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ANALYSIS OF THE TRANSIENT RESPONSE OF TEMPORAL ARTERY BLOOD FLOW DATA RELATIVE TO VARIOUS ANTI-G SUIT PRESSURE SCHEDULES

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A method is presented for objectively measuring the relative effectiveness of various G protective equipment or techniques by comparing the quantitative response of a subject's mean Doppler flow velocity signal to a series of modest G profiles when using each protective system in turn. The method is applied to evaluate two configurations of the Navy's new servo controlled anti-G valve in comparison with the standard ALAR valve during exposure to G profiles having various rates of G onset.

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SUMMARY

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INTRODUCTION AND BACKGROUND

Recent incidences of G-induced loss of consciousness (LOC) by aircrew flying high performance aircraft have reestablished the operational need for increased G-protection for aircrewmen and have prompted a renewed interest in the development of new and improved G-protective equipment and techniques. Of current concern is the rapidity with which these high performance aircraft can achieve high G-levels. This high rate of G-onset creates a period during which the physiological response of the aircrewman and the protective action of his anti-G suit lag behind the G profile, and during which visual symptoms which normally precede LOC and serve to warn the pilot, do not occur.[1]

In response to this operational need, a number of programs have been initiated or are planned by the U.S. Air Force and the U.S. Navy to investigate enhancements to the design of G protective equipment and techniques for increased effectiveness. Among those being considered are a new anti-G valve and anti-G suit, mixed breathing gases, positive pressure breathing, pilot positioning, body cooling, pilot conditioning, and pilot training programs.

An essential adjunct to the development of any new G protective system, however, is an acceptable method of evaluating it or assessing its individual contribution to enhancing the G tolerance of the aircrewman. Ideally such a method should be objective, non-invasive, repeatable, reliable and easily measureable. This paper presents one such method and applies it to compare the G protection effectiveness of a new servo controlled anti-G valve developed by the Navy[2] with that of a standard ALAR valve using G profiles having various rates of G-onset. The preliminary results of this testing were in fact used to define performance specifications for the Navy's servo valve.

DISCUSSION

The need for a reliable, noninvasive method for indicating cerebral blood supply to reinforce or replace the long used subjective endpoint criteria – peripheral (PLL) and/or central light loss (CLL) – has been voiced by many. Coburn[3] expressed concern for the reliability of subjective endpoint data provided by a poorly motivated subject who has only to cease responding to the visual stimulus even though he is capable of perceiving it. On the other hand, he stated that an overly motivated subject may strain during a run designed to measure relaxed G tolerance limits and in this way give a falsely high tolerance level. Once such method which Coburn recommended as useful in determining an objective visual endpoint was termed LOMA (Limitation of Occular Motility under Acceleration).[4]

Leverett and Zuidema[5] further cautioned that if PLL or CLL is used as an endpoint, then agreement should be reached as to how long loss of vision is to last. In other words, a subject's PLL or CLL must return within a specific time interval during a given G level before that level is accepted as the G-tolerance level. Tolerance level measurements may in fact vary from 0.5 to 1.0G depending on the duration of the endpoint. To meet this criteria, the subject must undergo a large number of centrifuge runs at or near his tolerance limit. This is not only dangerous but compounds the endpoint reliability problem by introducing the unknown factor of subject fatigue into the G-tolerance data.

Perhaps the most popular device currently being used at most acceleration facilities to objectively measure cardiovascular status during human acceleration stress studies, is the transcutaneous Doppler ultrasonic flowmeter. This device, which measures the pulsatile blood flow velocity in the frontal branch of a subject's superficial temporal artery, was tested by Rositano and others[6] on the NASA-AMES and USAFSAM centrifuges. Correlation was made with direct eye level arterial blood pressure measurements[7], as well as with visual decrements reported in the presence of several types of acceleration profiles[8]. These studies revealed that diastolic retrograde eye level blood flow increases with increasing G_Z level, and that this retrograde flow was followed by total cessation of flow for a period 2-20 seconds prior to the subject reporting 100 percent CLL (blackout) as illustrated in Figures 1 and 2. Figure 1 shows a subject, relaxed and wearing an unpressurized anti-G suit, exhibiting PLL during a 4 G, 4 sec. onset-time profile. Figure 2, on the other hand shows the same subject with his suit pressurized by a servo controlled valve, exhibiting PLL during a 5.5 G, 4 sec. onset-time profile. These results paralleled the observations of Duane[9] and Leverett[10] who reported the occurrence of retrograde flow followed by flow cessation in the retinal blood vessels just prior to blackout.

Thus the current application of the Doppler flowmeter in acceleration physiology is to monitor cardiovascular status during human acceleration experiments and to predict an impending subject blackout when flow cessation occurs. These applications primarily involve the analysis of the Doppler's pulsatile electronic signal in a qualitative manner. The area of application to which this paper is addressed, however, primarily involves the quantitative analysis of the mean Doppler flow signal. As a quantitative measure of relative changes in a subject's cardiovascular response to G, the mean Doppler flow data offers the opportunity to detect differences in G protection provided by one system or technique over another. This comparison can be made over a wide range of G profiles, most of which are considerably under the subject's G tolerance. Also, it enables the investigator to compare the effectiveness of each protective system or technique during specific phases of the G profile, e.g. during the G-onset period. This application has obvious implications for those concerned with evaluating systems designed to protect a pilot during high rates of G-onset.

It is to be noted that this comparison technique is not a new one. Variability between subjects with regard to experience, training, or motivation, and differences between testing facilities and testing criteria have produced a situation in which the only reliable method of evaluating the effectiveness of a new protective system is to compare it with a known system. Thus the known protective system becomes a baseline of the unknown system.

APPROACH

The possibility of using the Doppler flow velocity signal as a quantitative measure of relative changes in a subject's cardiovascular response to G had eluded this writer and possibly others for years because the primary interest in the signal had centered on the qualitative characteristics of the raw pulsatile signal, particularly as a predictor of impending blackout when cessation of flow occurs. It wasn't until more attention was focused on the response of the mean Doppler flow signal, $\overline{v}(t)$, during relatively low levels of G that the repeatability and consistency of this G response signal was recognized. $\overline{v}(t)$ is essentially a DC version of the pulsatile signal and lags it by approximately 1-2 seconds. Figures 3 and 4 demonstrate this consistency by showing the mean Doppler flow signal of a relaxed subject to three consecutive identical G-profiles having 8 second onset-times and 3.5 G, 15 second plateaus in each of two separate sessions. In the first session, figure 3, the subject's anti-G suit is unpressurized while in the second session it is pressurized by a servo controlled valve. While a difference in the pulsatile data between the two sessions does exist and is detectable by a trained observer, it is in the mean flow data that the difference is most obvious. Although not immediately apparent, this difference actually translated into a 1.5 G difference in G-tolerance. The subject with his suit unpressurized exhibited PLL at the 4 G level as shown in figure 1, while with his suit pressurized by the servo controlled valve, he did not exhibit PLL until the 5.5 G level, as shown in figure 2. Further observations of this mean Doppler flow response signal at incrementally higher and lower G profiles, substantiated the contention that, within limits, the signal could be assumed to vary linearly with G. [11] [12]

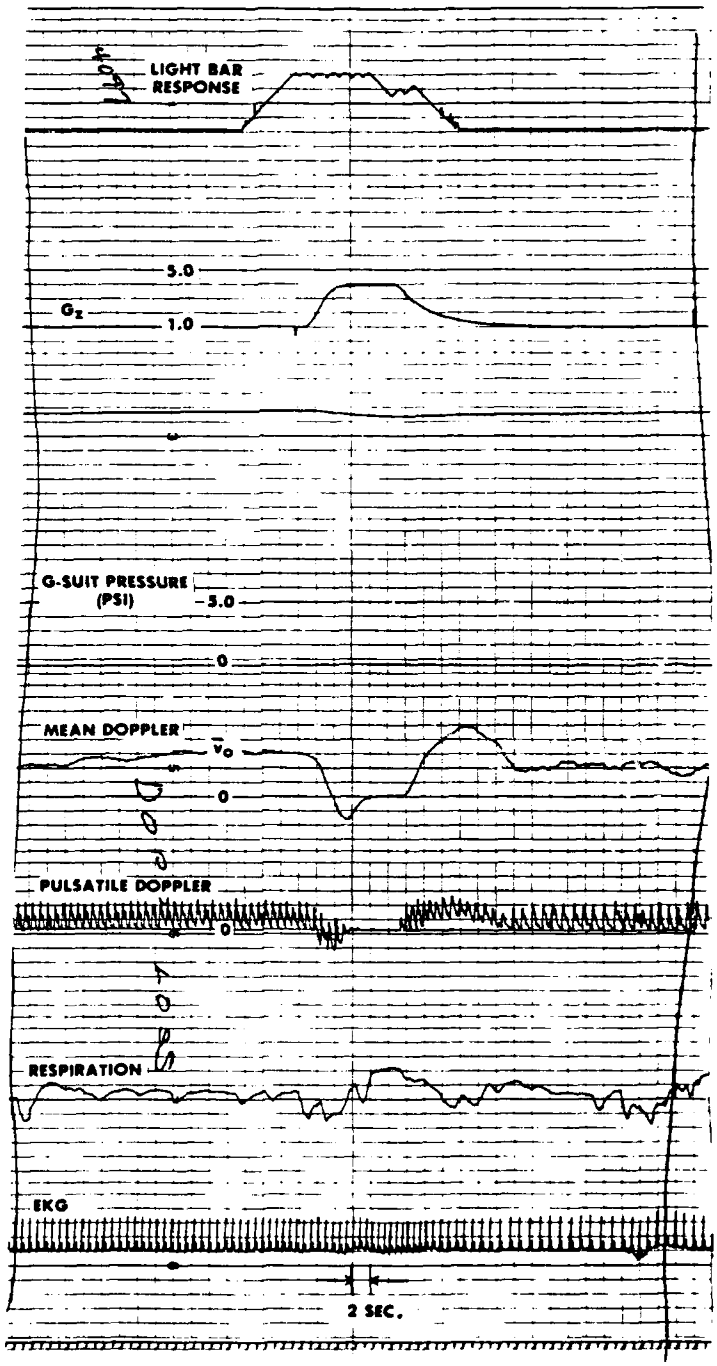

Figure 1. PLL episode experienced by a relaxed subject with his anti-G suit unpressurized during a 4 G, 4 sec. onset-time profile.

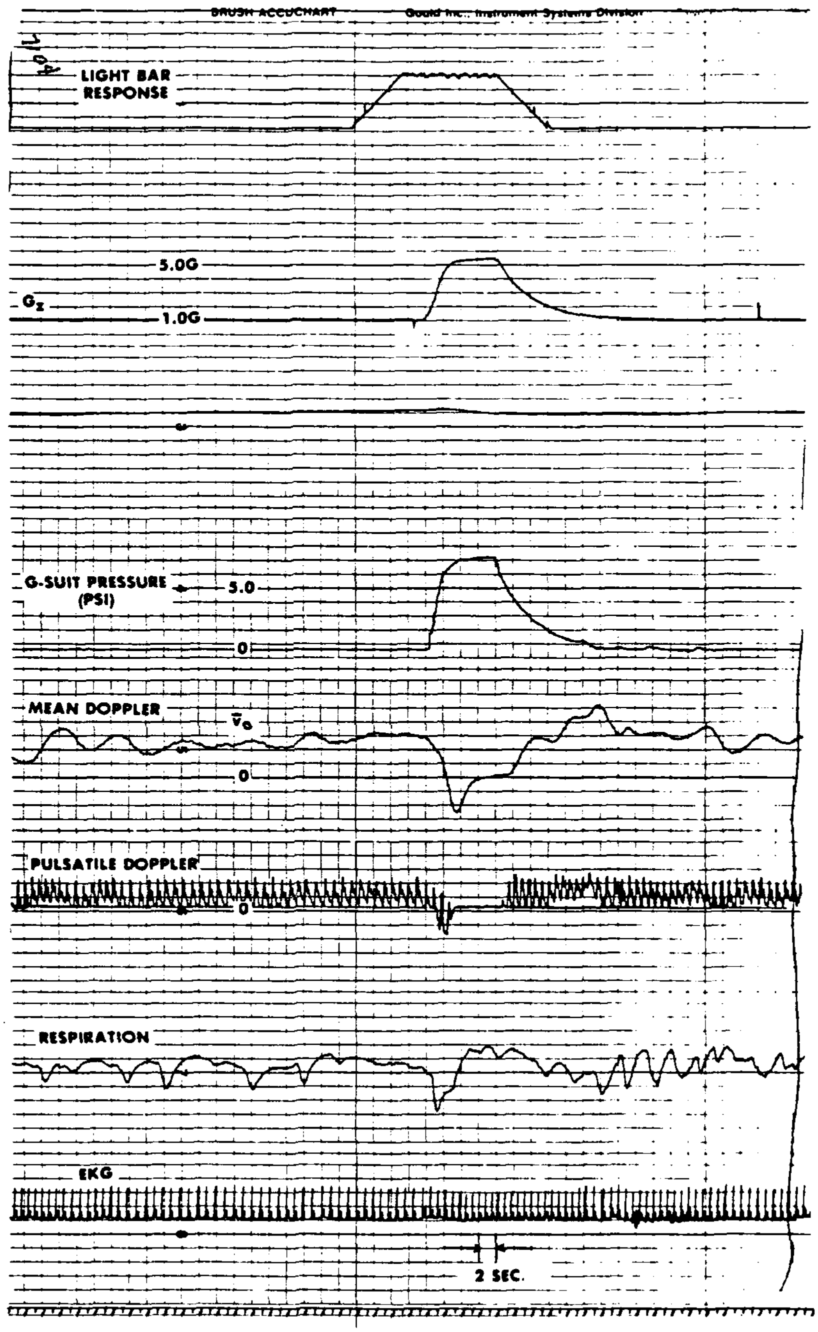

Figure 2. PLL episode experienced by a relaxed subject with his anti-G suit pressurized on a schedule to coincide with the G profile by a new servo-controlled anti-G valve to a level of 5.2 psi during a 5.5 G, 4 sec. onset-time profile.

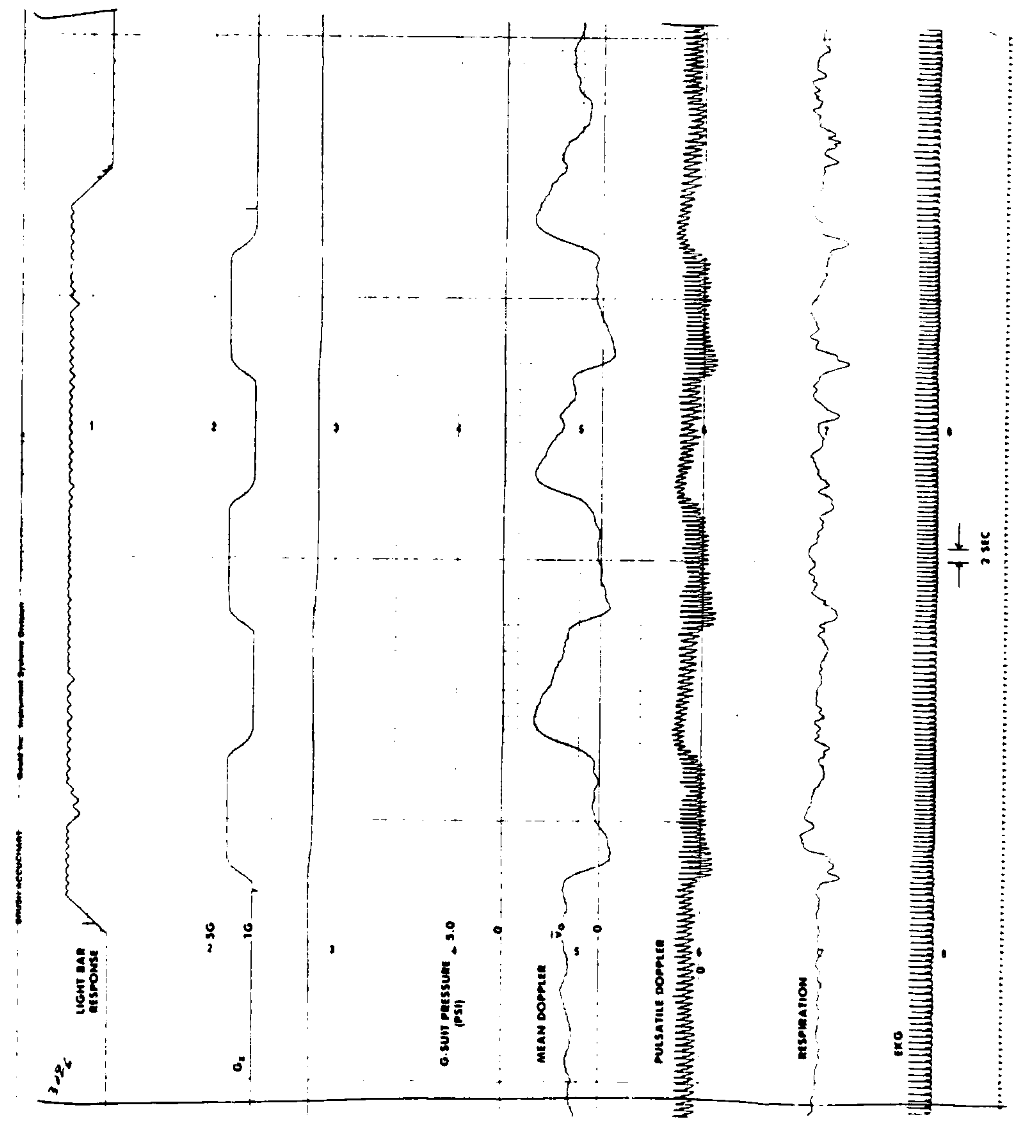

Figure 3. Consistency of the mean Doppler flow velocity signal $\overline{v}(t)$ of a relaxed subject with his anti-G suit unpressurized during three consecutive 3.5 G, 8 sec. onset-time profile.

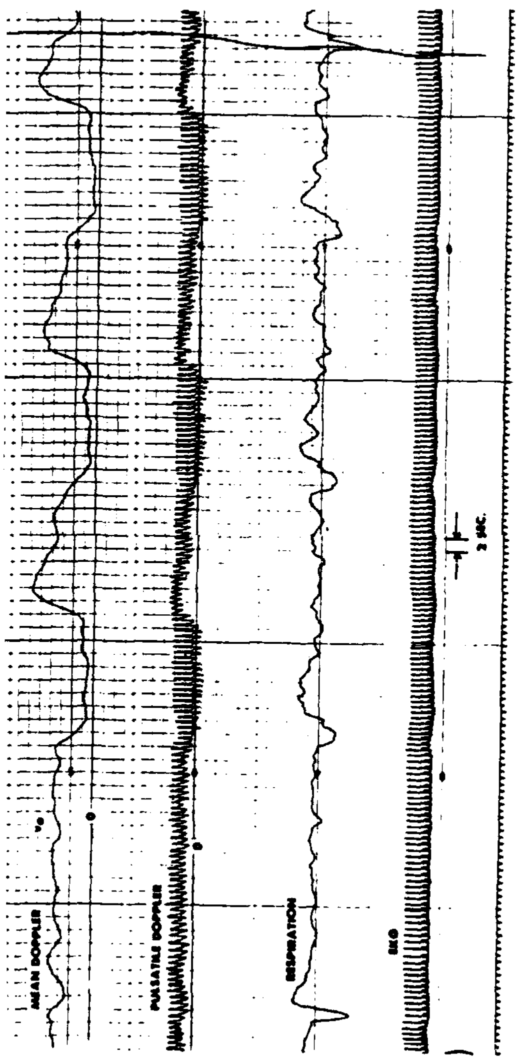

Figure 4. Consistency of a relaxed subject with his anti-G suit pressurized under control of the servo-controlled G valve to a level of 3.8 psi.

Another factor that has deterred m
the variations in the Doppler flow signal
on a subject is that it measures blood vel

The velocity flow signal can only b
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satile blood flow in elastic arteries the ra
estimated that, during normal arterial flo
could lead to radius changes of 7 to 10 p
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reported by Rositano, et. al. may not be
due to changes in pressure associated wit
misinterpretation of the Doppler flow si
relationship between volume flowrate, p
velocity. Of particular concern, are possi
diastolic portions of the Doppler pulse si
studies may eventually enable the easily
into volume flowrate signals which woul
vascular response to G. This in turn wou
proposed method for comparing G-prote
and limitations the proposed method is
compare the differences in G protection
pressurized on different schedules. This
formance specifications for a new anti-G
LOC problem associated with high rates

The method presented here was dev
relative changes in the effectiveness of a
are introduced which affect the perform
comparing human stimulus response dat
parison over a higher G range. Thus, a fu
in figures 1-4, is that differences that exi
high G levels can be detected at lower G
is being extrapolated here and not the ab

The change in the performance of t
by altering the pressure schedule of his a
stimuli selected were relatively low level
tative measure of the subject's response
his mean Doppler flow signal during and
results of this study are considered impo
as equally important.

a) The anti-G suit pressure schec
formance of the following anti-G valve c

1) No Pressure – Selected t
pre. .rized.

2) Standard Valve – Selected to represent the performance of the standard ALAR valve currently used in the fleet.

3) Servo Valve-Outlet (SVO) – Selected to represent the performance of a servo-controlled valve which uses an accelerometer voltage as the drive signal and a pressure transducer voltage measured at the outlet of the valve as the feedback signal.

4) Servo Valve-Bladder (SVB) – Selected to represent the performance of a servo-controlled valve similar to (3) but which obtains its feedback signal from a pressure transducer located in the suit bladder.

The SVB should obviously surpass the SVO in rapidly pressurizing the suit bladder on a time schedule to match that defined by the accelerometer. This improved performance of the SVB is achieved by permitting overpressurization at the valve outlet to compensate for pressure delays caused by the connector hose between the valve and the suit bladder.

Suit pressure time histories resulting from a 4 G, 2 sec. onset-time G profile for each of these valve configurations are shown in figure 5. It is to be noted that the suit pressures obtained when the servo valves are in control are not only more responsive than when the standard valve is in control but attain higher levels of pressure. This is because the G pressure scaling of 1.5 psi per G, common to both types of valves, starts at 1 G for the servo valves and at 2 G for the standard valve. This design for the servo valves does not preclude them from having a break-out level about 1 G.

b) The acceleration profiles used in this study were selected to demonstrate the importance of G-onset time as a factor to be considered when evaluating the effectiveness of a given G-valve configuration. Eighteen separate G profiles were used throughout the study, six levels having three onset times each, with a minimum of nine used for a given valve configuration. This limitation was applied to stay within a subject's G tolerance range and to permit sufficient time for reruns without introducing fatigue.

The G profiles were grouped according to their G-onset times of 2, 4 or 8 sec. The plateau of each profile was maintained for 15 sec., with the plateau G level ranging from 2 to 4.5 G in 0.5 G increments. The G-onset phase of the profile followed that of a haversine curve and represented a realistic and well defined shape for a centrifuge generated G profile. Thus the G profile was defined by the following formulae:

$$G = 1 + 1/2\,(G_p - 1)\,(1 - \mathrm{Cos}\,\frac{\pi t}{T_o}) \qquad o \leqslant t \leqslant T_o \qquad (1)$$

$$\dot{G} = \frac{\pi}{2T_o}\,(G_p - 1)\,(\mathrm{Sin}\,\frac{\pi t}{T_o}) \qquad (2)$$

$$G = G_p \qquad T_o \leqslant t \leqslant T_o + 15 \text{ Sec.} \qquad (3)$$

where:

G = Resultant Acceleration in G-units

$\dot{G} = \frac{dG}{dt}$, Time rate of change of G

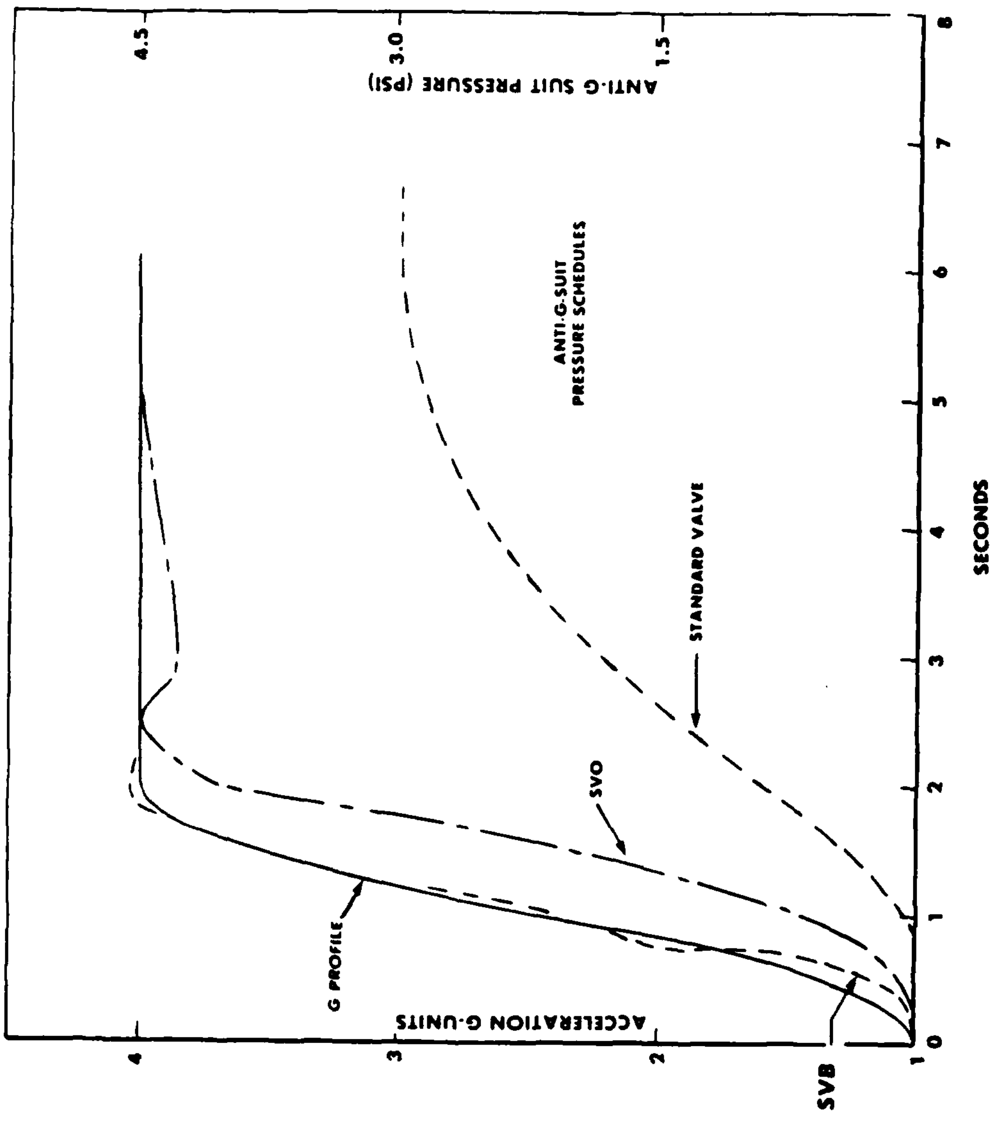

Figure 5. Suit pressure time histories resulting from a 4 G, 2 sec. onset-time G profile for the standard SVO and SVB valve configurations.

G_p = G level at plateau

T_o = G-onset time

Figure 6 shows the initial phase of three separate 4G profiles having onset times of 2, 4, and 8 sec. respectively.

For the purposes of this study it is not necessary to know the actual arterial flow rate as it varies in response to the stress of acceleration, but its relative magnitude when it is compared with the stabilized unstressed flow rate. Normalization of the flow rate signal eliminates the need to calibrate the signal and is based on the assumption that the subject's initial condition flow rate, not necessarily the flow rate signal, is consistent and representative of his physiologically stabilized unstressed state. Sufficient time must be allotted prior to and between G-runs therefore, for the subject to attain this stabilized condition. This normalization process also corrects for gradual changes in the signal strength of the transducer, such as may arise from changes in the acoustic coupling between the transceiver and the skin.

Unscheduled straining by the subject or movement of the transceiver during a G run can normally be detected in any suspect data by comparing it with previous runs for consistency. This straining may be induced by the subject to compensate for the lack of proper G-suit pressurization, for example. This in turn may mask the actual benefit or proper G-suit pressurization when it is applied. The transceiver signal itself should be monitored continuously, including periods both before and immediately following a data run, to assure that its well recognized signature is clean and not contaminated with noise. Variations in the cross-sectional area of the artery which are not taken into account when analyzing the velocity flow signal, can lead to possible misinterpretations concerning cerebral blood flow. Nevertheless, if the response data is consistent and repeatable, it can be used for the purpose intended here; i.e. to compare the effectiveness of different G-protective equipment or techniques.

The temporal artery Doppler flow velocity signal was selected as the measure of interest in this study because it provides a non-invasive, easily obtainable measure of relative changes in retinal blood flow. Under acceleration, a drop in retinal blood flow results in a reduction of oxygen level in the retinal blood supply, a condition empirically associated with the loss of visual function. This reduction in retinal oxygen level is related to the time average of the flow rate signal over a given time interval and not to the instantaneous value of the signal itself. This is illustrated in figure 7 which depicts the difference between a subject's mean Doppler flow velocity response when the pressure in his anti-G suit is controlled first by a standard valve and then by a SVO valve during exposure to the same 3.5 G, 2 sec. onset-time profile. While both responses drop to the same level, the SVO valve is observed to be more effective in protecting the subject than the standard valve. Thus the time average function (V(t), defined below, was selected as the quantitative measure of the subject's physiological response to G for this study.

$$\overline{V}(t) = \frac{100}{\bar{v}_o t} \int_o^t \bar{v}\,dt \qquad (4)$$

$$\overline{V}(T_1) = \frac{100}{\bar{v}_o T_1} \int_o^{T_1} \bar{v}\,dt \qquad (5)$$

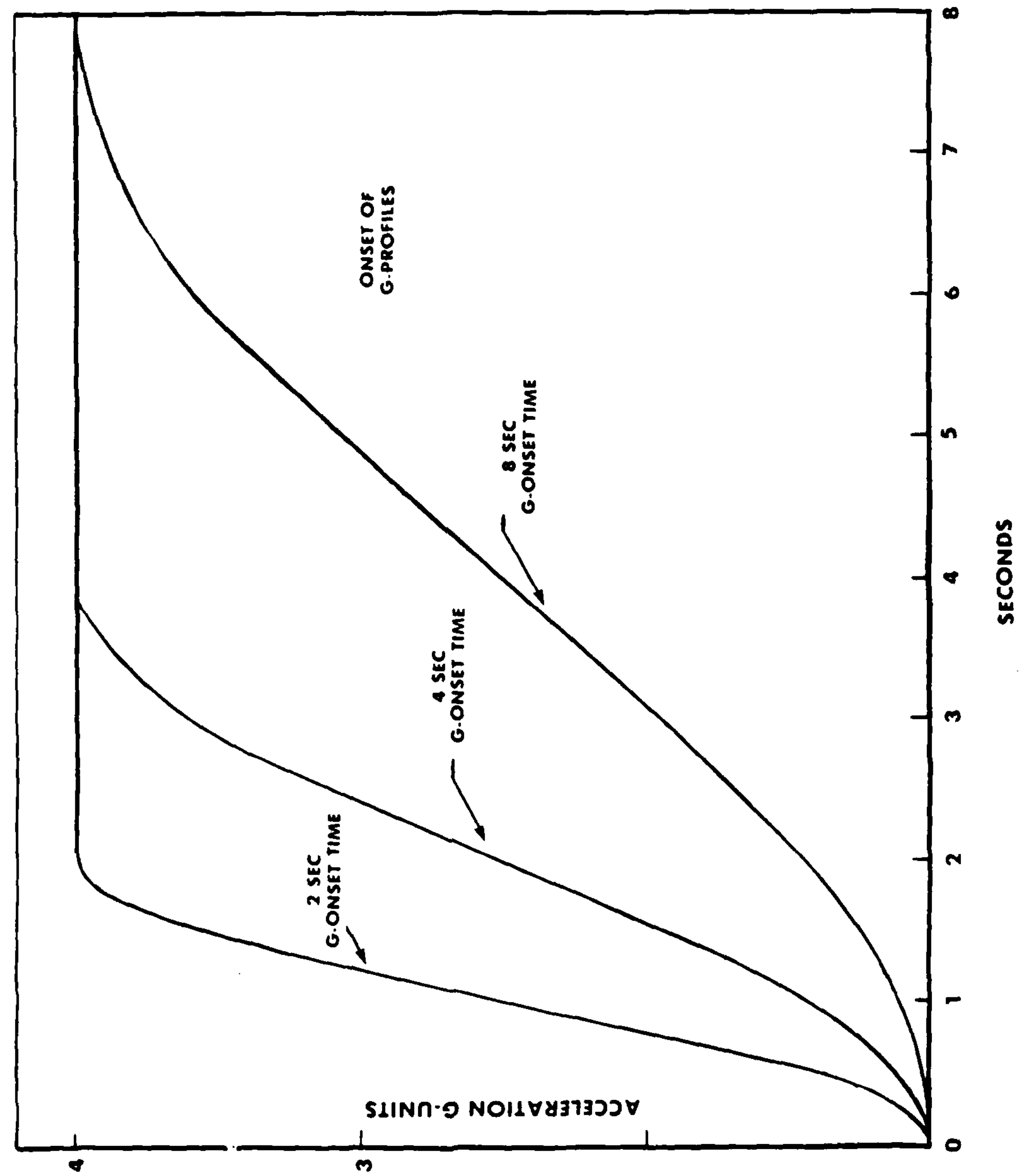

Figure 6. Initial phase of three separate 4 G profiles having onset-times of 2, 4 and 8 seconds.

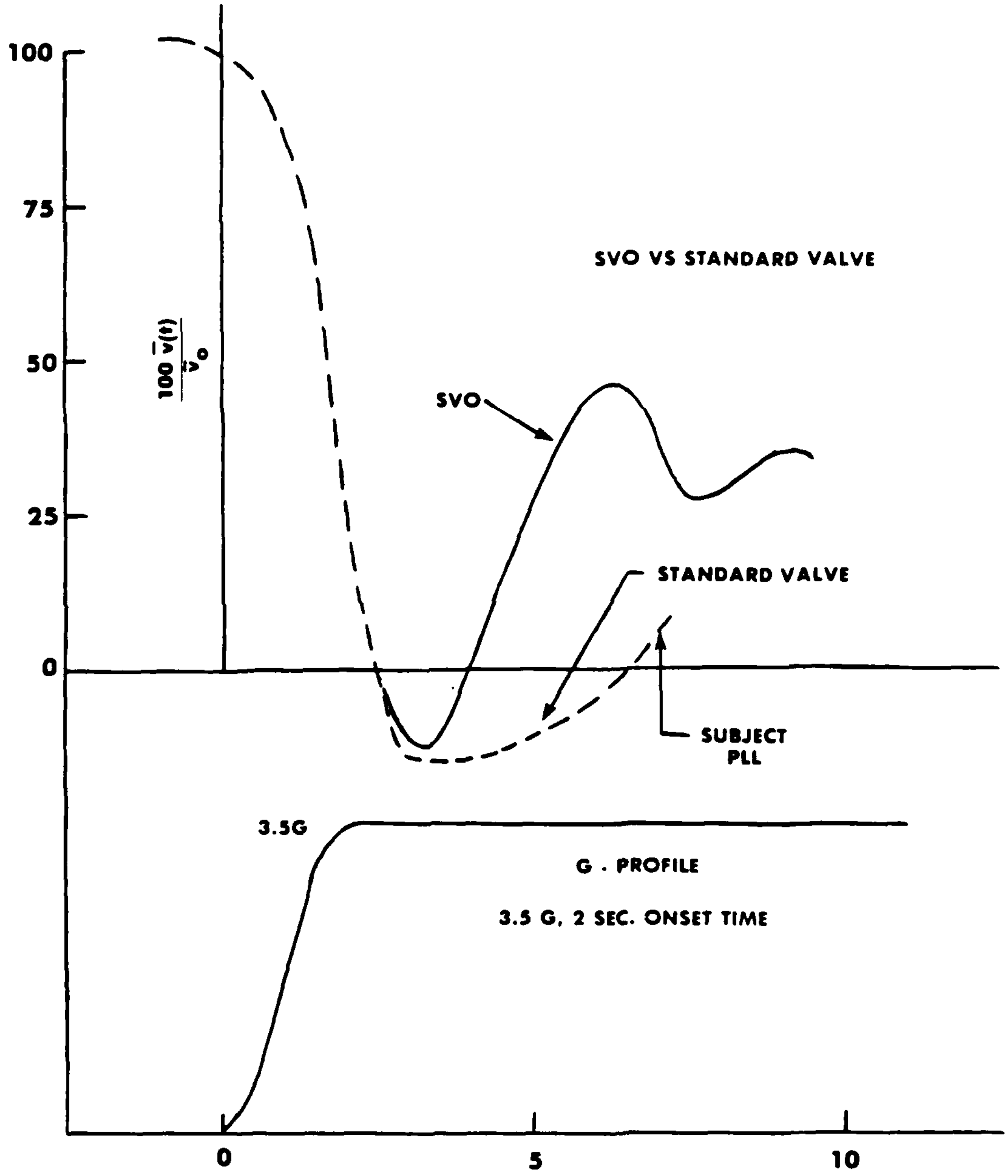

Figure 7. Mean Doppler flow responses to a 3.5 G, 2 sec. onset-time profile using the standard valve and the SVO valve configurations.

where:

$\overline{v}_o = \overline{v}$ at t = o

T_1 = G onset time + 3 sec.

While $\overline{V}(t)$ represents the normalized time average of the mean Doppler flow velocity signal as a continuous function of time, $\overline{V}(T_1)$ represents its time average over the specific time interval T_1. T_1 was selected as G-onset time plus the next 3 seconds in order to concentrate on the subject's transient response to the G-onset phase of the G-profile. If the G-valve configuration is effective against high rates of G-onset, its benefit should be apparent during or immediately following this phase. As illustrated in figure 8, which shows a relaxed subject's unpressurized response to a 2.5 G, 2 sec. onset-time profile, $\overline{V}(T_1)$ is obtained by dividing the shaded area by the crossed area and multiplying by 100. Its value of 40.5 means that its average velocity flow over the 5 second period following the G onset was 40.5 percent of its normal unstressed velocity.

Figures 9 and 10 provide additional evidence which involves the ear opacity signal, $\overline{E}(t)$ to support the selection of $\overline{V}(t)$ as the physiological measure of interest for this study. Here $\overline{V}(t)$ is plotted along with $\overline{v}(t)$ and $\overline{E}(t)$ for two separate runs in which a subject is exposed to 2.5 G and 3.0 G, 8 sec. onset time profiles, respectively. $\overline{V}(t)$ and $\overline{E}(t)$ are observed to agree remarkedly well in both phase and amplitude during both profiles until the G-offset phase of each profile occurs. No explanation is immediately available for this latter effect other than what has been stated previously concerning the difficulty of converting the velocity flow signals into volume flow signals. The ear opacity signal, $\overline{E}(t)$, is normalized and is essentially a relative measure of the blood content in the pinna of the ear. Wood, et. al.(14) have used relative changes in this signal to measure G protection afforded by water immersion.

RESULTS AND DISCUSSION

The human response testing phase of this study was conducted on the NAVAIRDEVCEN centrifuge which is particularly well suited to generate the required G-profiles. Three volunteers, all male, ages 22-31, participated in the tests. All had previous experience on the centrifuge and were well trained in the use of the light bar which provided a continuous measure of their peripheral vision.

Care had to be exercised throughout the tests to assure that a good Doppler pulse signal was being generated and that the subject returned to a stabilized physiological state prior to the start of each run. Also, we had to be on the alert for unscheduled straining maneuvers by the subject which would have contaminated the data in this "relaxed" study.

A typical set of data response curves is shown in figure 11 as recorded during three consecutive 2 second onset-time G profiles, for a "no pressure" valve configuration. Here the increase in the drop of the mean Doppler flow signal is seen to be approximately linear with the increase in G. The $\overline{V}(T_1)$ data tabulated in Table 1 bears this out. The "no pressure" values for each subject were found to vary linearly with G within the limits of the G profiles used here and a least squares line which intercepts at 100/1G was computed for each onset-time. The values of these slopes, along with their respective r^2 terms which measure the degree of fit for the data points, are provided in Table 2.

These straight lines, which represent each subjects unpressurized response to G, were then used as the reference lines for the $\overline{V}(T_1)$ data in Table 1 and three sets of difference values were derived

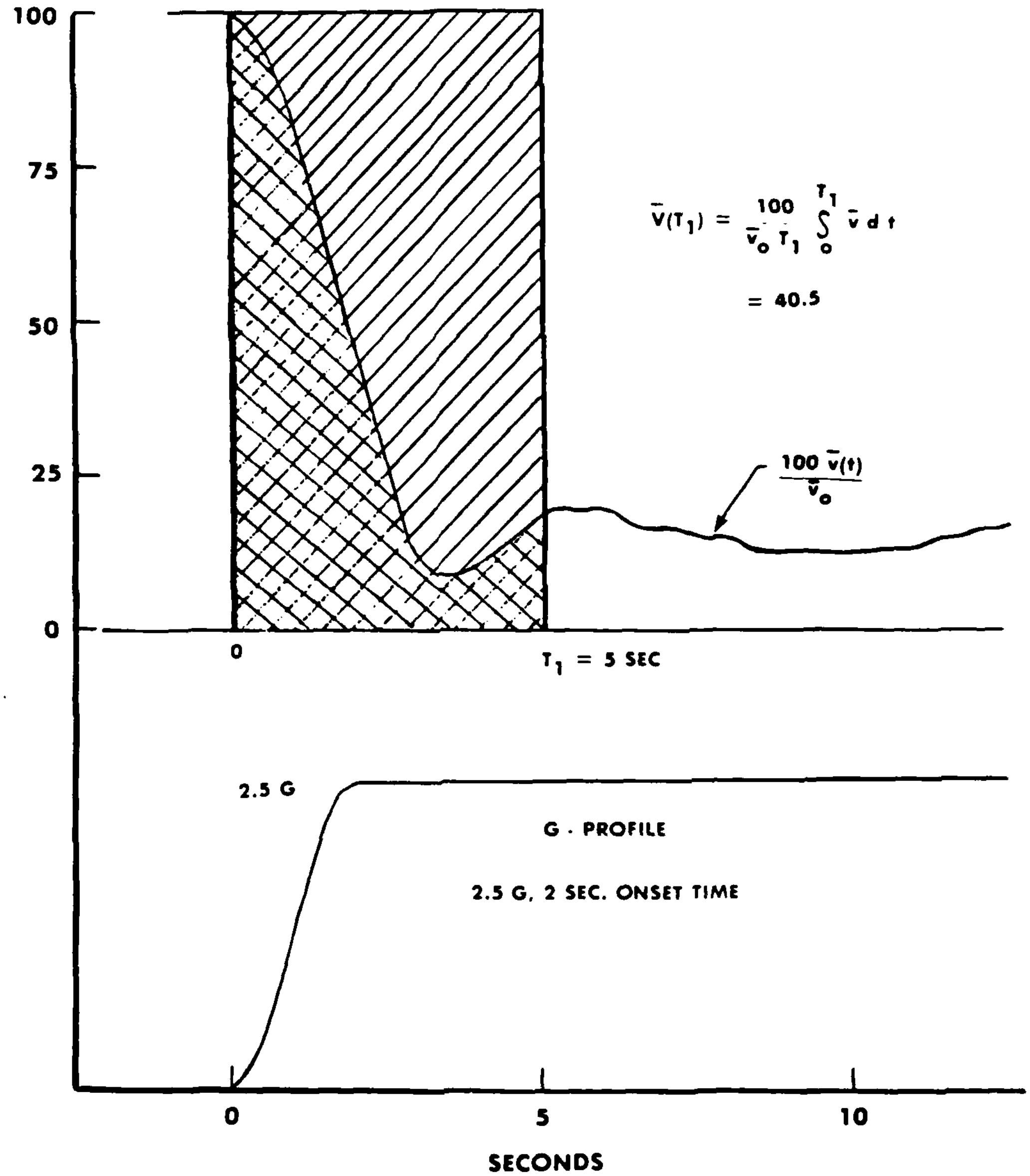

Figure 8. $\overline{V}(T_1)$ for an unpressurized subject's response to a 2.5 G, 2 sec. onset-time profile.

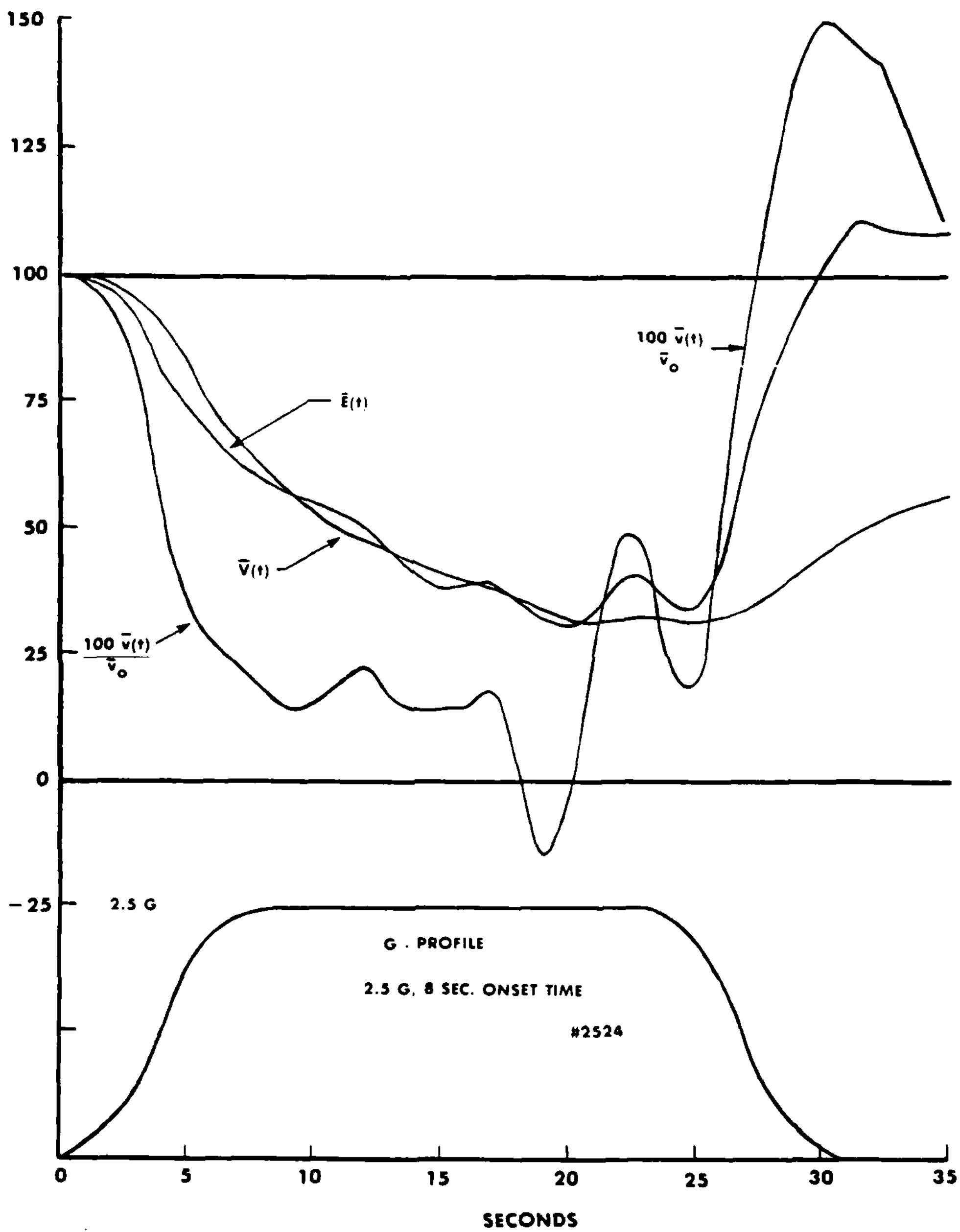

Figure 9. Close agreement between $\overline{V}(t)$ and $\overline{E}(t)$, the normalized ear opacity signal, for a 2.5 G, 8 sec. onset-time profile.

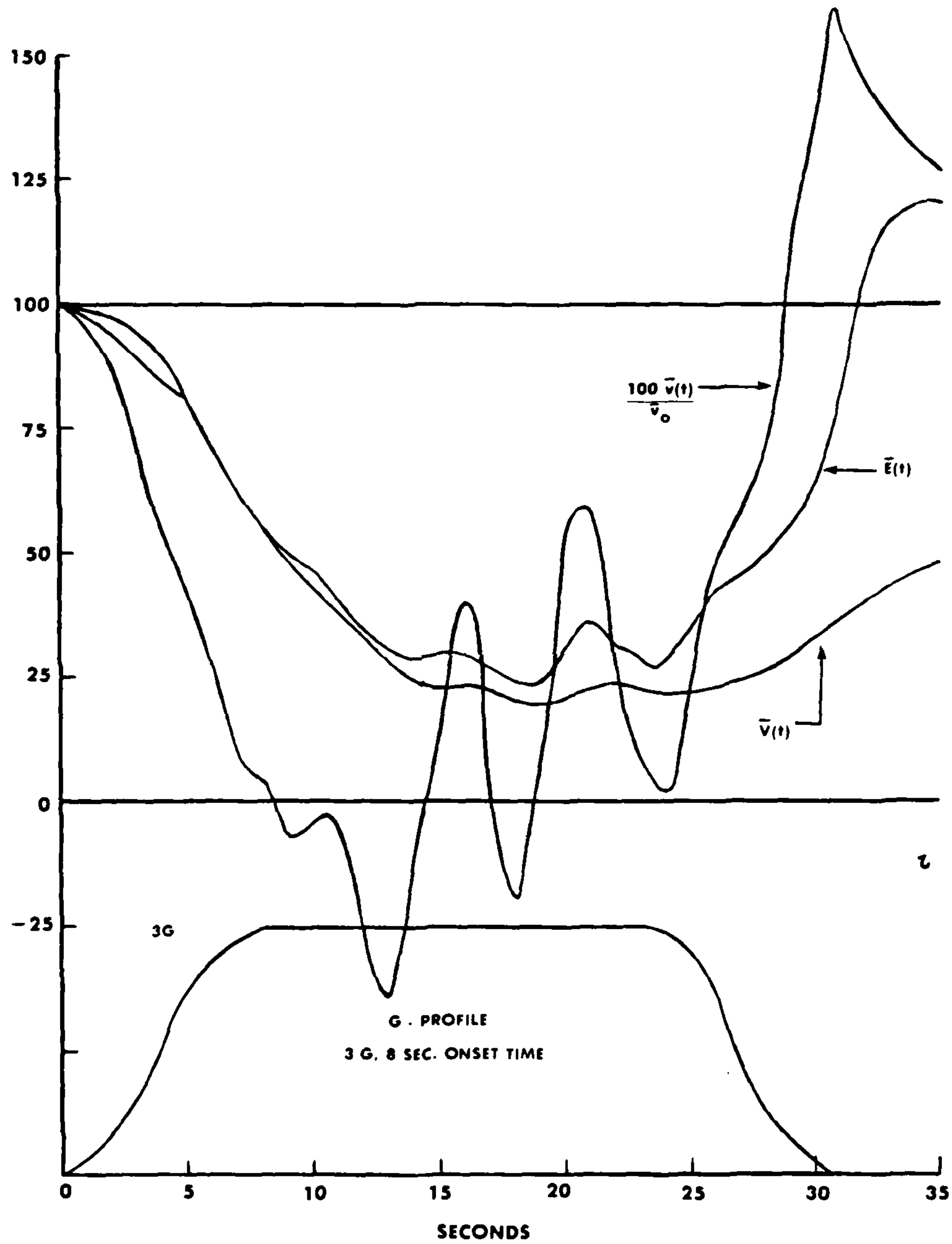

Figure 10. $\overline{V}(t)$ and $\overline{E}(t)$ at the 3 G level.

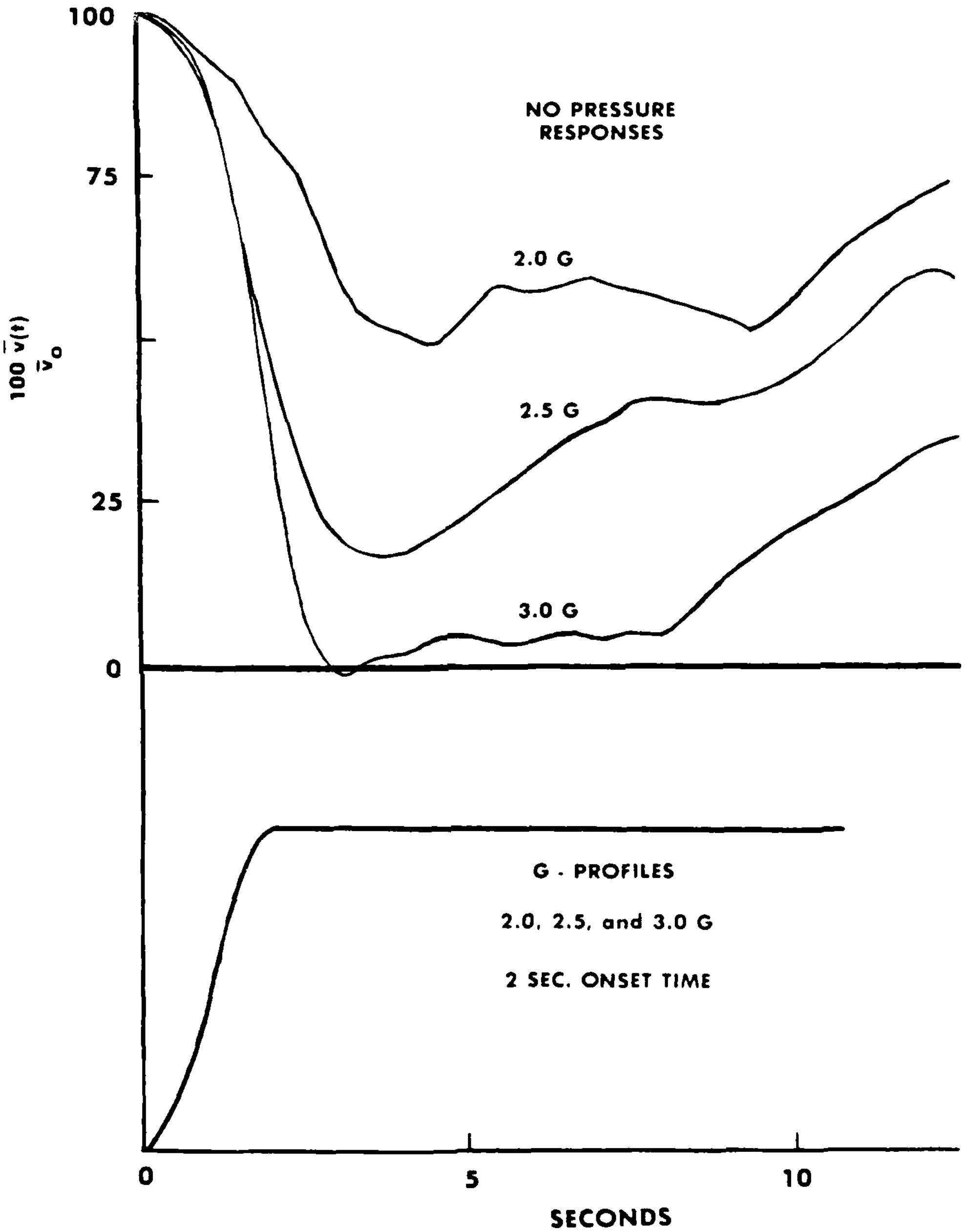

Figure 11. The linear relationship between $\overline{v}(t)$ and G demonstrated in these three consecutive "no pressure", response curves to G-profiles having a 2 second onset-time.

Table 1.

Table of $\overline{V}(T_1)$ Values

	G Values / ONSET TIME (SEC)	Subject (S-1) 2.0	2.5	3.0	3.5	4.0	Subject (S-2) 2.0	2.5	3.0	3.5	4.0	Subject (S-3) 2.0	2.5	3.0	3.5	4.0
NO PRESS	2	76.7	55.6	46.6	36.6		60.7	40.5	27.7			72.5	46.8	36.9	26.0	
	4	73.0	56.3	43.8	36.2		53.7	41.3	33.1			59.8	45.9	36.6		
	8	73.0	52.7	47.3	33.2		58.8	44.2	40.7			70.2	48.5	30.1		
STD.	2		59.0	45.5	31.8			43.1	31.8	12.4			49.8	34.0	18.0	
	4		57.0	42.0	32.9	29.0		42.6	25.0	9.2			54.2	38.9	28.0	
	8		54.0	40.0	34.5	28.4		57.6	45.6	27.0	12.8		52.0	41.7	31.5	
SVO	2			64.6	54.5	44.6			47.5	35.5	34.7			47.4	32.6	29.5
	4			60.9	53.5	38.9			54.6	48.6	32.6			51.6	41.0	23.2
	8			66.5	57.4	42.9		70.7	53.8	44.2	36.0			50.0	40.1	25.1
SVB	2			64.5	55.3	49.1			52.0	44.2	40.3			45.9	36.9	35.1
	4			64.2	56.2	47.9			56.0	44.6	40.6			43.4	37.8	27.4
	8			64.0	49.6	45.9		74.2	53.0	45.3	38.0			51.3	41.8	35.3

NOTE: Table I compares the $\overline{V}(T_1)$ data obtained for 3 different subjects, using 4 different G valve configurations and over a range of G profiles having three onset times.

Table 2.

Table of "No Pressure" Slopes of $\overline{V}(T_1)$ per G

Onset-Time	2 sec	r^2	4 sec	r^2	8 sec	r^2
Subject						
S-1	26.24	.9871	26.93	.9892	27.40	.9842
S-2	37.61	.9920	36.50	.9387	33.08	.9296
S-3	31.03	.9830	33.19	.9714	34.25	.9900
Avg.	31.6	.9874	32.21	.9664	31.56	.9679

NOTE: These slopes were derived from a least square fit of the "No Pressure" data points for each subject during G profiles having three separate onset times. The r^2 term measures the degree of fit.

lues were then averaged across subjects and plotted in
; show a measure of the improvements provided by each of
nce to the "no pressure" line which itself was averaged

ndard valve provides practically no benefit during the G
ively, while figure 14 provides evidence that the valve is
onset-time G profiles. This result would in fact be antici-
in figure 5. The servo valves, on the other hand, are seen
he effectiveness of the Anti-G suit during all of the G-
rforming the SVO during the 2 second onset-time profiles
13 and 14, however, that the SVB would prove to be better
and 8 second onset-time profiles also.

n the Doppler flow response curves for each valve configu-
e profile. Here, the standard valve is observed to be ineffec-
e, but fortunately does come into play before the subject
nce PLL during the succeeding 4G profile, however, due
d during the G onset period. Both servo valves are observed
de flow with the SVB outperforming the SVO. This
ctive system is critical during rapid onset G profiles to
eads to cessation of cerebral blood flow and eventual LOC.
ponds quickly to the G profile. Since cardiovascular com-
6 to 8 seconds after the onset of the acceleration[4], this
xes are activated during rapid onset G profiles. Concern for
ppressing the carotid baroreceptors which in turn would
red secondary to the benefit this valve provides in reducing

e method for evaluating the relative effectiveness of
d compares the quantitative response of the test subject's
e frontal branch of his superficial temporal artery to a
ch protective system in turn. The method was used to
f the anti G suit in protecting a relaxed subject to G when
rvo valve over that when it is controlled by a standard
sion of the valve was more effective than the SVO version
profiles. Additional tests performed in (2) have also
ontrolled anti-G valve increases the effectiveness of the
er platform against which the maneuver can be performed.
reported, in applying this method to other similar cases.
tolerance endpoints, and which compared the effect of
athing techniques, G profile shaping, anti-G suit design,

efore this method can be fully accepted as a reliable
ness of G protective systems. Some of these have been
more. However, much is to be said for a method in which
ry run and not just during the final run in a sequence
ch run should act to reinforce the data collected during
of the data can be enhanced.

Table 3.

Table of $\overline{V}(T_1)$ Data Using "No Pressure" Data As Reference

		Δ STD Valve				Δ SVO				Δ SVB			
G Values		2.5	3.0	3.5	4.0	2.5	3.0	3.5	4.0	2.5	3.0	3.5	4.0
Subject	S-1	-1.5	-1.9	-2.4			17.2	20.2	23.4		17.1	21.0	28.0
2 Sec	S-2	- .7	6.9	6.2			22.5	29.3	47.4		27.0	38.1	52.9
Onset Time	S-3	-3.8	-4.1	-4.6			3.3	10.0	22.5		7.8	14.4	28.0
Avg.		-2.0	.3	- .3			14.4	19.8	31.1		17.3	24.5	36.3
	S-1	-2.6	-4.2	.1			14.7	20.8	19.6		18.0	23.5	28.6
4 Sec	S-2	-2.7	-2.1	.3			27.5	39.8	42.0		28.8	35.7	50.0
Onset Time	S-3	4.1	5.4	11.1			18.2	24.1	22.9		4.6	20.9	27.1
Avg.		- .4	- .3	3.8			20.1	28.2	28.2		17.1	26.7	35.3

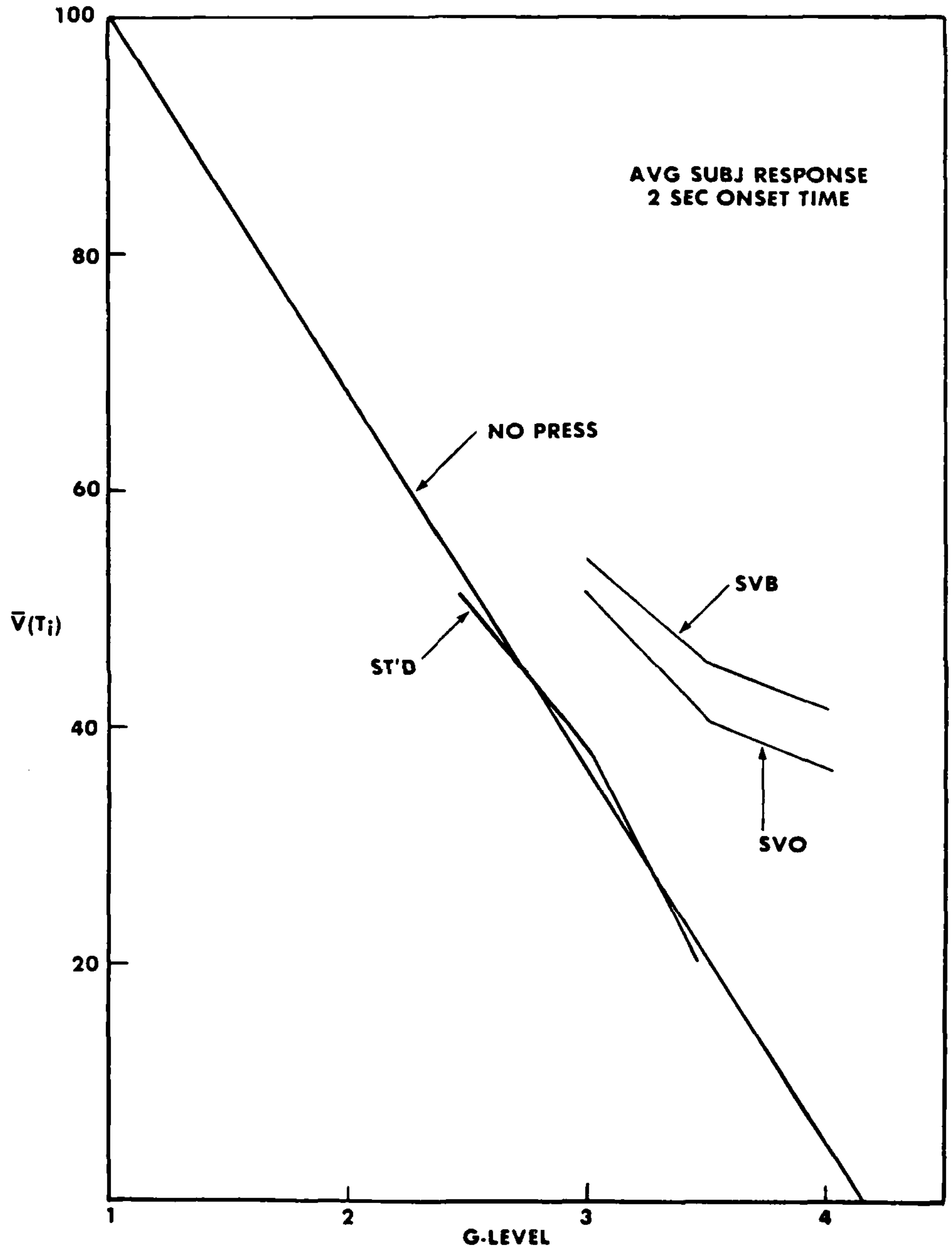

Figure 12. $\overline{V}(T_1)$ data averaged across subjects for the various valve configurations during 2 sec. onset-time G profiles.

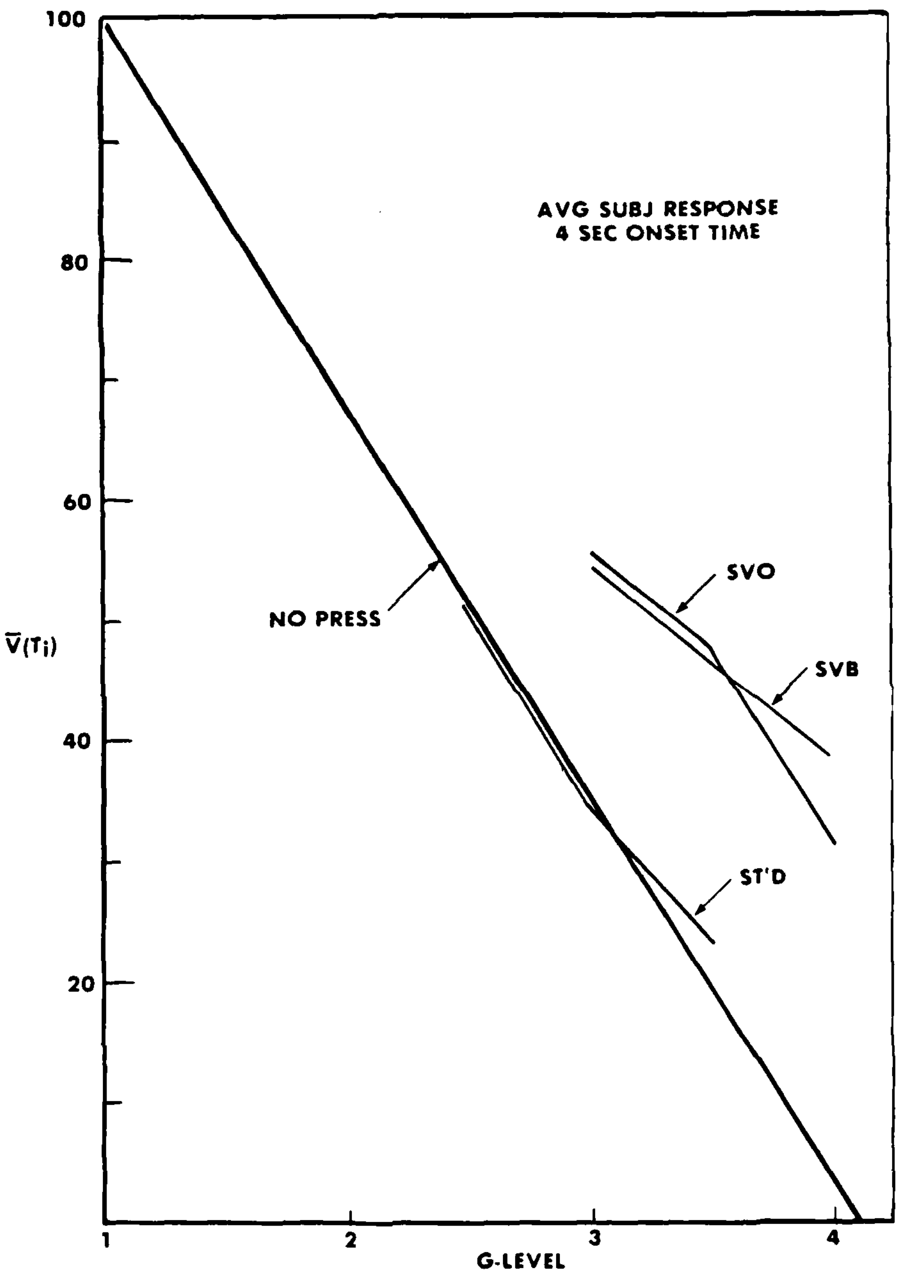

Figure 13. $\overline{V}(T_1)$ data averaged across subjects for the various valve configurations during 4 sec. onset-time profiles.

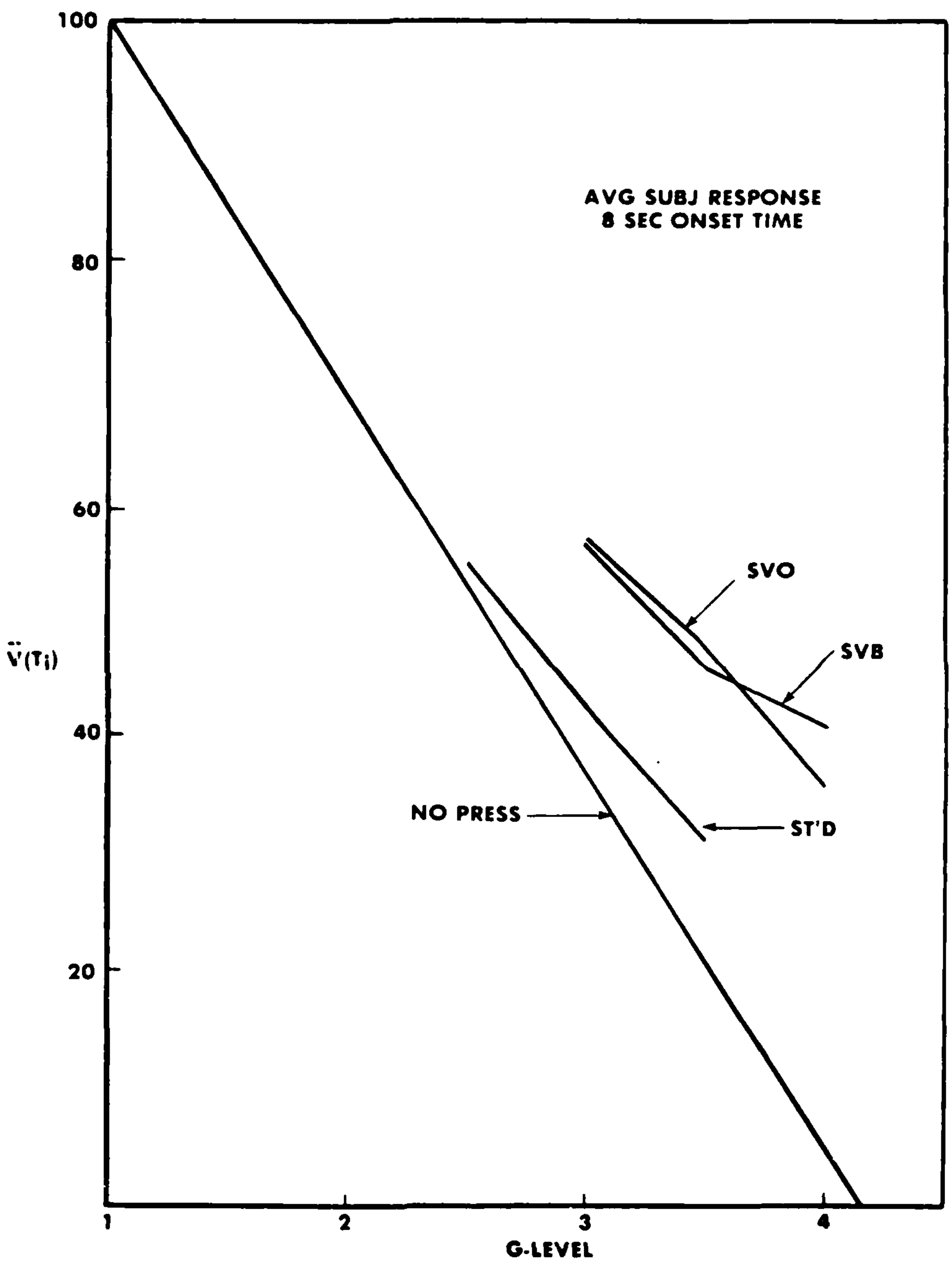

Figure 14. $\overline{V}(T_1)$ data averaged across subjects for the various valve configurations during 8 sec. onset-time G profiles.

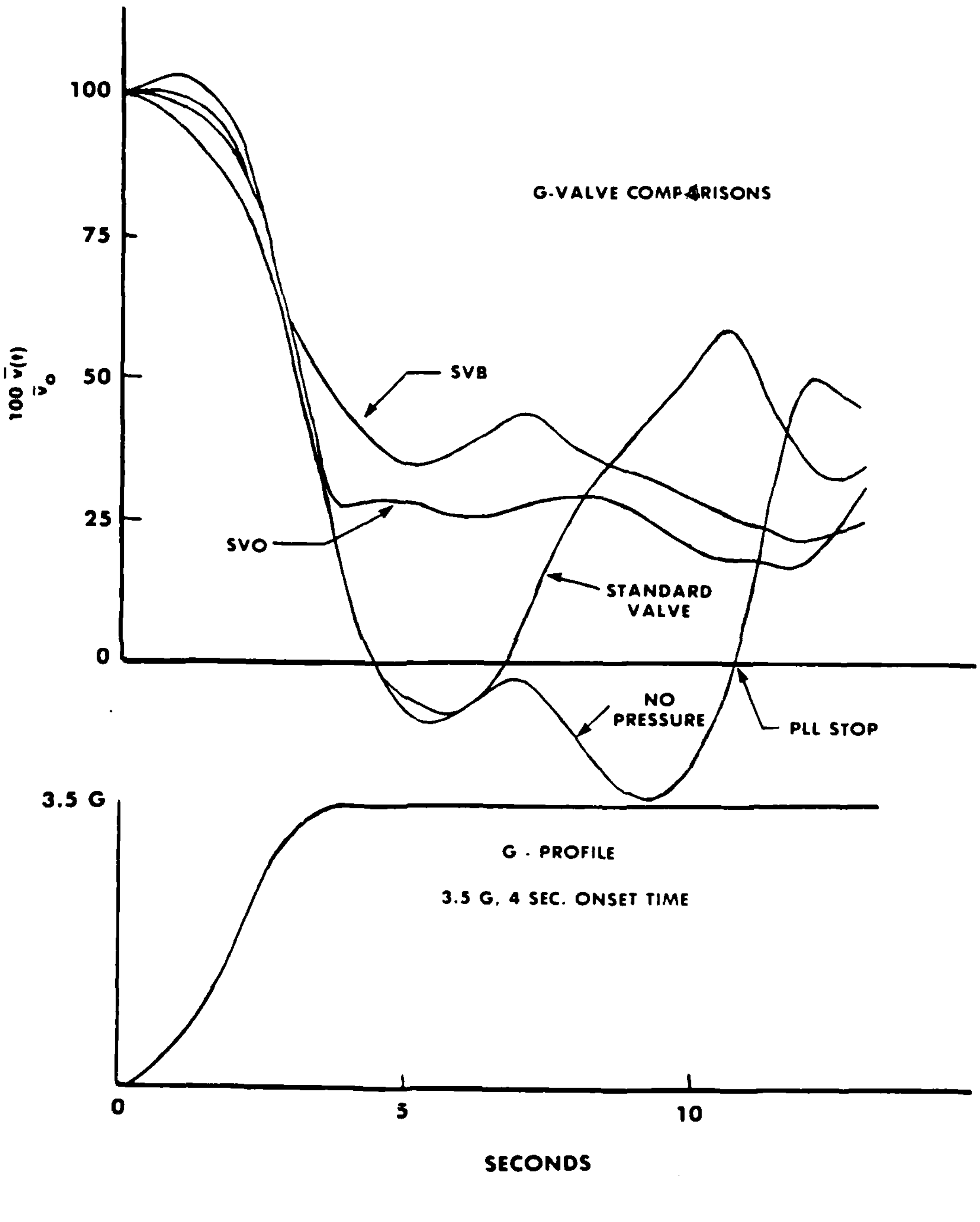

Figure 15. Doppler flow response curves for the no pressure, standard, SVO, and SVB valve configurations to a 3.5 G, 4 sec. onset-time profile.

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