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ADP010557

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THE EFFECT OF AIRCREW AGE ON +Gz TOLERANCE AS MEASURED IN A HUMAN-USE CENTRIFUGE

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INTRODUCTION

Pilots of high performance military aircraft are often exposed to positive acceleration stress (+Gz). This type of acceleration displaces blood in the head to foot direction. As the pressure in the vessels of the lower body increases, the vessels dilate, and a major portion of the blood from the upper part of the body is translocated to these lower vessels. The pooling of blood in the lower extremities translates into reduced cardiac output provoking the cardiovascular system, mainly by the activation of baroreceptor reflexes, to maintain adequate blood flow to the central nervous system (CNS) and thereby maintain normal brain function (1, 3, 11).

The physiologic symptoms of acceleration stress range from petechia hemorrhages (burst capillaries present in the limbs) to loss of vision and ultimately loss of consciousness with potential fatal consequences when it occurs in flight (1, 6, 11, 21). Mission effectiveness may also be affected by +Gz stress in that the lack of adequate blood flow to the CNS leads to degraded motor and cognitive performance. This degradation may then lead to aircraft accidents and incidents commonly labeled "pilot error." Hence, aircrew are routinely trained in the human-centrifuge to understand and better tolerate +Gz stress (10, 12, 18, 19).

A data repository was formulated in 1988 to compile information on aircrew who underwent acceleration tolerance training at the Naval Air Warfare Center (NAWC), Aircraft Division human-use centrifuge in Warminster, PA, USA. This program was known as the G Tolerance Improvement Program (GTIP) and was coordinated by personnel of the Crew Systems Technology Department of NAWC. The trainees participating in the program included members of the US Navy, Marines, and Air National Guard.

There is a concern that as the aircrew becomes older, their flight performance may not be adequate. Since tolerance to +Gz-stress is to a large extent dependent upon a healthy cardiovascular system, the propensity for increased vascular disease in individuals older than 35 yr. may indicate a reduced ability to tolerate repeated bouts of high +Gz-loads (17). Also, reaction time may slow down. For example, it has been estimated that the total time a pilot flying a 1,800 mph aircraft has to initiate a control sequence change in response to suddenly sighting another aircraft can be as long as 1.7s as follows: 0.3 s for visual acquisition, 0.6 s for recognition of impending danger, 0.5 s to select course of action and 0.3 s to initiate the desired control response (13). Given the response time of the aircraft, if the two planes were less than 4 miles apart, any response would be futile. Therefore, as reaction time slows, so does mission effectiveness. Measures of isometric strength also reduce with age, falling to 90 – 95% of maximum at 40 yr., 85% at 50 yr., and 80% at 60 yr., though not all strengths decline at this rate (e.g. back strength falls more rapidly, (14)). In response to these concerns, the US Navy acceleration research program limits subjects to 40 yr. and US aviators are relieved from flying at 60 yr. unless exempted by special wavier.

The purpose of this paper is to present data as it relates to aging and mission deficiency. Specifically, the relationship of age and acceleration tolerance as measured in a human-use centrifuge.

BACKGROUND

The purpose of the data repository is to improve +Gz-training methods and establish a large sample source of aircrew G tolerance characteristics. The repository consists of three sections structured in accordance to Microsoft® Access (Redmond, WA, USA) format. These sections are 1) trainee description; 2) +Gz profile description; and 3) cardiovascular response of the trainee to that +Gz profile. The first two sections are obtained from Run Sheet forms completed by the trainees and training personnel. The latter section is obtained from review of the trainee's electrocardiogram (ECG) which included 2 channels of ECG data based on sternal and biaxillary lead placement. These

Paper presented at the RTO HFM Symposium on "Operational Issues of Aging Crewmembers", held in Toulon, France, 11-14 October 1999, and published in RTO MP-33.

records are compiled for later review and entry of cardiovascular data into the database. All trainees considered for this paper either passed the appropriate physical examination requirements required for flight duty (Class I or II) or were determined to be fit for +Gz exposure by a qualified physician prior to insertion in the centrifuge.

The GTIP training protocol consisted of an approximately 2-hour lecture on the effects of +Gz stress on human physiology and the methods to combat this stress. Following this lecture each trainee was exposed to the acceleration environment in the human-use centrifuge for approximately 15 minutes. This device has been described in the literature (2, 5). While trainees underwent training in the centrifuge, their classmates witnessed the sequence of events thereby allowing them to learn from others and discuss the various techniques to better withstand +Gz. The GTIP program does not include a pass/fail valuation within its training protocol. However, the competitive nature of aircrew was evident. Upon termination of the +Gz exposure, each trainee was debriefed signifying the completion of the training day.

Technology to help combat acceleration stress includes the anti-G suit (AGS). The AGS is a protective garment used by aircrew to enhance tolerance to +Gz forces experienced in high performance aircraft. The AGS is a pair of trousers composed of inflatable air bladders strategically located over the calves, thighs, and abdominal areas. The subject dons the AGS, which is connected via a hose to an anti-G valve. The suit is activated in accordance to G exposure level. Activation of the AGS (inflation of the air bladders) exerts pressure against the lower limbs and abdomen. This pressure aids the cardiovascular system to maintain adequate blood flow to the CNS by forcing blood towards the head "counteracting" the effect of +Gz (3). Benefits of the AGS include increased G tolerance (G level), increased G exposure duration, and reduced petechia hemorrhage incidence. The AGS also aids the wearer to perform anti-G straining maneuvers (AGSM) as it provides the subject something to "strain against" and decreases the fatigue mostly generated by this effort. Resting G-tolerance levels as defined by loss of peripheral vision have been reported to average 3 G without and 4.5 G with an AGS.

The AGSM provides further protection against +Gz stress as follows. The "L-1" AGSM combines a periodic, 3 s strain (valsalva) against a closed glottis. A rapid exhalation and inhalation of < 0.5 seconds interrupts this strain. Tensing of all major muscle groups of the abdomen, arms, and legs is part of the effort. The AGSM provides an average 1.5 G protection above resting G tolerance levels (with AGS). This maneuver is also known as the "Hook" maneuver where the subject says the word "hook" as s/he begins to strain thereby ensuring a completely closed glottis. Other maneuvers include the "M-1" (partially closed glottis) and the Qigong (Q-G) Maneuver (10, 20, 22).

The GTIP profile included several exposures to +Gz. This paper discusses the gradual onset rate exposure portion of this profile as this exposure provides a measure of baroreceptor reflex response to the stress under discussion. Rapid onset rate profiles were also examined in that these better reflect the actual flight environment.

METHOD

A gradual onset rate (GOR) exposure was the first of a series of +Gz runs during a single GTIP training day. The GOR exposure commenced at a resting level of approximately 1.0 +Gz and increased at 0.1 G/s. Visual decrement was subjectively assessed by the trainees' inability to see an array of light emitting diodes (LEDs) placed in an arc describing 15° increments (150° total) 30 cm in front of the subject at eye level. The run proceeded until the trainee experienced 60° Peripheral Light Loss (PLL1), i.e., vision was confined to an arc describing 30° either side of the central point directly in front of the trainee. Once PLL1 was reached, the trainees were instructed to perform AGSM until peripheral vision was once again reduced to 60° (PLL2). The trainees then terminated the +Gz exposure by pressing a pre-selected button located on the control stick. The limit of the +Gz exposures was 9 +Gz. The profile was "open-loop" in that the trainee was not in control of the device but could stop the run at any time. A standardAGS was worn and activated during the +Gz exposure. This suit was either the CSU-13B/P or CSU-15B/P. There are no significant differences between these two suits. The inflation rate of the suit is approximately 1.5 pounds per square inch (psi) per +Gz. Inflation of the AGS bladders started at approximately 2 +Gz to a total of 11 psi when fully inflated at 9 +Gz.

The GOR exposure was followed by a series of rapid onset rate (ROR) exposures. The ROR exposures commenced at a resting level of approximately 1.0 +Gz. +Gz then increased at approximately > 6.0 G/s (haversine profile) until reaching a predetermined plateau level ranging from 5.0 to 9.0 +Gz. The plateau was to be maintained for a period of 10, 15, or 30 s. Both the G level and the plateau duration depended on the protocol of the time. That is, the protocol for the ROR exposures changed over the five years of training exercises under discussion. The ROR exposures were performed in sequence where the G level was increased by 0.5 or 1.0 G depending on the trainee's performance as the training exposure progressed. Most trainees experienced a total of four ROR exposures to 5, 7, 8, and 9 +Gz. The rest period between the runs was 1 minute or more. This period allowed the trainees to return to a resting heart rate similar to the one immediately prior to commencing the training runs. The AGS was worn and activated during the entire ROR exposure. The trainees were instructed to perform AGSM throughout these exposures. The ROR profile was also open-loop. Reasons for GOR and ROR run termination included 60° light loss, pain, fatigue, and G-induced Loss of Consciousness (G-LOC). Otherwise, the run was considered as "completed."

The centrifuge's cockpit configuration was similar to the F/A-18. A qualified physician monitored all exposures. Two channels of ECG activity were recorded during all runs (sternal and biaxillary lead placement).

The variables selected for GOR analysis were the subject relaxed +Gz tolerance as measured by PLL1; the subject straining tolerance (PLL2); and the protection afforded by the AGSM (PLL2 - PLL1). Incidence of G-LOC was also examined. Resting heart rate (RHR), maximum heart rate (MHR), and recovery heart rate (RCVHR) in beats per minute (bpm) available from 19 trainees were also examined to determine the effect of age on baroreceptor response to +Gz and recovery from the same. The variables selected for ROR analysis included G plateau duration and reason for run termination. Unfortunately, sufficient physiologic data were not available from these trainees for statistical analysis.

Statistical analysis included analysis of variance and multiple regression methods. Post-hoc analysis was performed as necessary. The null hypothesis is summarized as follows: "H_0: Age does not demonstrate to have a significant effect on G-tolerance as measured by the variables selected for this retrospective study." Level significance was selected as $\alpha = 0.05$. The statistical software used for data analysis was NCSS 2000© (Kaysville, UT, USA).

RESULTS

Information on 1,120 aircrew (74% pilots) who underwent acceleration tolerance training at the Naval Air Warfare Center human-use centrifuge was compiled. High performance aircraft was represented by 95% of the trainees (attack, 38%, fighter, 57%). Table 1 describes the aircraft type distribution of this sample. The repository included information on trainees from the US Navy/Marine Corps (70%) and Air National Guard (30%).

Table 1. Aircraft Type represented by 1120 GTIP trainees.

A4	A6	A7	AV8	A10	A37	F1	F2	F4	F14	F15	F16	F18	Other	Unknown	TOTAL
19	126	71	48	105	52	13	53	62	200	34	86	187	26	38	1120

Balanced GOR response data from 817 trainees were selected for further evaluation. The mean age (± S.D.) of this group was 31.4 ± 6.8 years (20 to 59 years). Figure 1 describes the age distribution of this sample. Trainees included 79% pilots; 14% "backseaters" (BS) such as weapons or radar intercept officers; 3% Flight Surgeons (FS); and 2% Physiologic Training Officers (PTO). The remaining 2% (n= 18) of the trainees did not specify their flight status. Table 2 describes their respective age distribution. Age was significantly different among the four groups (F=28.02, $p<0.000$) where the largest difference was that between FS and BS by approximately 11 years. Figure 2 describes this finding.

Table 2. Age distribution by trainee type (n= 799).

Value	Pilot	BS	FS	PTO
Mean	31.79	27.08	38.52	32.94
S.D.	6.67	3.63	10.76	5.66
number	642	118	23	16

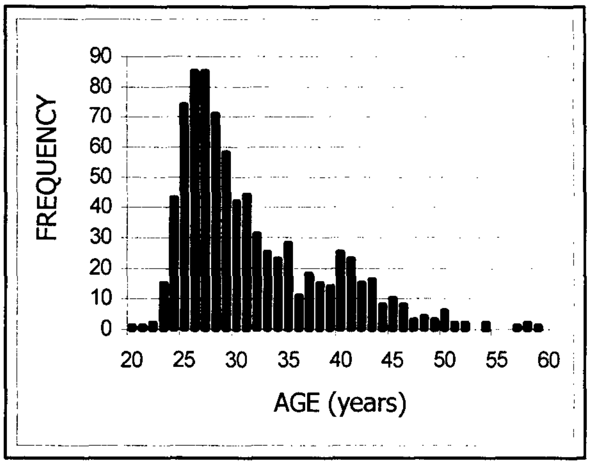
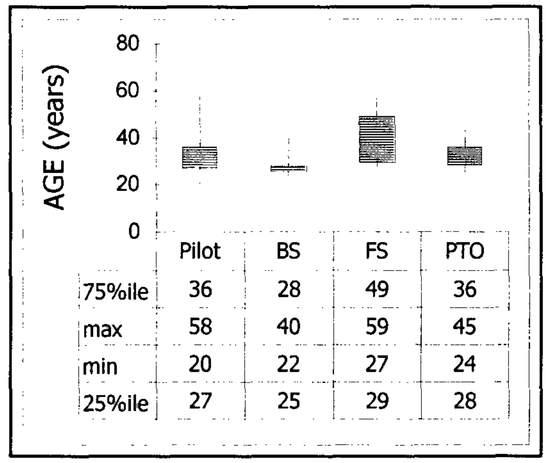


Figure 1. Age distribution of 817 GTIP trainees.



	Pilot	BS	FS	PTO
75%ile	36	28	49	36
max	58	40	59	45
min	20	22	27	24
25%ile	27	25	29	28

Figure 2. Distribution by flight status (n=799).

Of the 817 trainee-sample, 52 were smokers (≥ ½ pack per day). Their age (23 to 50 years) did not differ from non-smokers (33.3 ± 7.3 years). Eighty-five percent of the smokers were pilots (n=44), 10% were BS (n=5), and the remaining 5% represented 1 FS and 2 trainees whose flight status was unknown.

An analysis of the relationship between the amount of experience with +Gz-stress in flight and tolerance to GOR centrifuge exposures was conducted. It was found that the number of total and tactical flight hours as well as the number of flight hours during the 30 days prior to the training exposure did not affect +Gz tolerance.

Relaxed GOR tolerance was 4.9 ± 0.9 +Gz (n=817). Age did not demonstrate to have an effect on this tolerance ($F=4.43$, $r^2=0.005$). Figure 3 depicts the regression residuals and the predicted values of relaxed G tolerance as measured by PLL1.

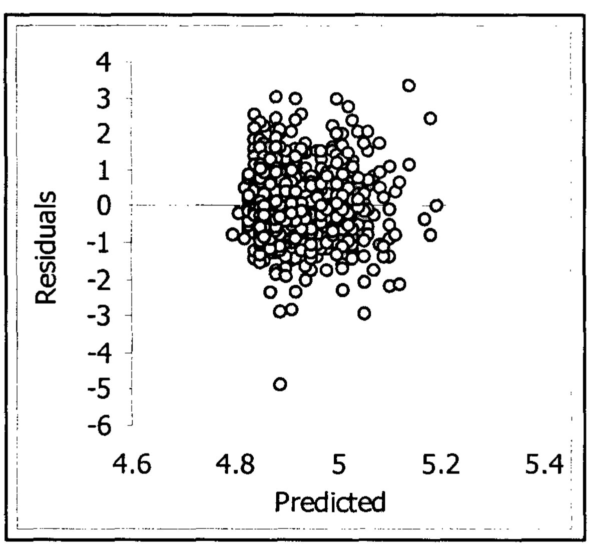


Figure 3. Age and +Gz tolerance as measured by PLL1.

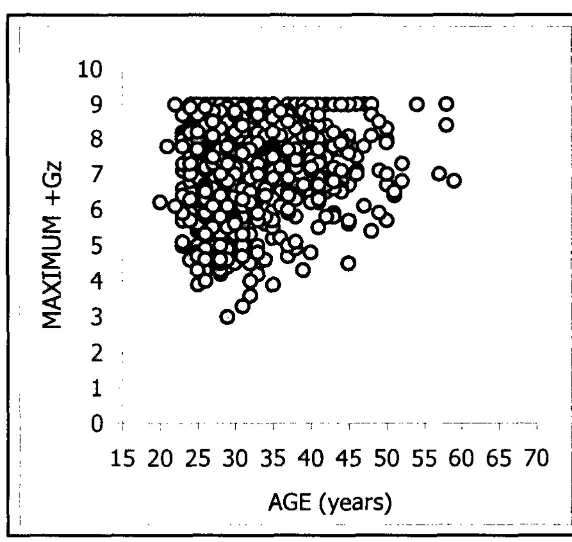


Figure 4. Age and +Gz tolerance as measured by PLL2.

Figure 4 demonstrates the relationship between age and +Gz tolerance as measured by PLL2. Straining tolerance was 7.2 ± 1.3 +Gz (n=817). Age did not demonstrate to have an effect on this tolerance ($F=14.59$, $r^2=0.017$). The protection afforded by the AGSM was 2.7 ± 0.8 +Gz (0.5 to 6.0 +Gz, n=674) and was not affected by subject age ($F=5.40$, $r^2=0.007$).

Of 896 complete GOR trainee data sets addressing the reason for run termination, 91% (n=817) were terminated for normal reasons (i.e., PLL); 7% (n=59) were terminated due to G-LOC, and 2% (n=20) were terminated for other reasons (i.e., centrifuge computer safety stop, other technical reasons, etc). Age did not demonstrate to have an effect on G-LOC incidence. Table 3 compares the incidence of G-LOC and normal run terminations.

Table 3. Incidence of G-LOC and normal +Gz exposure termination and percentage of total per age group.

AGE	Normal	%	G-LOC	%
25	136	*92.5*	11	*7.5*
26-31	385	*93.7*	26	*6.3*
32-37	136	*92.5*	11	*7.5*
38-43	108	*94.7*	6	*5.3*
44-49	36	*90.0*	4	*10.0*
50-55	12	*100.0*	0	*0.0*
56-61	4	*80.0*	1	*20.0*
Total	817		59	

Exposures where heart rate data was analyzed (n=19) ranged from 5 to 9 +Gz (5.5 ± 1.3 +Gz). The mean age representing this data set was 34.8 ± 8.9 (23-52 years). The change described by MHR-RHR was 57 ± 21 bpm. The change described by MHR-RCVHR was 69 ± 27 bpm. The difference was statistically significant (t=3.09, p=0.006). Multiple regression demonstrated that age and the +Gz level at which the MHR occurred (GMHR) explained 52% percent of the variability in MHR-RCVHR (r^2 age = 0.33, $pT_{\beta 1}$= 0.001; r^2 GMHR= 0.51, $pT_{\beta 2}$= 0.027). The model was described by MHR-RCVHR= 64.12 – 2.03*age + 10.68*GMHR (F=8.51, p=0.003, power = 0.66). All recovery heart rates were noted within the first 75 s. Figure 5 depicts this relationship at various +Gz levels.

Similarly, no statistically significant relationship was found when the change MHR-RHR was considered with respect to age and GMHR. However, simple regression examination of residuals appeared to delineate two separate age groups as follows. The change MHR-RHR appeared to increase with age for trainees ≤ 34 years old (r=0.56). The same was true for MHR-RCVHR (r=0.60). However, regression analysis did not demonstrate statistical significance. The change MHR-RHR was higher for trainees ≤ 34 years old (69 ± 19 bpm) than for trainees 37 to 52 years old (44 ± 14 bpm). This 25 bpm difference was significantly different (t=3.10, p=0.006). The change MHR-RCVHR was higher for trainees ≤ 34 years old (88 ± 22 bpm) than for trainees 37 to 52 years old (49 ± 15 bpm). This 39 bpm difference was significantly different (t=4.5, p=0.000). Figure 6 describes these findings. The larger symbols represent the 5 smokers in this sample.

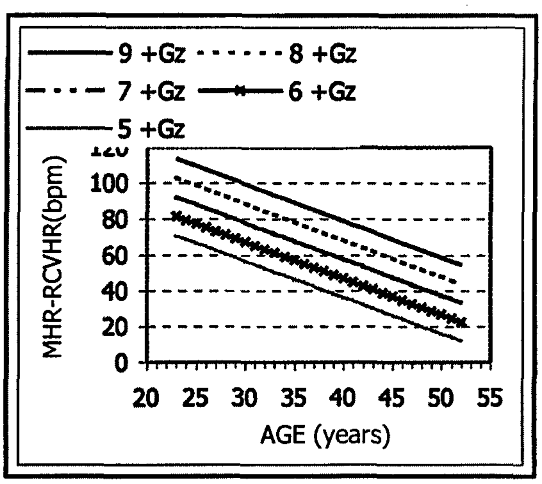


Figure 5. Change from maximum heart rate to recovery heart rate after exposure to various +Gz levels.

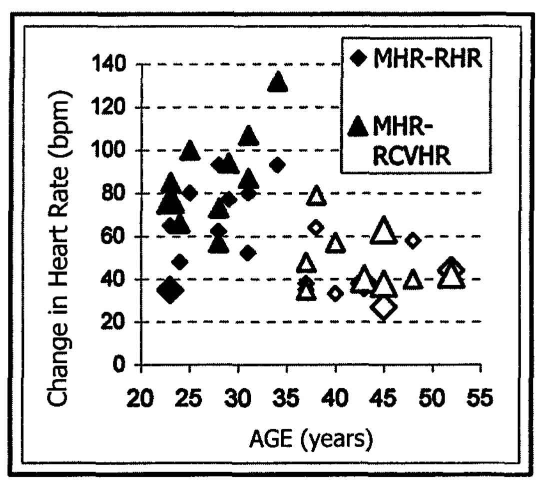


Figure 6. Change from in heart rate from maximum during +Gz exposure and its rest level.

For the purposes of this paper, examination of the ROR exposures concentrated on individuals aged above 49 years. Eighteen trainees' data were analyzed. Their flight status was 11 pilots, 6 flight surgeons, and 1 trainee who did not provide this information. One of the pilots was a smoker (for 30 years). Table 4 presents these trainees' characteristics.

Table 4. Characteristics of 18 trainees over 49 years of age.

n=18	AGE	Total Flight Hrs.	Tactical Flight Hrs.	Height (in.)	Weight (lbs.)
Minimum	50	30	0	65.0	145.0
Maximum	61	25000	6000	76.0	215.0
Average	53	4418	2412	70.4	183.7
Standard Deviation	3.8	5854	2156	2.6	18.4

Age did not show to have an effect on the trainees' ROR tolerance in that their progress through the training protocol was similar to those of age less than 49 years. Performance of the trainees, including those over 49 years of age, did not seem to be affected by ROR run-number sequence. Data was available from sixteen of these oldest trainees. Specifically, for the second run of the training day, fifteen of these older trainees completed their run successfully (6 +Gz plateau for 30 seconds). For the third run of the training day, data was available from 16 of these trainees. Thirteen of these older trainees completed their run successfully (ranging from 5.5 to 8 +Gz for a plateau duration of 15 or 30 seconds). For the fourth run of the training day, data was available from 13 of these trainees. seven completed their run successfully (ranging from 7 to 9 +Gz for plateau duration of 15 seconds). For the fifth run of the training day, data was available from 13 of these trainees. Seven of these older trainees completed their run successfully (ranging from 7 to 9 +Gz for plateau duration of 10 or 15 seconds). Finally, two of the trainees continued on up to completing an eighth ROR exposure successfully (up to 10 seconds at 9 +Gz, ages 50 and 51). All of the ROR exposures which ended prematurely were due to light loss, fatigue, etc., except for two exposures which were terminated due to G-LOC (both during the 5th run of the training day). Incidence of light loss, fatigue, etc. was similar for all age groups (20 – 60 yr.).

The reasons trainees gave for run termination were not related to age regardless of exposure type (GOR or ROR) or +Gz level achieved (5 to 9). Examination of the totality of the data repository yielded 4,746 exposures. 3,280 runs were completed (70%) while 271 incomplete runs were due to G-LOC (5%) (terminated by an observer) and 1195 (25%) were halted by the trainee for other reasons. Table 5 presents the data in accordance to the trainees' age range.

Table 5. Breakdown of outcome of training runs by age range, completion, or incompletion (G-LOC or other reason) (p= percentage of age group, n= number).

AGE	Runs by age (n)	Completed runs (n)	Completed (p)	G-LOC (n)	G-LOC (p)	Other incomplete (n)	Other (p)
< 29	2241	1575	0.70	125	0.06	541	0.24
< 39	1720	1170	0.68	104	0.06	446	0.26
≤ 49	707	486	0.69	39	0.06	182	0.26
> 49 - 61	78	49	0.63	3	0.04	26	0.33
Totals	4,746	3,280		271		1,195	

DISCUSSION

Acceleration stress effects on human physiology have been studied since the 1930's. The first protective response against +Gz forces is a series of reflex cardiovascular changes. Upon exposure to +Gz stress, there is an immediate hydrostatic pressure drop from the aorta to the carotid sinus generating a simultaneous stimulation of the vasomotor center. This action results in vasoconstriction, increased blood pressure, increased contractility and a rise in heart rate. Reflex tachycardia occurs in an effort to normalize the blood supply to the brain and other tissues. Simultaneously, the vasomotor center and other areas of the reticular formation transmit impulses to the abdominal muscles resulting in higher muscle tone and contraction of abdominal viscera. These events compress the abdominal venous reservoirs to translocate blood out of the abdomen toward the central circulation (11). Anxiety, AGSM, and the AGS enhance these protective measures.

The characteristics of the ECG response to +Gz exposure have also been reported in the literature. Heart rate increases in anticipation of the exposure and subsequently with G level. Heart rate then returns to its resting state approximately one to two minutes after the exposure. Heart rate does not predict +Gz tolerance but it is monitored to assess an appropriate response to the stress. There is a greater change in heart rate per +Gz level as acceleration increases during gradual onset runs than rapid onset runs. This change is reduced by 50% as the onset rate increases from 0.1 G/s to 1.0 and 6.0 G/s (4, 7-8, 16).

The difference in age relative to flight status was not surprising. Number of flight hours also showed a difference with age as expected. Note that flight hour experience, including flight hours during last 30 days prior to the exposure did not affect +Gz tolerance. During the training lecture, trainees were told that G-tolerance was reduced as time between +Gz exposures increased. In the development of the NAWC centrifuge subject pool, it was found that subjects needed G exposures on at least a monthly basis to maintain a consistent behavior in the centrifuge. A USAF study of this relationship found that while relaxed GOR tolerance was unaffected after a four week layoff, G endurance tolerance was significantly reduced (15). This reduction was attributed to a lack of recent practice with the AGSM. The USAF study did not address the effect of layoff on straining tolerance to gradual or rapid onset exposures. One factor not addressed in the present study was the relative quality of the trainees' AGSM. The concern that effective G-tolerance (with protection) will degrade without practice and recent +Gz exposure has led the US Navy training centrifuge staff at Lamoore, CA to consider having pilots return to the centrifuge for annual refresher training.

The greater change in RHR-MHR in the younger trainees is probably related to their overall lack of experience in the high +Gz environment and the anxiety typically associated with first centrifuge exposures. In the human-centrifuge training environment, as compared to an aircraft, pilot are passive riders rather than in active control of the +Gz-load. The younger trainees may have demonstrated a more emotional response than their older peers with possibly higher levels of circulating norepinephrine. The difference in change in heart rate past age 35 is difficult to interpret since the data is confounded by the smoking variable. Also, time of heart rate recovery was not noted in this preliminary analysis. The increased sympathetic activity expected of smokers has been reported to mask the parasympathetic response typically observed during recovery from GOR exposures (9).

It would be expected that the decrease in maximal breathing capacity and the reduced muscle mass and therefore muscle power with age affect physiologic response to stress. Also, vascular tone along with other related parameters that may affect peripheral resistance typical of the aging process may reduce this response. Cardiac output itself is reduced as much as 50% from the teens to 80s. However, this assertion is based on data derived from the general population. It does not take into account that aircrew are not sedentary, are generally in excellent health and free of disease, and are not older than 60 yr. Individuals in the database included in this study all successfully passed Class I and II flight physicals and were healthy. In the case of both the GOR and ROR exposures, subjects demonstrated appropriate, uneventful and successful cardiovascular responses to +Gz stress seemingly unrelated to age. In fact, the infrequent incidents of G-LOC all resolved uneventfully.

This study focussed on ECG responses to GOR exposures because they have been shown to provoke a significantly greater cardiovascular response than rapid onset exposures. However, aviators rarely, if ever, experience such prolonged slow onset rate +Gz exposures in flight. Aircrew may be exposed to onset rates of 6 G/s or higher during repeated maneuvers over the course of a mission. G tolerance is a global term that has various subcategories. Cardiovascular G tolerance refers to the ability of the heart and vasculature to counteract the effects of +Gz-stress over time (typically 10 to 15 s). This is typically determined using GOR exposures. Neurologic G tolerance refers to the ability of the central nervous system to resist +Gz stress over a period of 5 to 7 s (the buffer period afforded by oxygen present in the cerebral tissues at +1 Gz). Rapid onset exposures (≥ 3 G/s) are used to assess this tolerance. G endurance tolerance refers to the ability to maintain vision and consciousness during repeated bouts of high +Gz-stress. This tolerance is assessed through the use of simulated aerial combat maneuvers in which alternating levels of +Gz stress are repeated until subjects are exhausted.

The training scenario experienced by these trainees did not address their level of G endurance tolerance. Of recent interest is the effect on G-tolerance of transitions between less than +1 Gz to greater than +1 Gz (known as the "push pull" effect, PPE). The database contains exclusively positive Gz exposures. It is unknown whether tolerance to repeated or PPE type exposures is affected by the age of aviators. Given the operational nature of these exposures, additional study is required to completely address the issue of age and G tolerance.

CONCLUSION

Based on the variables examined in this retrospective study, there does not seem to be a significant effect of age (20 – 61 years) on tolerance to gradual and rapid onset +Gz exposures as measured in the human-use centrifuge.

ACKNOWLEDGEMENTS

The contents of this paper would not have been possible without the cooperation of the trainees who underwent acceleration exposures in the Warminster centrifuge. We thank them for their support. Members of the Naval Air Warfare Center, Crew Systems Technology Departmentwere invaluable in the compilation of the data reported herein. Their patience and enthusiasm is appreciated.

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