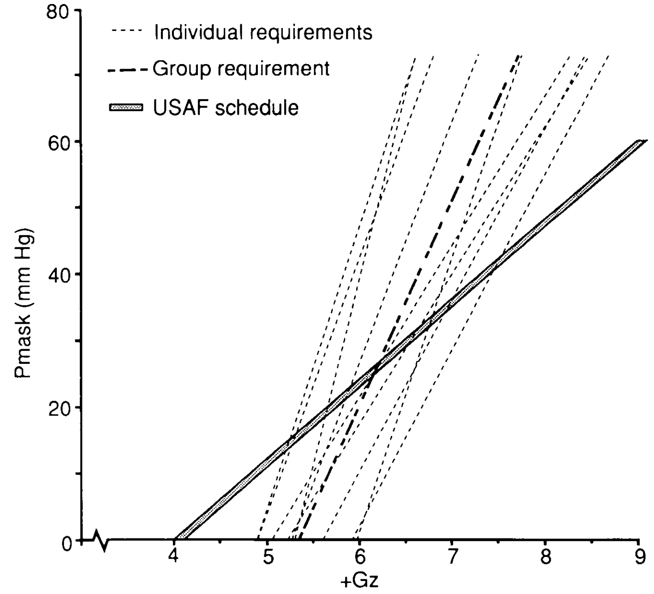

Fig. 4. Mask cavity pressure from USAF PBG schedule compared with individual subject and group mean pressure breathing requirements.

If a PBG schedule were developed from the group data, the three subjects with PBG requirement lines completely to the right of the group slope would improve their $+G_z$-intensity tolerances above the control condition. For the remaining six subjects, a PBG schedule based on the group data would be inadequate. Either the $+G_z$ level is too high before PBG begins, and/or the required slope of pressure increase exceeds the pressure delivered. If this pool of subjects represents the pilot population, a PBG schedule beginning at $+5.34\ G_z$ and delivering 31.85 mm Hg/$+G_z$ would help one-third of pilots to reach $+7.7\ G_z$ relaxed. The others must supplement PBG with AGSM, even though the regulator has the potential to deliver greater pressure.

The single schedule that would allow all individuals to remain relaxed to their greatest personal $+G_z$ level is a schedule based on the most "$+G_z$-intolerant individual." A large range of Y intercepts and slopes was found among the subjects. The lowest Y intercept was $+4.85\ G_z$ and the greatest inverse slope was 58.14 mm Hg/$+G_z$. To provide complete protection for all subjects, the PBG schedule must consider the most extreme requirements: 1) the overall lowest Y intercept (X, Y coordinates 4.85 and 0 in Fig. 4), and 2) the ability to reach 73 mm Hg at the $+G_z$ level corresponding to the lowest overall $+G_z$-intensity tolerance achieved with maximum PBG (X, Y coordinates 6.58 and 73 in Fig. 4). These two points describe a schedule which starts PBG at $+4.85\ G_z$, increases the pressure at 41.55 mm Hg/$+G_z$, and provides a maximum pressure of at least 73 mm Hg. All subjects would be protected to at least +6.6 G_z without AGSM. With this schedule, the average subject would realize an increase in relaxed $+G_z$-intensity tolerance of 2.2 $+G_z$.

This schedule contrasts sharply with PBG schedules proposed by others. The USAF schedule (1), although developing pressure sooner, increases pressure more gradually and requires supplemental AGSM even at low $+G_z$ levels. Prior and associates (12) found that a PBG schedule providing 10 mm Hg/$+G_z$ beginning at +4.0 G_z only increased relaxed $+G_z$ tolerance by 0.4 $+G_z$. Using ratings of satisfaction with the PBG schedule while wearing full coverage anti-G trousers, a PBG schedule providing 14 mm Hg/$+G_z$ beginning at +3 G_z was suggested subsequently by Prior (13). The PBG schedule developing from our data would delay recruitment of the AGSM as long as possible by optimizing the pressure output from the PBG regulator.

Because there is a range of individual PBG requirements, the proposed single PBG schedule would expose relatively $+G_z$-tolerant pilots to greater intra-pulmonary pressures than they might require for that $+G_z$ level. There are medical risks with PBG. Conditional problems can develop with the ears and sinuses (7). Arm pain is often reported with PBG (13) and high airway pressure can interfere with communication. However, the pulmonary overpressurization with PBG, which could result in pneumothorax and air embolism especially in medically unfit individuals, is an exaggerated concern. The increased intra-pulmonary pressure is always counteracted by the equally-pressurized jerkin (and by the G-suit), allowing only a very narrow trans-respiratory pressure gradient. Also, the PBG ceiling remains at 73 mm Hg.

Modifications to the Schedule

The data leading to the proposed PBG schedule were collected during gradual $+G_z$-onset rate profiles and some subjects rode the centrifuge to almost complete visual blackout. Although necessary for the experiment, these are unrealistic conditions in high $+G_z$ flight environments. The onset rate of $+G_z$ may be as high as 10 $+G_z$/s, and a clearer central visual field is necessary for operations and flight safety.

Cardiovascular reflexes (19) increase blood pressure and increase $+G_z$-intensity tolerance on average by 1 $+G_z$ (6,17) to 2 $+G_z$ (5) compared to $+G_z$ conditions with minimal reflexive response. With an onset rate of 0.1 $+G_z$/s, cardiovascular reflexes would have been fully mobilized by the time the visual endpoint was reached. A more rapid $+G_z$-onset rate would require PBG to begin at a lower $+G_z$ level to substitute for the reflexes which have not yet responded. Therefore, the schedule should be modified to begin PBG at least 1 $+G_z$ below the level suggested by the gradual $+G_z$-onset rate profile to ensure a sufficient blood pressure increase.

To provide a wider and clearer visual field at the measured $+G_z$-intensity tolerance level, blood pressure at the retina must be increased. By shifting the PBG schedule an additional 0.5 $+G_z$ unit to the left (i.e., increasing the mask cavity pressure for a given $+G_z$ level), the PBG level at $+G_z$-intensity tolerance would be increased by 21 mm Hg. Eye-level blood pressure would increase and provide an improved visual field. Therefore, positive pressure breathing would commence at +3.3 G_z; the slope would remain at 42 mm Hg/$+G_z$; and the maximum PBG level remains at 73 mm Hg.

Fig. 5 shows the modifications to the proposed PBG schedule. The PBG requirements are transposed leftward by 1.5 $+G_z$ to produce a new PBG schedule which accounts for decreases in relaxed $+G_z$-intensity tolerance due to rapid $+G_z$-onset and the benefits of a wider visual field. Having considered the $+G_z$ level at which PBG should start, we know of no reason to modify the slope of the schedule.

The PBG schedule developed here requires further testing in the centrifuge. The initial schedule was based on experimental data. The subsequent schedule, relevant to the air combat environment, is an extrapolation of this data. This process, however, has raised a number of considerations and has shown that a wide empirical basis is lacking for development of PBG schedules. The PBG schedule developed here remains to be evaluated under varying $+G_z$-onset rates. Even with current G-suits, PBG significantly increases relaxed $+G_z$-intensity tolerance. The PBG schedule may require further modification when combined with partial reclination or with full-coverage anti-G trousers.

Summary

Based on reliable visual criteria, relaxed $+G_z$-intensity tolerance increases linearly as the PBG level is increased. Increasing the G-suit pressure compared to the standard inflation scheme did not alter this relationship. A PBG schedule was developed based on the fol-

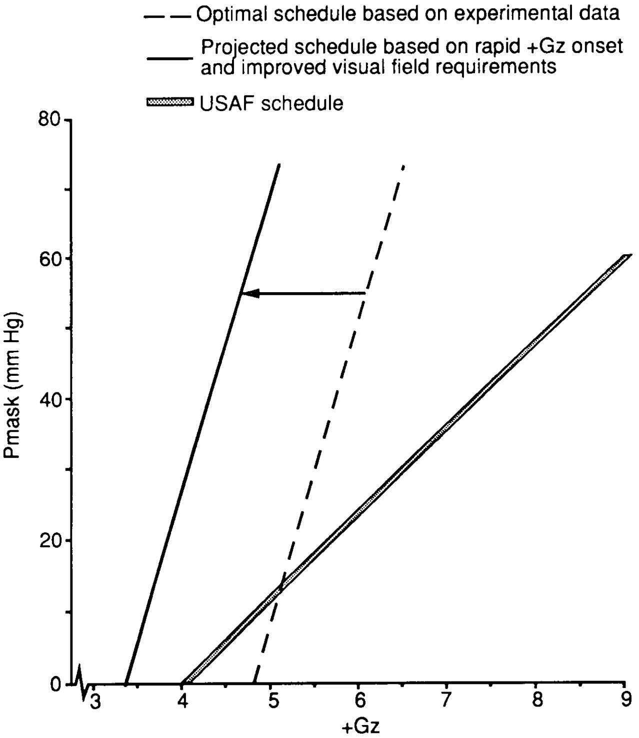

Fig. 5. PBG schedule based on experimental data and modified PBG schedule (transposed leftward 1.5 $+G_z$) to accommodate rapid $+G_z$-onset and wider visual field requirements.

lowing: 1) a wide range of individual pressure breathing requirements; 2) the $+G_z$-onset rate; and 3) visual status. The proposed schedule begins PBG at $+3.3\ G_z$ and increases mask cavity pressure at 42 mm Hg/$+G_z$ to at least the 73 mm Hg PBG limit.

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