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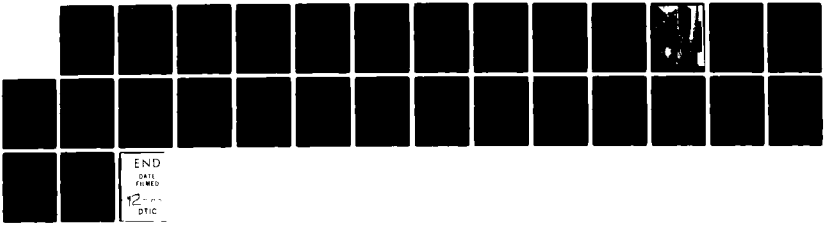

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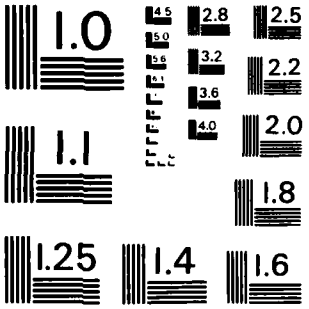

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BLOOD FLOW MEASUREMENTS UNDER HIGH-G CONDITIONS: EARLY PREDICTION OF Gz TOLERANCE

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A method is presented for the prediction of man's $+G_z$ tolerance in human centrifuge experiments without exposing the subject to excessive levels of positive gravity. The parameter that is measured is blood velocity in the temporal artery using an ultrasonic doppler velocimeter. Rather than using the cessation of forward blood velocity as an end point in $+G_z$ tolerance studies, it is possible to use physiologic compensatory responses to decreased cerebral blood pressure as predictors of ultimate cessation of blood flow to the head. Five subjects were exposed to five different $+G_z$ onset ramps and the results

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ABSTRACT

A method is presented for the prediction of man's +Gz tolerance in human centrifuge experiments without exposing the subject to excessive levels of positive gravity. The parameter that is measured is blood velocity in the temporal artery using an ultrasonic doppler velocimeter. Rather than using the cessation of forward blood velocity as an end point in +Gz tolerance studies, it is possible to use physiologic compensatory responses to decreased cerebral blood pressure as predictors of ultimate cessation of blood flow to the head. Five subjects were exposed to five different +Gz onset ramps and the results are discussed in this report.

(1) Blood Flow; (2) Doppler; (3) Acceleration

INTRODUCTION

Modern high performance aircraft, from jets to space vehicles, are capable of generating and sustaining acceleration forces at rates, magnitudes and durations that exceed the tolerance limits of their human operators. The primary effect of +Gz (head-to-foot) acceleration forces is such that the downward loading of the blood in the heart-brain hemodynamic column decreases the ability of the heart to pump blood to the level of the brain. The net result of increasing +Gz or sustaining high-G maneuvers is that blood is pooled in the lower extremities and abdomen while the head is relatively deprived of blood flow. Therefore, during increasing +Gz, the reduction of blood pressure at head level is manifest as a diminution of visual function progressing through loss of visual acuity, loss of peripheral vision, loss of central vision, complete "black-out", and finally loss of consciousness (11).

Taking a more quantitative look at the hydrostatic pressures in a pilot's vascular system when he is seated upright at +1 Gz will help to explain the effects of increased +Gz. At +1 Gz assume arterial pressure of 120 mmHg at the level of the heart, 96 mmHg at head level, and 170 mmHg at the feet of the seated pilot. This indicates a pressure drop of 24 mmHg at the head relative to the heart level. As +Gz is increased, and if we assume the heart level pressure to remain at 120 mmHg, then the pressure at head level will decrease at a rate of 24 mmHg/Gz. Therefore, theoretically, the pilot should be able to withstand up to 120/24, or +5 Gz, before the arterial pressure at the level of the head becomes

zero and blood flow to the head ceases (5).

Continuing with the same model, let us consider the cause of visual symptoms as a function of +Gz. Intraocular pressures are of the order of 20 mmHg. Thus, blood flow to the retina should cease at a +Gz level of approximately (120 - 20) mmHg/24 mmHg = 4.2 Gz which is about 1 Gz less than that at which the brain itself is deprived of blood flow. Therefore, visual symptoms provide a reasonably safe predictor for impending loss of consciousness under +Gz conditions.

The preceding discussion represents only a static approximation of human cardiovascular functioning in acceleration environments. Actual human +Gz tolerance limits are higher than indicated above since we failed to take into consideration any physiologic compensatory responses to the applied stress. That is, as blood pressure in the upper part of the body decreases the carotid baroreceptors respond and cause peripheral vasoconstriction to counter the fall in pressure.

Various methods are used to enhance G-tolerance (7). One, is to supinate or pronate the pilot so that G forces are applied along the chest to spine (Gx) axis rather than from head to foot. In this position, the heart and brain experience about the same hydrostatic pressure and G-tolerance is improved by about 2 - 3 G (3)(8)(10). Another enhancement technique is to prevent pooling of blood in the lower extremities and abdomen when the pilot is seated upright. This is accomplished by the use of an anti-G suit (AGS) consisting of a series of five inflatable bladders snuggly secured around the calves, thighs and abdomen which

inflate with increasing +Gz and apply external pressure to these areas. This provides support to the circulation by preventing venous pooling in the lower extremities, by increasing venous return, and by elevating the diaphram to lift the heart closer to the brain. Thus, the AGS can provide up to 2 G additional protection by increasing the volume of blood available for circulation (4)(8)(24). A third technique is the use of respiratory straining maneuvers (such as the M-1 maneuver) during which the pilot crouches in his seat, tenses his extremities, and forcibly exhales against a partially closed glottis. This maneuver decreases the heart to brain column distance, prevents pooling of blood in the extremities, and raises intrathoracic pressure providing another 1 - 2 G of increased tolerance (3)(18)(22).

Irrespective of the particular method or combination of techniques used to improve G-tolerance, it is important to be able to evaluate the relative degrees of protection afforded by the various methods (6). Such evaluations are carried out on man-rated human centrifuge facilities, such as the Naval Air Development Center's Dynamic Flight Simulator (DFS), shown in Figure 1. A number of invasive and non-invasive techniques have been used to measure blood flow to the head as an objective measure of G-tolerance. These include: cannulation of the radial artery to directly measure arterial pressure while the arm is supported at head level (13); various oximetric and plethysmographic techniques to measure blood content changes in the ear lobe and lower limbs as measures of decreased supply to the head

Figure 1: U.S. Naval Air Development Center's Dynamic Flight Simulator human centrifuge

and pooling in the lower extremities respectively (1)(2)(16)(23); ultrasonic doppler velocity measurements from the temporal artery to measure the movement of blood to the head (12)(17); and direct observation of retinal arteries to determine cessation of blood flow to the eye (9)(14).

In addition, several indirect techniques for measuring changes in G-tolerance are currently in use. These techniques use the diminution of visual function as measures of reduction or cessation of blood flow to the head under +Gz. The two methods in use today are subjective measures requiring the subject to track his peripheral vision limits while experiencing +Gz. A sweep is provided which the subject operates to respond to fixed flashing lights in the periphery of his visual field or a hand controller is used to adjust the position of a series of small lamps located on a circular bar centered at eye level (7) (Figure 2).

LOC as an end point is not used in acceleration physiology experiments or +Gz tolerance evaluations. Although temporary LOC in centrifuge experiments does not cause lasting side effects and is not in general considered dangerous to the health of the subject, it has several drawbacks. First, it is psychologically undesireable since subjects tend to loose their desire to continue with the experiment due to possible headaches, disorientation, or convulsions upon recovery. Also, recovery times from LOC to full functional consciousness are variable from episode to episode. Lastly, LOC episodes tend to fatigue the subject altering his +Gz tolerance artificially on subsequent runs (19)(20).

Results obtained by using the two most current methods at

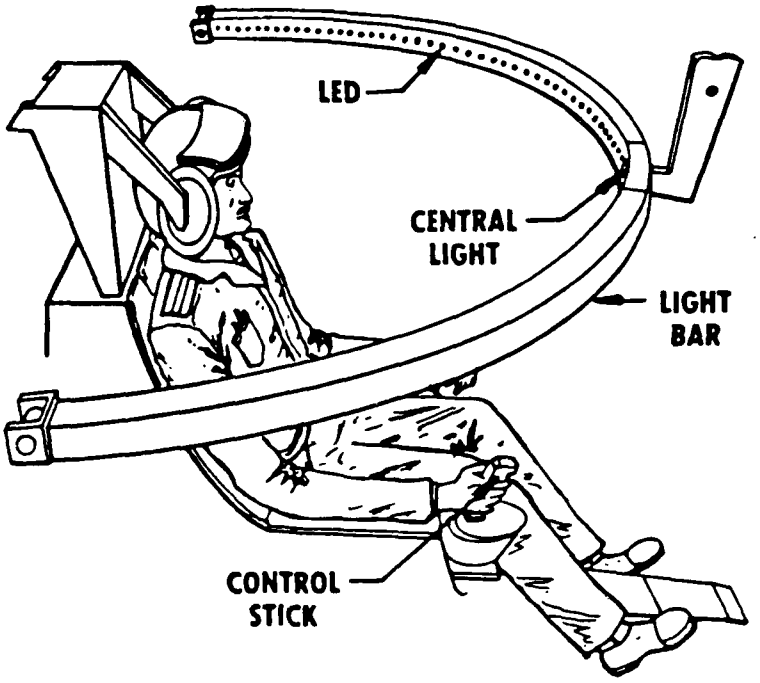

Figure 2 - Peripheral vision tracking light bar. The light bar consists of a series of red light emitting diodes (LED's) positioned every 1.5 degrees on either side of a central white target lamp. To operate the bar, the subject pulls back on the control stick to turn on LED pairs in the periphery of his visual field. As vision closes in during exposure to positive acceleration, the subject reduces pressure on the control stick letting the lights move in with his diminishing visual field. Without active control stick pressure, the lights automatically converge on the central target lamp.

the Naval Air Development Center's DFS Facility are shown in Figure 3. The top trace shows the output of an ultrasonic Doppler flow meter which measures pulsatile blood velocity in the superficial temporal artery, the lower trace shows the subject's performance on the peripheral vision tracking light bar (Figure 2) and the middle trace shows a gradually increasing +Gz acceleration profile. Notice, as the +Gz increases, the temporal artery blood flow velocity pulsations gradually decrease in amplitude and the base line goes through a short interval of apparent net negative blood flow velocity (starting about 6 seconds before loss of central vision), finally decreasing to zero as the end point is reached (12)(17). End point, or tolerance limit, is determined by the performance on the peripheral vision tracking light bar. At our facility, the end point is reached when the subject has manipulated his side arm controller to show that only a central visual arc of 60 degrees is present, at which point the centrifuge run is automatically terminated. This procedure provides a safety margin as compared to the use of "blackout" (100% light loss) as an end point, since the latter brings the subject dangerously close to complete loss of consciousness (LOC).

This method of determining end points for gradually increasing acceleration stress has been found to be very satisfactory and capable of giving reproducible results (21). However for onset rates greater than about 0.5 +Gz/s even the use of the 60 degree peripheral vision arc does not provide enough of a warning to prevent LOC. For faster onset rates of +Gz, the progression of visual loss symptoms is also speeded up, thus,

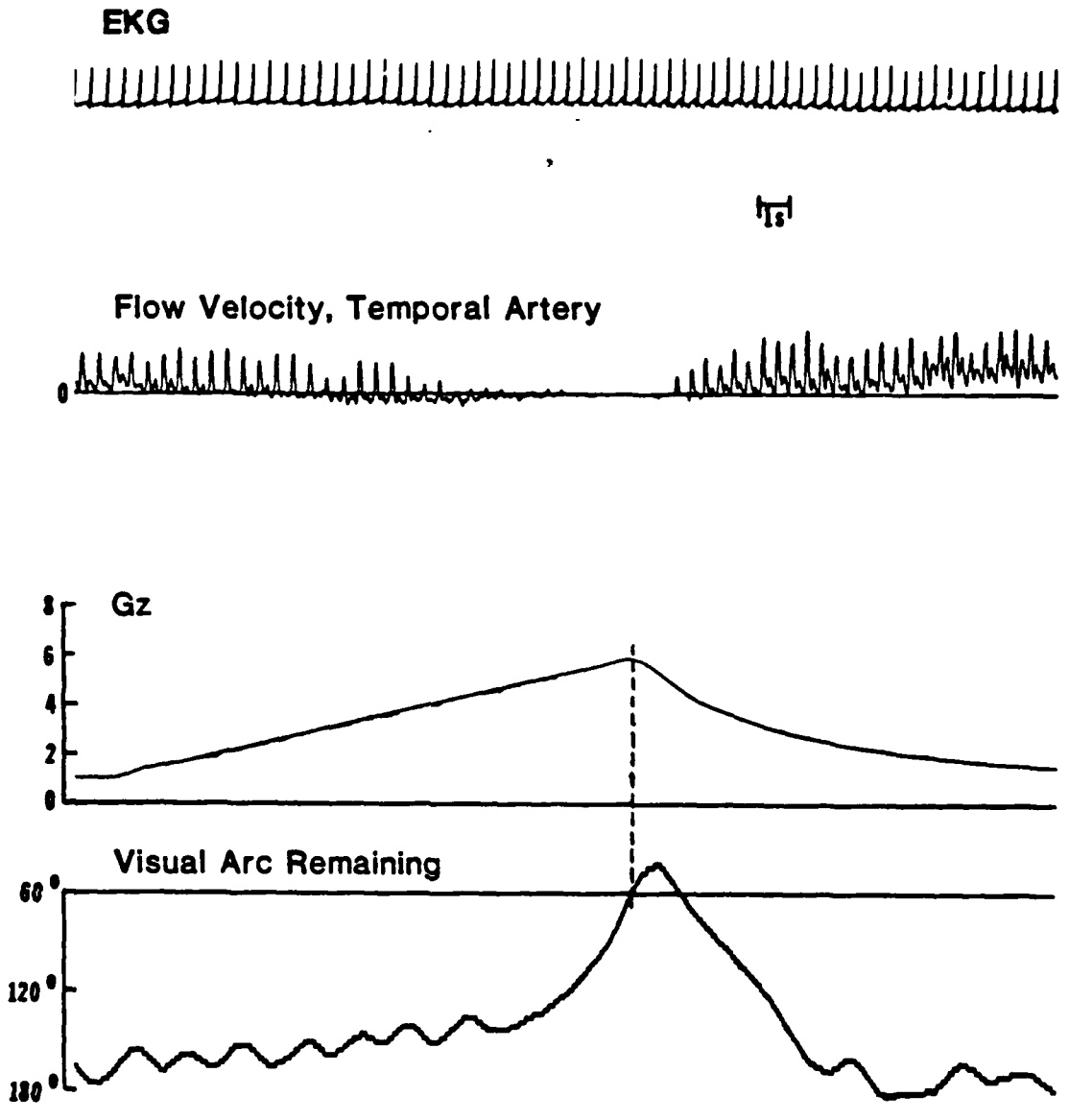

Figure 3 - Diminution of visual field arc and temporal artery blood flow velocity during exposure to $+G_z$. The acceleration tolerance endpoint was reached when only 60 degrees of visual arc remained.

there is little or no warning that LOC is imminent (15). The study presented in this paper was undertaken to explcre the possibility of using the mean doppler velocity signal as an earlier predictor of end point than that obtained with either the light bar or the more objective pulsatile doppler flow signal.

METHODS

Five male volunteer subjects who had passed a standard U. S. Navy flight physical and ranged in age between 20 and 31 years (mean 26 years) were exposed to various linear acceleration profiles. All subjects were experienced centrifuge riders and had extensive training and experience in the use of the Naval Air Development Center's peripheral vision tracking light-bar (Figure 2). Communications between subject and investigator were maintained via an open microphone and low light level video camera mounted inside the centrifuge gondola allowing continuous viewing of subjects throughout the experiments. Physiologic instrumentation included: a directional ultrasonic Doppler flow meter (L M Electronics model 1012) with a miniature 8.2 MHz transducer located over the frontal branch of the superficial temporal artery, two channels of EKG, remotely operated sphygomomanometer for intermittent blood pressure readings, and a heart rate meter. Both pulsatile and mean blood flow velocity were recorded from the Doppler flow meter.

All subjects were exposed to five different acceleration rates under two experimental conditions. In all cases, the subjects were seated upright with a seat back angle of 15 degrees back from the vertical. The two experimental conditions were:

(a) relaxed and unprotected and (b) relaxed but protected by the AGS which was inflated with a servo-controlled anti-G valve. The AGS in this case was inflated at a rate of 1.5 psig/Gz beginning at the onset of the acceleration profile. All acceleration profiles were linearly increasing ramps, starting from a baseline of 1.03 Gz. The five onset rates were 0.1, 0.2, 0.3, 0.4, and 0.5 Gz/s.

End points were determined using the NADC light bar to measure the loss of peripheral vision. Thus, the acceleration ramps were automatically terminated when the subject's cone of vision in the horizontal plane was reduced to 60 degrees, i.e., 30 degrees on each side of the central light of the light bar. Also, as a safety precaution, the medical monitor would terminate the experiment if the Doppler flow meter indicated cessation of blood flow velocity in the temporal artery for 5 seconds. This secondary end point criterion was not required since all subjects properly activated the light bar tracker.

RESULTS

Figure 4 shows a typical record. Here the light bar tracking, pulsatile Doppler flow signal and the +Gz profile are shown along with the mean Doppler flow signal. As expected, once the +Gz is applied, the mean Doppler flow signal starts to decrease, indicating a drop in arterial pressure as a function of +Gz. Part way up the acceleration ramp, however, the mean flow signal stops decreasing, or even slightly increases momentarily, and then continues to fall with increasing +Gz. This plateauing, or dip in the mean Doppler signal, indicates the point at which the physiologic compensatory mechanisms respond to a fall in

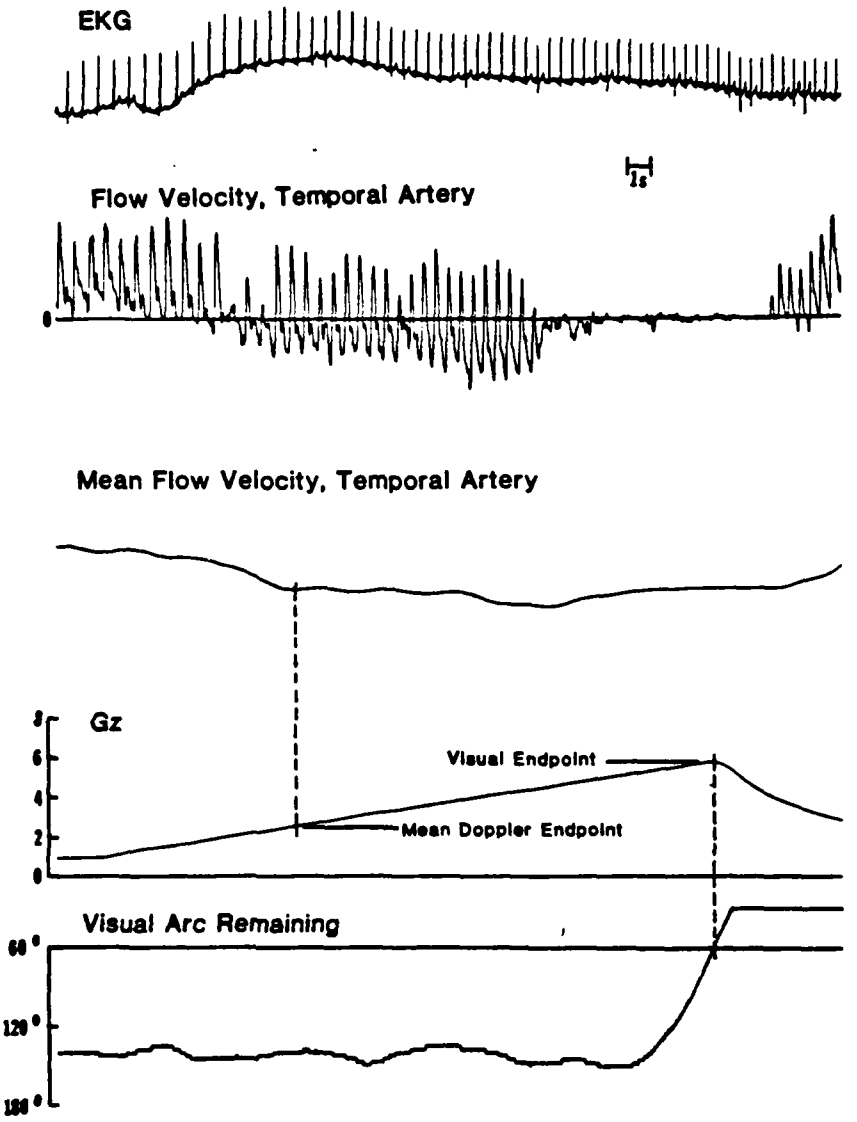

Figure 4 - A typical record showing reduction in visual field and decrease in temporal artery blood flow velocity as a function of positive acceleration. The mean blood flow velocity trace indicates the point at which cardiovascular reflexes responded to a drop in acceleration induced head level blood pressure (Mean Doppler Endpoint).

arterial pressure at the carotid sinus. After the response has occurred, the increasing +Gz causes flow to decrease even further, eliciting visual symptoms and cessation of the pulsatile Doppler signal. The data presented here indicate that the dip or plateau in the mean Doppler flow signal (cardiovascular endpoint) is a reliable predictor of the subject's ultimate +Gz tolerance (peripheral vision endpoint) and provides a further protection from LOC.

Acceleration tolerance end points for all five subjects are presented in Tables I and II. Both visual end points and mean Doppler end points are indicated for relaxed, uprotected subjects in Table I and for the same subjects protected by the AGS in Table II. Mean values for both end point criteria and for the two experimental conditions are summarized in the tables and are also depicted graphically in Figures 5 and 6.

Figure 5 shows the mean values obtained during unprotected tolerance determinations. Linear regression equations for these data are:

$$(+Gz\ Tolerance) = 4.05 + 3.7 \times (Gz\ Onset\ Rate), \quad (1)$$

($r^2 = 0.97$), using visual end point criteria and:

$$(+Gz\ Tolerance) = 3.05 + 3.1 \times (Gz\ Onset\ Rate), \quad (2)$$

($r^2 = 0.93$), using mean Doppler end point criteria. Curves for these regression equations are shown in the figures as dashed

TABLE I: ACCELERATION TOLERANCE END POINTS (Unprotected)

Subjects	Conditions*									
	.1V	.1D	.2V	.2D	.3V	.3D	.4V	.4D	.5V	.5D
S1	4.5	3.1	4.3	4.0	4.5	4.2	5.2	4.0	5.5	5.1
S2	3.6	3.0	4.2	3.6	4.9	3.9	5.0	3.9	6.0	4.4
S3	5.1	3.4	6.2	4.5	6.0	4.6	6.3	4.6	7.1	5.1
S4	4.8	3.7	4.8	3.3	5.3	3.6	5.4	4.3	5.6	5.1
S5	4.2	3.3	5.0	3.5	4.6	3.8	5.2	3.9	5.7	3.9
Mean	4.4	3.3	4.9	3.8	5.1	4.0	5.4	4.1	6.0	4.7
S.D.	.58	.27	.80	.48	.61	.39	.51	.31	.65	.56
Mean Diff.	1.1		1.1		1.0		1.3		1.3	

(* .n = onset rate in G/s.; V = visual end point; D = mean Doppler end point)

TABLE II: ACCELERATION TOLERANCE END POINTS (Protected by AGS)

Subjects	Conditions*									
	.1V	.1D	.2V	.2D	.3V	.3D	.4V	.4D	.5V	.5D
S1	5.1	3.7	5.5	5.0	6.4	5.1	6.8	5.6	7.8	6.0
S2	5.2	3.6	6.4	4.3	6.2	4.8	7.0	4.9	8.0	5.9
S3	5.5	3.5	6.4	4.8	7.6	5.6	8	5.0	8.0	6.5
S4	6.2	4.2	8.0	3.9	7.0	5.3	7.0	5.6	7.6	6.2
S5	4.4	3.4	5.2	3.9	5.5	4.3	6.0	4.6	6.2	5.0
Mean	5.3	3.7	6.3	4.4	6.5	5.0	7.0	5.1	7.5	5.9
S.D.	.65	.31	1.09	.51	.80	.50	.71	.40	.76	.56
Mean Diff.	1.6		1.9		1.5		1.6		1.6	

(* .n = onset rate in G/s.; V = visual end point; D = mean Doppler end point)

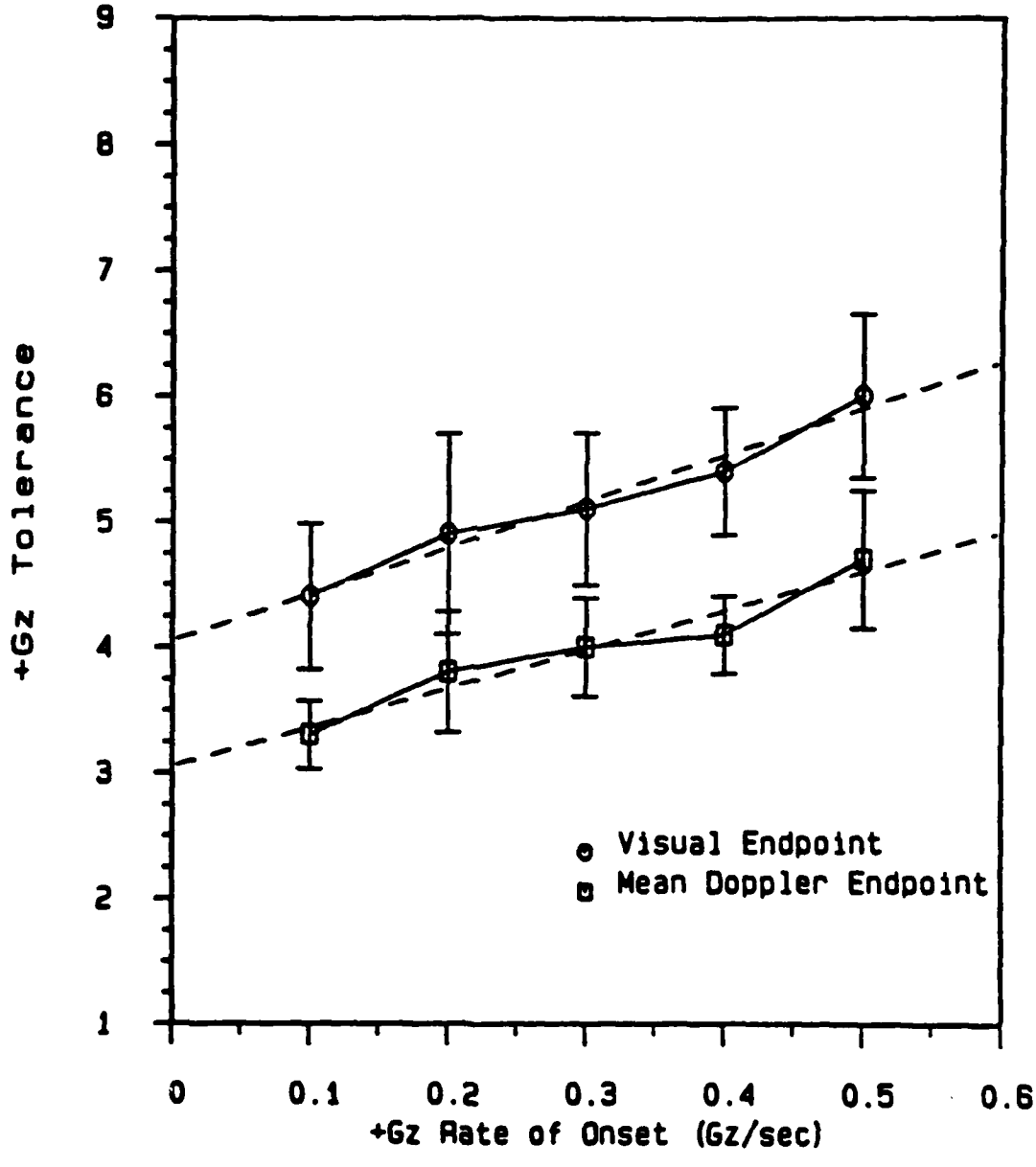

Figure 5 - Acceleration tolerance as a function of +Gz onset rate (unprotected subjects).

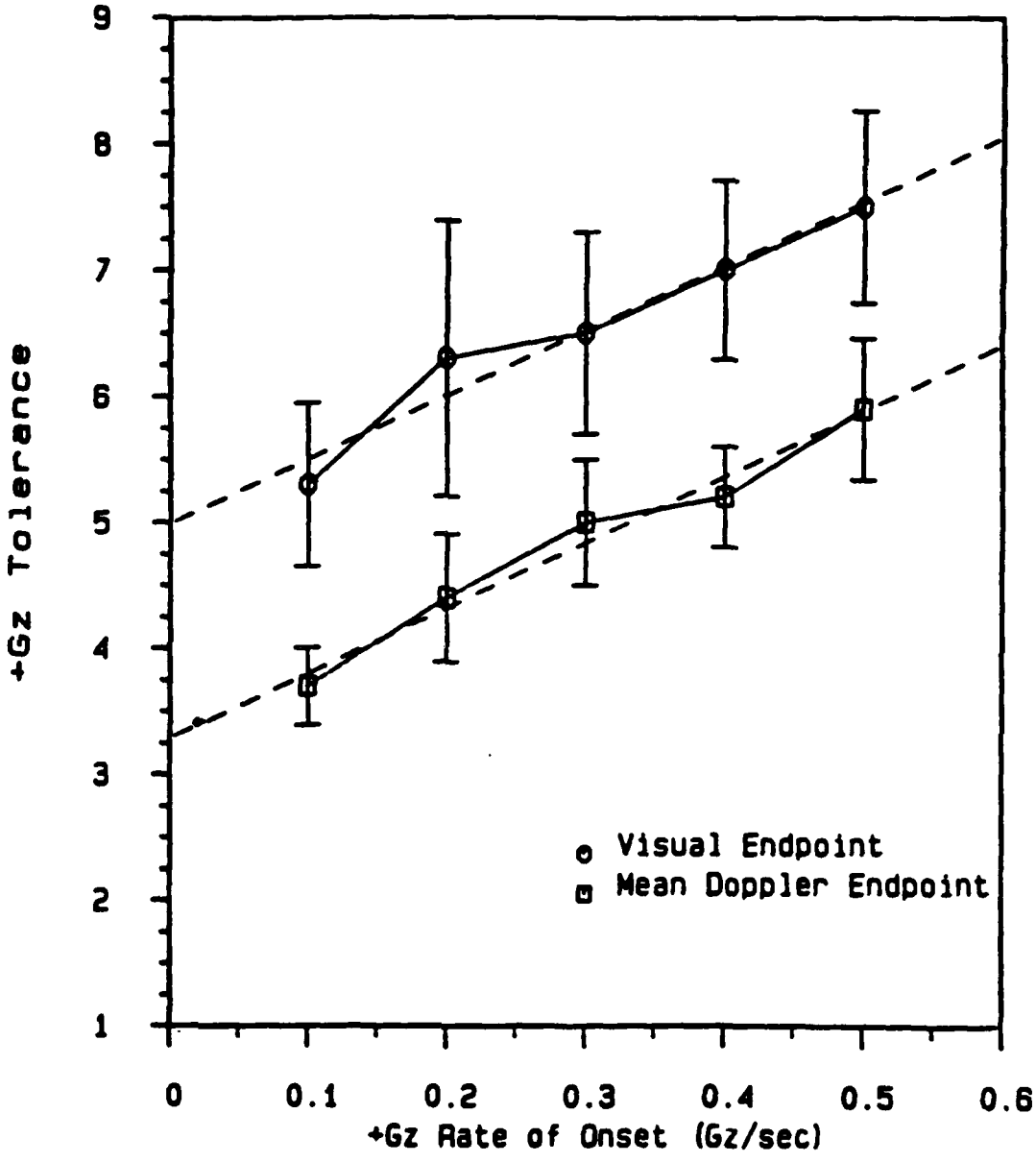

Figure 6 - Acceleration tolerance as a function of $+G_z$ onset rates (subjects protected by Anti-G suit).

lines. No significant difference was found between the slopes of these curves ($t = 0.991$; $DF = 6$; $p > 0.5$). An evaluation of the mean difference between the visual and mean Doppler end point data shows a mean separation of 1.16 $\pm$ 0.134 Gz over the range of +Gz onset rates used in this experiment.

Figure 6 summarizes the mean values obtained during runs in which subjects were protected by an AGS. The linear regression equation for these data (dashed lines), based on the visual end point criterion, is:

$$(+Gz\ Tolerance) = 4.99 + 5.1 \times (+Gz\ Onset\ Rate), \quad (3)$$

($r^2 = 0.95$) and, based on the mean Doppler end point criterion, is:

$$(+Gz\ Tolerance) = 3.28 + 5.2 \times (+Gz\ Onset\ Rate), \quad (4)$$

($r^2 = 0.98$). Again, there is no significant difference between the slopes of these curves ($t = 0.124$; $DF = 6$; $p >> 0.5$). The mean difference between visual and mean Doppler end point data is 1.64 $\pm$ 0.152 Gz over the range of onset rates used in this experiment. Thus, for +Gz onset rates ranging from 0.1 Gz/s to 0.5 Gz/s, the end points determined using cardiovascular reflexes measured from the mean Doppler velocity signal are as reliable predictors of +Gz tolerance as those measured using the peripheral vision tracking light bar.

DISCUSSION

The results of this study indicate that the mean Dopple

velocity signal from the superficial temporal artery can be used as an early predictor of ultimate +Gz tolerance, as measured by a light bar, for gradually increasing levels of +Gz stress. Although the light bar is the current method of choice for determining end points in acceleration research, it has several drawbacks. First, it is an indirect measure of blood flow to the head, requiring test subjects to perform a subjective task to determine their +Gz tolerance. This requires training, practice, and motivation on the part of the subject to give reproducible and useful results. On the other hand, even experienced subjects can give erronous results due to fatigue, disinterest, or maliciousness. Secondly, the use of visual symptoms as end point criteria bring subjects close to LOC, especially for faster rates of +Gz onset since there is less time to respond to the visual warning (15).

Use of the more objective cardiovascular response, as measured by the mean Doppler velocity signal, eliminates these disadvantages. This method allows us to directly measure the response time of the cardiovascular system to the drop in head-level blood pressure due to +Gz exposure. Training and experience are not required, since the measure is of an autonomic physiological resp se mechanism to the applied stress. Finally, and perhaps most important, is the fact that the early prediction of ultimate end point provides a greater protection from LOC than the use of visual symptoms, especially at higher onset rates of +Gz stress.

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