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ORIGINAL RESEARCH

The Effect of Varying Time at $-G_z$ on Subsequent $+G_z$ Physiological Tolerance (Push-Pull Effect)

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Introduction: Previous studies have demonstrated decreased $+G_z$ tolerance when preceded by 0 G_z or $-G_z$, referred to as the "push-pull effect." The purpose of this experiment was to observe the effect of varying time duration at $-G_z$ on the push-pull effect. ***Methods:*** During single sessions, six subjects (three men, three women) were subjected to five relaxed exposures to +2.25 G_z on the NAMRL Coriolis Acceleration Platform (CAP). The first and last exposures were control runs that were preceded by +1 G_z. Each experimental run was preceded by −2 G_z for 2, 5, or 15 s. Blood pressure (BP) was monitored using the Finapres at the level of the clavicle. Visual light loss was assessed at +2.25 G_z using a light bar. ***Results:*** Mean BP was significantly reduced when the +2.25 G_z exposures were preceded by −2 G_z. Following 15 s of −2 G_z, mean BP decreased more and was slower to recover than for 2 and 5 s of −2 G_z. Reported incidents of visual light loss were: 1 following 2 s, 2 following 5 s, and 4 following 15 s at −2 G_z. There were no reports of visual light loss during control runs. ***Conclusion:*** During relaxed conditions, the push-pull effect is augmented by increasing duration of the preceding $-G_z$.

OUR EARLIER study showed that $+G_z$ tolerance is reduced more than expected for 10–12 s when the preceding G_z exposure is zero or negative (1). The findings confirmed earlier speculation (2,5,7,10) and were consistent with the results of other workers (6,12). This reduction in $+G_z$ tolerance was termed the "push-pull effect."

Lehr and colleagues presented data suggesting that reduced $+G_z$ tolerance following $-G_z$ occurs after as little as 2 s exposure, and is more reduced as the period of $-G_z$ exposure increases (6). The purpose of this study was to test the hypothesis that tolerance to $+G_z$, as indicated by change in blood pressure (BP) and incidence of visual light loss, is reduced more as the time duration of preceding $-G_z$ increases.

METHODS

Subjects

Three male and three female U.S. Navy volunteers between 23 and 35 years of age were briefed on the aims, risks, procedures, privacy rights, and benefits of this research. All gave their informed consent to the experiment, which was carried out in accordance with the rules of the Declaration of Helsinki. All subjects were certified medically fit for exposure to the proposed acceleration profiles. Pregnancy tests on the women were negative. Subjects avoided strenuous exercise and the use of coffee, alcohol, or tobacco on the day of the experiment. All subjects were familiar with the apparatus, procedures, and range of G_z under investigation as a result of previous participation in familiarization sessions and other studies, during which they experienced all $\pm G_z$ exposures included in the experimental protocol. None of the subjects experienced motion sickness during this study.

Apparatus

The Naval Aerospace Medical Research Laboratory (NAMRL) Coriolis Acceleration Platform (CAP), used in this experiment, has been described previously (1,4). Applications of $-G_z$ and $+G_z$ were made possible by the unique capability of the CAP device to combine angular and linear motion. The subject carrier was a 1.2-m long cubical capsule mounted to the movable platform. As detailed in an earlier report (1), alterations in subjects' environmental $\pm G_z$ accelerations were achieved by placing each subject in a supine seated position, then moving the capsule linearly along the track, during CAP rotation. When moved through the center of rotation, the direction of centripetal acceleration reversed. Thus, subjects were exposed to $+G_z$ when rotated with "feet-out," and $-G_z$ when rotated "head-out." The magnitude of $\pm G_z$ depended on distance of the capsule from the center of rotation.

Commands to initiate changes in capsule position were issued by a programmable arbitrary function generator (Wavetec, Model 275, San Diego, CA), which assured that each subject received identical $\pm G_z$ acceleration inputs, in accordance with the experimental design.

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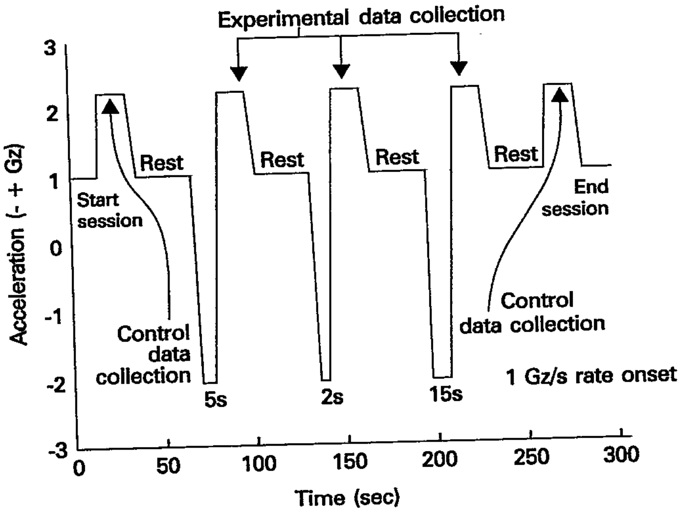

Fig. 1. Typical G_z exposure profile for one session showing 2 control and 3 experimental segments, each separated by a 30-s rest period at +1 G_z. BP data were collected at 15-s periods of exposure to +2.25 G_z for each condition, as indicated.

In addition to a two-way intercom and video monitor, an enable switch controlled by the subject facilitated rapid identification of distress or loss of consciousness. Peripheral vision loss was assessed using a light bar system having a central flashing red light and four flashing green lights positioned at visual angles of ±25° and ±35° to the left and right of midline, at subject eye level.

Procedures

During a single session, each relaxed subject was exposed to a series of five G_z transitions (called segments) ranging from −2 to +2.25 G_z. The segments were classified either as control or experimental and were separated by 30-s rest periods at +1 G_z. Two identical control segments, conducted at the beginning and end of each session, bracketed three experimental segments. The control segments exposed the relaxed subject to +1 G_z for at least 30 s, followed by +2.25 G_z for 15 s, and then a return to +1 G_z. The three experimental segments exposed the relaxed subject to −2 G_z for each of 2, 5, and 15 s, followed by +2.25 G_z for 15 s, and then return to +1 G_z. The rate of change of G_z for all segments was 1 $G \cdot s^{-1}$. The **Fig. 1** plot, starting 15 s before the first control segment, illustrates a typical G_z exposure profile.

The possibility of autonomic adaptation to G_z (3) led to data acquisition using all six possible order combinations of experimental segments. Each subject was assigned to a different combination to achieve group balance.

Physical measurements consisted of track position, G_y and G_z accelerometer data, continuous electrocardiogram (ECG) data, and continuous digital artery blood pressure (BP) wave forms recorded via a noninvasive monitor (Finapres Model 2350, Ohmeda, Austell, GA). This monitor was used successfully in a previous experiment (1). It has been demonstrated to be an accurate method of estimating means and variability of radial BP (11), and has been shown to be a valid tool in acceleration research (9). The monitoring cuff was placed on a left-hand finger of the subject, and secured over the right clavicle with a modified Velcro® glove. Hence, BP was recorded at the level of the clavicle (upper thorax). Accelerometer, track position, electrocardiogram (ECG), BP wave form, and enable switch data were transmitted through patch panels and slip-rings to the control room where they were simultaneously displayed on strip charts and stored on a Macintosh IIFX computer.

Visual light loss from retinal ischemia that results from decreased cranial BP is commonly used as a $+G_z$ tolerance endpoint in acceleration research (8). During each of the five exposures to +2.25 G_z in each session, subjects were instructed to view the center red light of the light bar, and verbally describe changes in the red or green lights as they occurred. All verbal communications were recorded. Subjects were interviewed immediately after each session to clarify and expand on the verbal reports. Written records were kept of these interviews.

Analysis

Objective data: By extrapolation between peaks on the BP analog recording, systolic blood pressures (BP_s) were derived for each second of the 15-s period in which subjects were exposed to +2.25 G_z. Mean and variance values for all subjects were appropriately grouped in "control" or "experimental" data sets. The control data set included 15 BP_s values for each of the two periods at +2.25 G_z immediately following exposure to +1 G_z. The three experimental data sets each included 15 BP_s values for the periods at +2.25 G_z acceleration immediately following exposure to −2 G_z for 2, 5, or 15 s. Data sets were labeled as +1 G_z (control), or 2-, 5-, or 15-s (experimental) data sets. Similar data sets were derived for diastolic blood pressures (BP_d) and pulse pressures (PP).

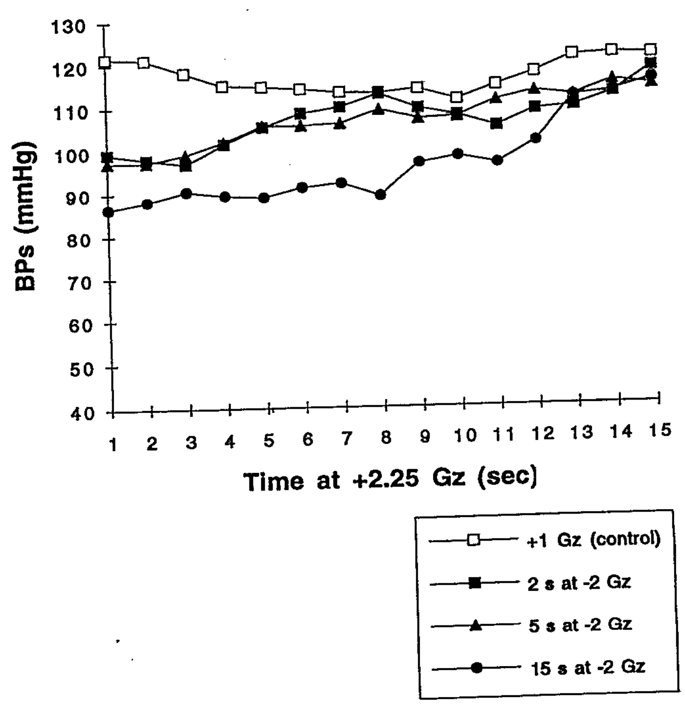

Fig. 2. Mean values of systolic blood pressure (BP_s) vs time at +2.25 G_z exposure for +1 G_z control (0 s at −2 G_z), and 2, 5, and 15 s at −2 G_z.

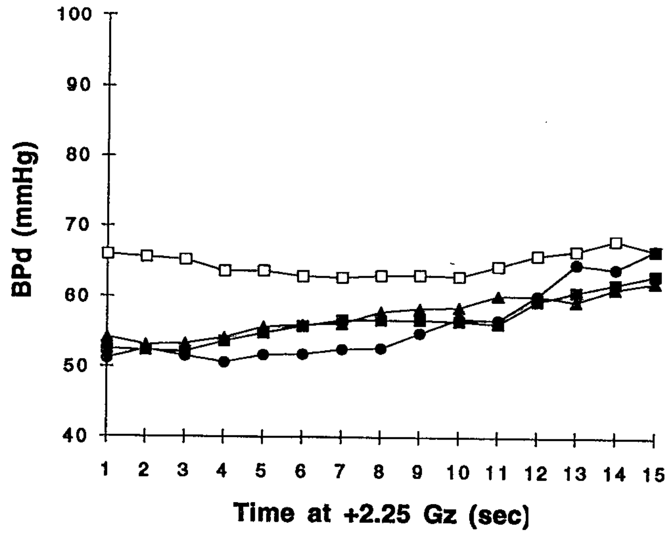

Fig. 3. Mean values of diastolic blood pressure (BP_d) vs time at $+2.25\ G_z$ exposure for $+1\ G_z$ control (0 s at $-2\ G_z$), and 2, 5, and 15 s at $-2\ G_z$. (Legend as in Fig. 2.)

Each control and experimental data set was divided into 15 elements corresponding to each of the 15 s at $+2.25\ G_z$. A single tail *t*-test computation compared each experimental data set element with the corresponding control data set element. Analyses were done using Microsoft Excel version 4.0 (Microsoft Corporation, 1992). Significant differences in BP were determined between experimental and control conditions at each of the 15 s of $+2.25\ G_z$. Statistical significance was defined as $p < 0.05$.

Additional analyses were undertaken on BP_s data only. The 15-s period of exposure to $+2.25\ G_z$ was subdivided into three 5-s intervals. Each interval consisted of five elements for each of the control and experimental data sets. Mean and variance values for BP_s were obtained for each of the three intervals. A Microsoft Excel computation was used to compare each experimental data set against control data sets for each interval. The *p* values were determined and tabulated for each comparison.

Subjective data: Subjective data were analyzed by reviewing audio recordings and debriefing records. Subjects who described visual loss of any of the lateral green lights during $+2.25\ G_z$ or loss of the central red light were categorized as having experienced light loss on that segment. Subjects who described either color loss or no loss of light were categorized as having experienced *no* light loss.

RESULTS

Objective Data

Fig. 2 shows mean BP_s obtained at each second of $+2.25\ G_z$ exposure for the $+1\ G_z$ (control) and 2-, 5-, and 15-s (experimental) data sets. Minimum recorded BP_s was lowest for the 15-s data sets, and remained lowest throughout 13 of 15 s of exposure to $+2.25\ G_z$. Plots of the 2- and 5-s data sets are very similar to each other in appearance, and indicate lower BP_s values than the $+1\ G_z$ plot. The 2- and 5-s data are significantly different from the corresponding $+1\ G_z$ data at each of the first 2-s exposure to $+2.25\ G_z$. After 2 s, differences are not significant. The 15-s data are significantly different from the corresponding $+1\ G_z$ data for each of the first 5-s exposure to $+2.25\ G_z$, before significance is lost.

Fig. 3 shows mean diastolic blood pressures (BP_d) obtained at each second of $+2.25\ G_z$ exposure for the $+1\ G_z$ and 2-, 5-, and 15-s data sets. BP_d values for all experimental data sets were very similar at 1 s of exposure to $+2.25\ G_z$. Although all experimental data plots indicate that BP_d values were below $+1\ G_z$ values, differences are only significant ($p < 0.05$) for the first 3 s of the 2-s data set. The 5- and 15-s data sets did not demonstrate significant differences due to increased variance associated with the increased time at $-G_z$. For example, at 1 s, variance was 147 for the 2-s data set, 258 for the 5-s data set, and 408 for the 15-s data set. This trend continued throughout each second of $+2.25\ G_z$ exposure.

Fig. 4 shows mean PP obtained at each second of $+2.25\ G_z$ exposure for the $+1\ G_z$ and 2-, 5-, and 15-s data sets. All experimental data plots indicate values initially below the $+1\ G_z$ data plot, but the differences were not significant ($p > 0.05$) for the 2 s data, and significant at only the first 1 s exposure for the 5 s data. However, differences were significant during each of the first 5 s of the 15-s data set.

Table I describes results of the further analysis undertaken on BP_s data only, comparing $+1\ G_z$ (control) and 2-, 5-, and 15-s (experimental) data sets at 5-s intervals. Results of statistical comparison between all pairs at these intervals are summarized in the table. During the first 5-s interval, mean BP_s for the 2-s data set was significantly lower than BP_s for the 15-s data set ($p = 0.0392$) and $+1\ G_z$ data set ($p = 0.0009$). BP_s for the 5-s data set was significantly lower than BP_s for the 15-s data set ($p = 0.0452$) and $+1\ G_z$ data set ($p = 0.0018$). BP_s for the 15-s data set was significantly lower than BP_s for the $+1\ G_z$ data set ($p = 0.0000$). During the second 5-s interval, BP_s remained significantly lower for the 2-s data set compared to 15-s data set ($p = 0.0039$). During the last 5-s interval, BP_s remained significantly reduced for the 15-s data set compared to the $+1\ G_z$ data set ($p = 0.0482$).

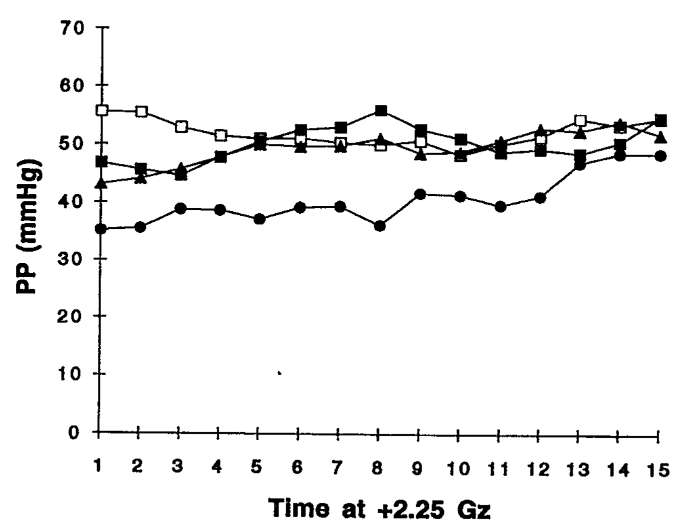

Fig. 4. Mean values of pulse pressure (PP) vs time at $+2.25\ G_z$ exposure for $+1\ G_z$ control (0 s at $-2\ G_z$), and 2, 5, and 15 s at $-2\ G_z$. (Legend as in Fig. 2.)

TABLE I. THE p VALUES OF BPs COMPARISONS DURING 15 s EXPOSURE TO +2.25 G_z WHEN SUBDIVIDED INTO 5-s INTERVALS, FOR ALL CONDITIONS OF PRECEDING ± G_z EXPOSURE. +1 G_z (CONTROL) IMPLIES 0 s AT −2 G_z.

Conditions Compared	0–5 s	6–10 s	11–15 s
2 s vs +1 G_z	0.0009*	0.2900	0.0574
2 s vs 5 s	0.4940	0.3754	0.3758
2 s vs 15 s	0.0392*	0.0267*	0.3307
5 s vs +1 G_z	0.0018*	0.1877	0.1925
5 s vs 15 s	0.0452*	0.0576	0.6479
15 s vs +1 G_z	0.0000*	0.0039*	0.0482*

* Significant difference ($p < 0.05$)

Subjective Data

Table II presents subjects' reports of visual light loss, by category, during the 15-s exposures to +2.25 G_z under control and experimental conditions. As indicated, no light loss was reported during the 12 control segments. Following the 2-s experimental condition, one of six subjects reported light loss. Following the 5-s experimental condition, 2 of 6 subjects reported light loss. Following the 15-s experimental condition, four of six subjects reported light loss.

DISCUSSION AND CONCLUSIONS

The results show that the decrease in physiological tolerance to $+G_z$ that follows $-G_z$ is affected by the time duration of preceding $-G_z$ exposure. Physiological tolerance was estimated using BP data presented in Fig. 2–4, as well as subject reports of light loss in Table II. Inspection of the figures indicates that BP reduction at +2.25 G_z was greater as time at $-G_z$ increased. The positive association of BP response in the figures with subject reports of light loss in Table II, supports a conclusion that physiological tolerance to +2.25 G_z decreased as time at $-G_z$ increased. This conclusion is supported statistically, particularly when BP_s is compared over three 5-s intervals of +2.25 G_z. As indicated at Table I, mean BP_s over the first 5 s of +2.25 G_z exposure was lower for 15-s experimental data than either the +1 G_z (control) and/or other experimental conditions. The significant difference between 15-s data and 2-s data persisted into the second 5-s interval. The 15-s data remained significantly different from +1 G_z data into the final 5-s interval, well after the 2- and 5-s data had lost comparative significance. Inspection of Fig. 2–4, and statistical analyses presented in Table I support the finding that +2.25 G_z physiological tolerance was reduced more as time exposure to −2 G_z increased.

TABLE II. SUBJECTS' REPORTED INCIDENTS OF VISUAL LIGHT LOSS DURING 15-s EXPOSURE TO +2.25 G_z, FOR ALL CONDITIONS OF PRECEDING ± G_z EXPOSURE. +1 G_z (CONTROL) IMPLIES 0 s AT −2 G_z.

	+1 G_z (control)	2 s −2 G_z	5 s −2 G_z	15 s −2 G_z	Total
Light loss	0	1	2	4	7
No light loss	12	5	4	2	23
Total	12	6	6	6	30

Several confounding factors were associated with this experimental method. These factors are associated with the short arm of the CAP, the transient $\pm G_y$ that occurs during linear movement across the rotating CAP, and the +1 G_x relative to the positioned subject that is associated with Earth's gravity. These factors were previously discussed in detail (1), and overall were considered to ameliorate the push-pull effect. As the discussion is equally applicable to the results of this study, these confounding factors are not considered an important influence on results or conclusions herein.

Based on the observed decreases in BP associated with experimental and control condition comparisons, the consistency of the objective and subjective results, and the generally ameliorating influences of possible confounding factors, we conclude that the hypothesis is supported. Tolerance to $+G_z$, as indicated by change in BP and incidence of visual light loss, is reduced more as the time duration to preceding $-G_z$ increases.

The results confirm earlier findings (1,6,12) that $+G_z$ tolerance is diminished by preceding $-G_z$ (push-pull effect). The results also confirm the conclusions of Lehr et al. that decreased $+G_z$ tolerance is reduced by as little as 2 s exposure to $-G_z$.

A common technical flight limitation for military jet aircraft is −3 G_z for 15 s. In this experiment, the three $-G_z$ time durations chosen for study were selected to explore the physiological response within the full range of this flight limitation. The experiment was designed to supplement previous data that included results from 10 s of −2 G_z exposure, and to further explore the effects of very brief −2 G_z exposures (2 s). **Fig. 5** is a reiteration of Fig. 2, with the vertical scale expanded and the addition of two data plots obtained earlier (1). The two additional plots are indicated by dashed lines and show earlier +1 G_z control data and the data from 10 s of −2 G_z. Inspection of Fig. 5 indicates a similarity in the two plots of control data (+1 G_z data sets), indicative of good repeatability. The position of the 10-s data plot, between the 5- and 15-s data plots (for the first 10 s) is consistent with the notion that the push-pull effect is a repeatable, graded response to $-G_z$ that is positively associated with increased time at $-G_z$. Although mean ages and resting blood pressures in subjects were similar between the studies, this figure is presented with the caution that the studies were not identical in design. The first study ($n = 12$) was gender-balanced for run order, while the present study ($n = 6$) was not. As the implications of these differences are uncertain at this time, further analysis was not done.

Although the operational relevance of the push-pull effect remains unknown, the probability of a significant decrease in $+G_z$ tolerance after only 2 s of $-G_z$ exposure should raise suspicions of an unappreciated flight hazard. Future research should examine the influence of $-G_z$ duration less than 2 s, to elucidate the effect of environmental influences, such as turbulence, on $+G_z$ tolerance. Tolerance to high levels of $+G_z$ with rapid onset rates should be understood following $-G_z$ exposure. Continued educational efforts should alert flight crews to the possibility of a hazard. The implications of the push-pull effect with short-duration $-G_z$ exposure should also be

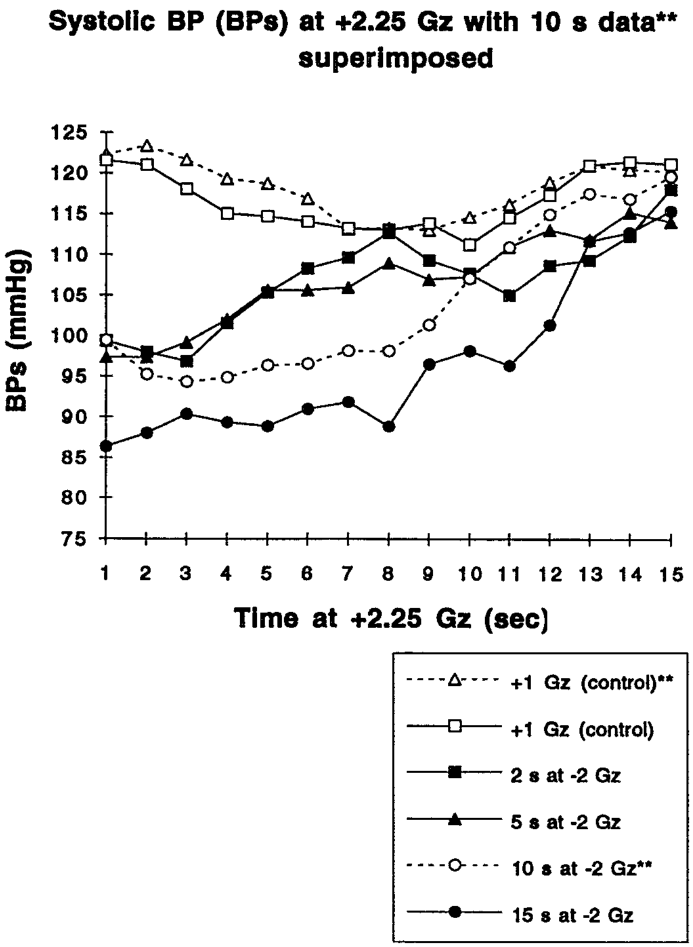

Fig. 5. Reiteration of Fig. 2 with BP_s scale exaggerated and +1 Gz (control)** and 10 s at $-2\ G_z$** plots added. **denotes that these data were taken from a previous report (1).

considered by designers, particularly those involved in protective systems.

SUMMARY AND RECOMMENDATION

When exposed to $+2.25\ G_z$, BP is significantly reduced if the exposure is immediately preceded by $-2\ G_z$. This reduction in BP occurs with as little as 2 s exposure to $-2\ G_z$, and becomes more reduced as the time at $-2\ G_z$ increases. These findings and others (1), together with simultaneous and consistent reports of light loss, support the conclusion that $+G_z$ tolerance is reduced by preexposure to $-G_z$, where the degree of $+G_z$ tolerance reduction depends on the magnitude and time of the preceding $-G_z$ exposure. Additional research is recommended to assess the operational implications of these findings.

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