FOREWORD

This work was done by the Acceleration Section, Biophysics Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 7222, "Biophysics of Flight," and Task 722202, "Acceleration in Flight and Escape." The authors would like to thank Mr. John W. Frazier and Mr. Justin Taylor for their considerable technical assistance in this study.

ABSTRACT

The cardiovascular and respiratory responses of test pilots are compared with the AMRL centrifuge panel members during headward (+ G_Z) and forward (+ G_X) accelerations. Vital capacity decreased in all subjects with increasing forward acceleration. No significant difference existed between the cardiorespiratory performance of test pilots and that of the nonrated personnel that constitute the AMRL centrifuge panel. No correlation was noted between blackout and pulse rate, but correlation did exist between resting control and + $5G_Z$ pulse rates. An extensive number of anthropometric measurements, indices of physical fitness, and measurements made during other stress did not correlate with tolerance to headward (+ G_Z) acceleration or with respiratory performance during + G_Z and + G_X acceleration.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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SOME CARDIORESPIRATORY RESPONSES OF FLYING AND NON-FLYING PERSONNEL TO DIFFERENT VECTORS OF ACCELERATION WITH CORRELATION OF THESE RESPONSES TO OTHER VARIABLES

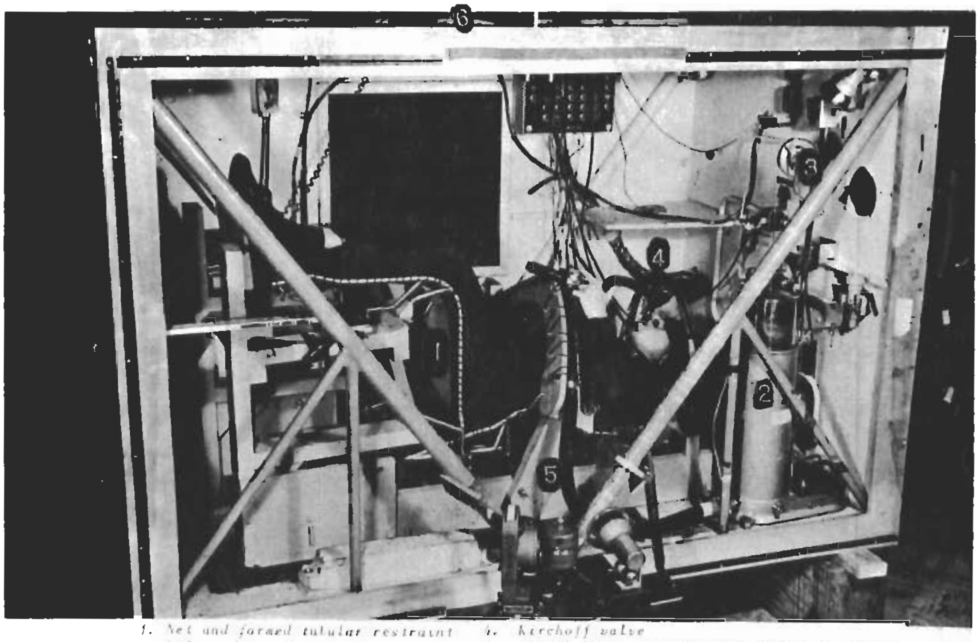
INTRODUCTION

This report stems from a recent opportunity to study the responses to different profiles of acceleration of a select group of 31 test pilots. The motivation of this group was quite high, as shown by repeated psychiatric interviews and a battery of clinical psychologic tests (ref. 1). The subjects were, in fact, frankly competitive. Their responses to headward and forward accelerations ($+ G_z$ and $+ G_x$) are compared (except for $+ G_z$ tolerance) to those of the volunteer panel of the 6570th Aerospace Medical Research Laboratories (AMRL) human centrifuge in a series of 141 separate centrifugations. The comparative cardiorespiratory responses of both groups are discussed. In addition, attempted correlation of these findings with extensive anthropometric data, indices of "physical fitness" and other variables is presented.

METHODS

Accelerative force was created by a centrifuge with a 22-foot radius. Subjects were positioned in the free-swinging cab that maintains the vector resulting from the gravitational attraction of the earth and centripetal acceleration perpendicular to the floor of the cab. An unconventional restraint system (ref. 2) was used, formed of contoured tubular frame and raschel net (figure 1) with adjustments designed for anthropometric fit of the 5th to the 95th percentile of USAF personnel.

Three separate profiles of acceleration were studied (figure 2). The sequence of presentation of these profiles was varied randomly. Although anti-G suits were not used, the subjects were permitted whatever straining maneuvers they were accustomed to use in order to prevent or delay blackout.



1. Net and forward tubular restraint
2. Balanced Benedict-Roth spirometer
3. Linear potentiometer
4. Kirchoff valve
5. Smooth-bore, semi-rigid 1 inch I.D. tubing
6. Center light task

Figure 1. Subject in Position on Free-Swinging Gondola of AMRL Human Centrifuge

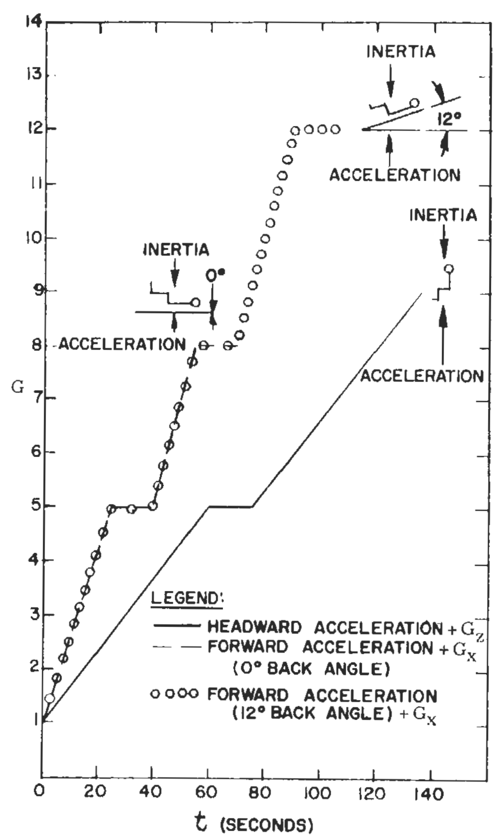


Figure 2. Acceleration Profiles

During headward acceleration (+ G_z) the subjects were exactly parallel to the inertial force (0°) with thighs flexed 90° on the trunk and knees flexed 90°. Subjects in the lowest percentile group required the use of urethane cushions to prevent excessive footward sink during acceleration. An arbitrary limit of headward acceleration was set at +9 G_z since the margin of difference between the levels of blackout and unconsciousness becomes small above +8 G_z. If blackout did not occur by +9 G_z the centrifuge stopped automatically. Blackout was recognized by failure to respond within 2 seconds to a central light signal offered at least every 4 seconds by an experienced central observer. The largest error possible therefore (assuming that blackout occurred immediately after answering the center-light) would be 6 seconds and would represent 0.40 G.

Two test series were run in forward accelerations (+ G_x). In one the subjects were perpendicular to the inertial force and in the other they were inclined 12° toward the direction of acceleration (figure 2).

The profiles of accelerations seen in figure 2 define the plateaus during which vital capacity and 0.5 second timed expiratory capacity were obtained. The control values for these maneuvers were established with the subject in position on the centrifuge some 3 minutes prior to centrifugation.

The expired air for these pulmonary function tests was collected in a specially balanced Benedict-Roth respirometer from which the carbon dioxide absorbent chamber had been removed. Displacement of the respirometer bell was transmitted to a multichannel recorder by a linear potentiometer coupled to the pulley of the respirometer bell chain. Respiratory rate was monitored by a mouthpiece thermistor just proximal to a Kirchoff valve (25-cc dead space). This tubing circuitry is shown in figure 1. Semi-rigid smooth-rubber tubing of 1 inch inside diameter was used throughout the expiratory circuit. The volume of this tubing was approximately 750 cc.

Electrocardiographic tracings were obtained from a modification of placement of the standard lead II and were both monitored and recorded continuously during each run. At the higher accelertions, above 8-10 G, myographic noise from the tense skeletal muscle mass caused interference that obscured the baseline of the electrocardiograms. Unfortunately the mechanisms of the arrhythmias which occurred at the higher G levels were masked by this interference, since at 10-12 G the P wave and even T waves were difficult to read with reasonable certainty.

RESULTS AND DISCUSSION

Headward Acceleration

Table I shows the response to headward acceleration of gradual rate of onset (1 G/15 seconds) in terms of blackout and pulse rates. Because gradual onset of acceleration, as used in this study, allows ample time for cardiovascular reflexes to compensate for the inertial insult to circulation (ref. 3), the mean blackout, +7.0 G_z ±1.2, was considerably higher than that usually found in + G_z acceleration. The range for blackout in the test pilot group extended from +4.7 to +9.0 G_z. Two of the test pilots reached this arbitrary cut-off point of +9.0 G_z without blacking out; a feat made more remarkable when one considers that anti-G suits were not used and the gradual onset of acceleration plus the vital capacity measurement kept these subjects above +5 G_z for 75 seconds of the 135 seconds required to reach +9 G_z. Tolerance to headward acceleration (+ G_z) was determined under different conditions in the centrifuge panel, so that comparison should not be made between the two groups. (The panel members were instructed to relax during acceleration; the test pilots were allowed to strain.)

TABLE I

RESPONSE TO HEADWARD ACCELERATION (+ G_z) OF GRADUAL RATE OF ONSET (1 G/15 SECONDS) IN TERMS OF BLACKOUT AND PULSE RATES

		+ G_z (Headward Acceleration)				+ G_x (Forward Acceleration)						
						0° Back Angle			12° Back Angle			
		Blackout (G)	Pre-run Control Pulse	5G Pulse (Beats/min)	Pulse at Blackout	Pre-run Control Pulse	5G Pulse	8G Pulse	Pre-run Control Pulse	5G Pulse	8G Pulse	12G Pulse
Pilots (N = 31)	Mean	7.0	104	160	175	87	108	107	87	111	111	118
	S.D.	1.2	18	24	21	16	14	15	14	17	15	21
	S.E.	0.2	3	6	4	3	3	3	2	3	3	4
Panel (N = 15)	Mean	5.5	109	166	174	99	116	131	93	121	125	121
	S.D.	0.9	14	16	15	17	19	21	17	18	16	22
	S.E.	0.2	4	4	4	5	6	7	5	5	5	8

S. D. = Standard Deviation
S. E. = Standard Error
N = Number of Subjects

No significant correlation was found to exist between the control pulse rate and the blackout level, the control pulse rate and the blackout pulse rate, or pulse rate at blackout and the blackout level. There was a real ($0.01 > P > 0.001$) but moderate correlation ($r = + 0.59$) existing between the control pulse rate and the pulse rate at +5 G_z. The mean increase from control to +5 G_z pulse rate was 35 ± 3 percent.

Brief, relative bradycardia associated with one or more extrasystoles occurred near peak acceleration (viz: blackout level) in 6 of 31 members of the test pilot group. One of the 15 centrifuge panel members had a single ectopic beat (not associated with a bradycardia) and a second member had intermittent sinus arrest. The incidence of arrhythmias resulting from + G_z accelerations found in this study may be low since the technical quality of the electrocardiograms at high accelerations occasionally did not permit detection of the P wave or the P-R interval. In addition, the arrhythmias reported here may be related to the unusually prolonged accelerations and to the slow rate of onset used.

Table II shows the effect of headward acceleration (+ G_z) upon the vital capacity and timed expiratory capacity. At +5 G_z the vital capacity is 55 percent of the control value for the test pilot group and 48 percent in the centrifuge panel group. The control 0.5-second forced expiratory capacity was 59 ± 13 percent for the pilots and 49 ± 14 percent of the control vital capacity for the panel members, but at +5 G_z there was no significant changes between either group (63 ± 19 percent and 64 ± 17 percent).

TABLE II

COMPARISON OF CARDIORESPIRATORY RESPONSES OF PILOT AND PANEL GROUPS

			$+G_z$	$+G_x$				
				0° Back Angle		12° Back Angle		
			5 G	5 G	8 G	5 G	8 G	12 G
PILOTS (N = 31)	Control Vital Capacity (Liters)	$\bar{x}$	4.00	3.75	3.75	3.70	3.70	3.70
		± SD	.48	0.45	0.45	0.48	0.48	0.48
	Experimental Vital Capacity (Liters)	$\bar{x}$	2.20	1.68	0.48	1.60	0.55	0.20
		± SD	0.41	0.43	0.37	0.53	0.43	0.22
	Control Forced Expiratory Capacity (0.5 sec., percent)	$\bar{x}$	59	59	59	55	55	55
		± SD	13	11	11	12	12	12
	Experimental Forced Expiratory Capacity (0.5 sec., percent)	$\bar{x}$	63	80	86	77	91	94
		± SD	19	18	26	20	13	13
PANEL (N = 15)	Control Vital Capacity (Liters)	$\bar{x}$	3.88	3.85	3.85	3.75	3.75	3.75
		± SD	0.73	0.58	0.58	0.57	0.57	0.57
	Experimental Vital Capacity (Liters)	$\bar{x}$	1.85	1.45	0.48	1.45	0.45	0.05
		± SD	0.68	0.33	0.45	0.43	0.40	0.08
	Control Forced Expiratory Capacity (0.5 sec., percent)	$\bar{x}$	49	50	50	53	53	53
		± SD	14	8	8	17	17	17
	Experimental Forced Expiratory Capacity (0.5 sec., percent)	$\bar{x}$	64	82	91	77	93	100
		± SD	17	16	24	16	3	0

$\bar{x}$ = Mean SD = Standard Deviation

Forward Accelerations (+ G_X)

Forward accelerations up to +12 G_X did not seem to present a serious cardiovascular challenge. Table I shows that only moderate increase over the resting (control) pulse rates occurred during forward acceleration. No clinically significant difference was found between the pilot group and the panel group, although the panel members tended toward consistently higher pulse rates in all situations, including the prerun "resting" control.

One of the test pilots had four extrasystoles and another had sudden bradycardia; all of this occurred at peak (+12 G_X) accelerations.

Dermksian and Lamb (ref. 4) have repeatedly emphasized the significance of the well established causal relationship existent between respiratory maneuvers and cardiac arrhythmias. Since all subjects vigorously performed forced expiratory capacities two or more times during each profile of forward (+ G_X) and headward (+ G_Z) acceleration, the relative lack of arrhythmias during these tests appeared a more provocative finding than their rare presence during this series. Fear of the vago-inhibitory reflexes previously held by the medical monitors at the AMRL centrifuge facility has been considerably attenuated as a result of this series as well as subsequent studies of acceleration characterized by repeated respiratory maneuvers (refs. 5, 6).

During forward acceleration, we are most interested in pulmonary responses since the primary limitation to + G_X (forward acceleration) is generally conceded to be respiratory distress of one sort or another. This distress is variable, and ranges from dyspnea through severe and limiting pain at various thoracic sites, characteristically being most intense during the inspiratory phase. No real difference in ventilatory capability during acceleration existed between the test panel used for such studies and the group of test pilots. Both groups showed comparable, although severe, reductions in vital capacity which was proportionately related to the magnitude of the accelerations (table II).

Also of interest was the lack of relationship found between the back angles of 0° and 12° and the volumes of air that could be moved during acceleration. Previously, a 25° back angle has been shown to strongly influence the rate of decrement of vital capacity during acceleration when compared with a 0° back angle (ref. 3). The present study showed that 12° does not influence vital capacity during forward accelerations up to +8 G_X when compared to 0° since no significant change was relatable to this variable (table II).

Correlation of Acceleration with other Variables

Because an unusually extensive anthropometric survey was made to characterize the test pilot group, and because their responses to other stress tests were concurrently studied, we expected that some anthropometric or other variable obtained without centrifugation might correlate with pulmonary performance and tolerance to both headward (+ G_Z) and forward (+ G_X) acceleration, thus providing selective criteria. For example, one might reasonably expect tolerance to + G_Z to relate directly to the difference in heart-to-eye height in a group of pilots of similar experience and proficiency. Regretfully, for prediction of performance would be a true convenience to all military surgeons, this was not found to occur.

Although 104 variables have been cross correlated for this group of 31 test pilots (ref. 1), only those correlations which are significant statistically ($r = 0.45$ when $N = 31$), or which bear interest by their lack of statistical significance will be presented. The following relationships are considered especially noteworthy and are charted in table III.

TABLE III

CORRELATION BETWEEN + G_x AND + G_z WITH VARIOUS INDICES

NOTE: ● connects variables with correlation coefficient (r) greater than +0.449, (or with N = 31, there is 99 percent confidence that this is not chance alone)

			Decrease in Vital Capacity at +5 G_z	Decrease in Vital Capacity at +5 G_x (0°)	Decrease in Vital Capacity at +8 G_x (0°)	Decrease in Vital Capacity at +5 G_x (12°)	Decrease in Vital Capacity at +8 G_x (12°)	Decrease in Vital Capacity at +12 G_x (12°)	Blackout Level - Positive + G_z
AMRL	Acceleration	Decrease in Vital Capacity at +5 G_z							
		Decrease in Vital Capacity at +5 G_x (0°)							
		Decrease in Vital Capacity at +8 G_x (0°)		●					
		Decrease in Vital Capacity at +5 G_x (12°)	●	●	●				
		Decrease in Vital Capacity at +8 G_x (12°)	●	●	●	●			
		Decrease in Vital Capacity at +12 G_x (12°)	●	●	●	●	●		
		Blackout Level - + G_z							
Lovelace Foundation	Clinical Examination	Vital Capacity			●	●	●	●	
		Maximum Breathing Capacity							
		Milliters Oxygen/Pulse							
		Lean-Body Mass	●						
		Protein-Bound Iodine							
		Resting Urine Sample Catacholamine							
AMRL	Anthropometric Indices	Cervical Height							
		Transverse Diameter of Chest							
		Transverse Diameter of Waist							
		A-P Diameter of Chest							
		A-P Diameter of Waist							
		Chest Circumference							
		Suprasternal Notch to the Waist							
		Cervical to the Waist							
		Lean-Body Weight							
		Sitting Height/Stature							
		Trochanteric Height/Stature							
		Chest Depth/Chest Breadth							
		Waist Depth/Waist Breadth							
		Hip Breadth/Chest Breadth							
		Present Weight							
		Stature							
AMRL	Thermal Stress	Pulse							
		Systolic Blood Pressure							
		Diastolic Blood Pressure							
		Weight Body Temperature							
	Physical Fitness	Tilt Table Test Score							
		Harvard Step Test Score							
		Flack Test Score							
		Valsalva Overshoot Test Score							
		Treadmill Test Score							
		Cold Pressor Test Score							

Of all the tests performed at other institutions or during exposure to other stresses, correlation existed primarily between vital capacity obtained during + G_X acceleration and vital capacity as established "on the ground" at the Lovelace Foundation. Vital capacity at +5 G_Z did not correlate with vital capacity at ground, but did correlate with lean body mass as determined at the Lovelace Foundation.

Hunter (ref. 8) also has unsuccessfully attempted to correlate what he termed "heart-brain distance" and sitting height against threshold to headward (+ G_Z) acceleration. He used a rate of onset of 1 G/10 seconds; this report used 1 G/15 seconds.

Kennedy et al (ref. 9), in a similar study that used 100 aircrew members as subjects, found no relation existent between blackout threshold and age, weight, body measurement, and response to tilt tests.

Because pulmonary responses to + G_X and + G_Z accelerations and pulse and blackout response to + G_Z accelerations bore no relationship at all to a variety of anthropometric indices, hemodynamic responses to heat stress, as well as most "physical fitness" tests that have ever been construed, we concluded that cardiopulmonary tolerance to acceleration can be determined only by actual measurement during such accelerations. Further, we all believe that the only selective value to such test accelerations as performed with the human centrifuge is that of negative selection. That is, if a subject is hemodynamically susceptible to acceleration (as would be manifest by a very low threshold to blackout or by acceleration induced serious cardiac arrhythmias) such susceptibility could be noted. However, the presence of reduced tolerance to acceleration is improbable in experienced test pilots whose very survival represents proof of relative hemodynamic integrity.

SUMMARY

A group of experienced test pilots and a group of nonrated centrifuge panel members underwent headward (+ G_Z) and forward (+ G_X) accelerations on a contoured net seat. No significant difference was found to exist in the responses of these two groups.

Two of the members of the test pilot group were able to reach +9.0 G_Z acceleration without the occurrence of blackout.

No correlation was found between pulse rate and blackout level. Correlation did exist between resting pulse rate and pulse rate at +5 G_Z.

Vital capacity decreased about 50 percent in both groups at +5 G_Z.

Forward accelerations up to +12 G_X caused little change in pulse rate and relatively few, minor, EKG abnormalities despite the concurrent performance of vigorous respiratory maneuvers.

Vital capacity decreased with increasing forward acceleration. A change in back angle from 0° to 12° did not significantly influence the rate of decrement in vital capacity. Half second forced expiratory capacity represented an increasing portion of total vital capacity as the forward acceleration increased.

Blackout tolerance during headward acceleration (+ G_Z) and respiratory performance during headward (+ G_Z) and forward acceleration (+ G_X) did not correlate with an extensive number (104) of anthropometric measurements and physical fitness tests nor was correlation found between + G_X and + G_Z acceleration responses and measurements made during other stressful situations.

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