The Duration of Tolerance to Positive Acceleration

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PREVIOUS studies of positive g (headward acceleration) have concerned, principally, exposure of the seated subject to forces generally limited to a few seconds in duration. Beyond this limit in time there is an area of acceleration tolerance remaining virtually unexplored, particularly that area involving accelerations of sub-blackout magnitude. The forces encountered in existing high performance vehicles as well as those anticipated in future rocket-propelled systems made imperative this investigation of man's ability to withstand low magnitude positive accelerations applied over relatively long periods of time.

METHODS

A group of eight young adult males varying widely in positive g tolerance was chosen from the trained volunteer centrifuge panel. Each subject was accelerated at levels of 3.0, 3.5, 4.0, 4.5, and 5.0 g, which were maintained until terminated by one of three reasons: (1) fatigue or blackout (loss of peripheral and central vision) of the subject; (2) appearance of cardiac abnormalities of rate or rhythm upon the electrocardiograms recorded continuously on all subjects; or (3) the attainment of a previously agreed upon arbitrary time limit which automatically concluded the experiment. The rate of onset of acceleration was 0.07 g per second, a slow rate chosen to allow time for the compensatory cardiovascular reflexes to be fully activated.[4,8]

Subjects to undergo positive acceleration* on the human centrifuge sit in a chair inside an enclosed passenger compartment at the end of the centrifuge arm. When the centrifuge is in motion this compartment, being freely movable, swings through an arc of 87 degrees, the top of the compartment tipping toward the center so that the long axis of the subject's body is parallel to the resultant vector of acceleration determined by gravitational attraction of the earth and the force generated by the centrifuge.

A first series of experiments was made without the subjects having protection of anti-G suits. Later, a selected number of experiments was duplicated with the subjects wearing anti-G suits, thus enabling duration of tolerance in the two situations to be compared. After each experiment an interval of time sufficient for complete

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*Positive acceleration is the generally accepted term used to describe acceleration in a headward direction with the corresponding inertial force then acting upon the subject in a caudal direction, head to foot.

recovery was allowed to elapse before another experiment was attempted.

The suit used in this study was the standard U. S. Air Force cutaway anti-G garment, type CSU-3/P. This suit, worn on the lower half of the body, incorporates five encased bladders, one over the abdomen and one each over the thighs and calves.

The experiments were made in darkness. The signal lights used to determine visual loss were similar to those described in a previous report.[6] The arbitrary limits decided upon for each g level were: one hour at 3.0 and 3.5 g, and twenty, ten, and four minutes at 4.0, 4.5, and 5.0 g, respectively.

A later series of experiments was made at 6.0 g, utilizing five of the original subjects and three others from the volunteer centrifuge panel. Anti-G suits were worn and a time limit of two minutes was placed on the run. The same slow rate of onset of acceleration as well as the same criteria for concluding the experiments as outlined above were used.

RESULTS

The data summarized in Table I present the various durations of tolerance at each level of acceleration by the eleven subjects used in this study. Included are the data from the separate series of experiments at 6.0 g.

TABLE I. DURATION OF TOLERANCE TO POSITIVE G (in minutes)

Subject	Level of G										
	Without G-Suit					With G-Suit					
	3.0	3.5	4.0	4.5	5.0	3.0	3.5	4.0	4.5	5.0	6.0
1	60′ AL	52′30″ Ft	20′ AL	8′17″ Bo	4′ AL	—	—	20′ AL	10′ AL	5′ AL	2′ AL
2	40′ Er	22′40″ Ft	4′ 5″ Ft	1′30″ Bo	2′50″ Bo	60′ AL	—	—	2′37″ Bo	4′ AL	—
3	45′ Er	26′ 4″ Ft	21′ AL	10′ AL	2′30″ Bo	—	40′53″ Ft	—	10′ AL	4′ AL	35″ Bo
4	60′ AL	23′45″ Ft	9′10″ Bo	6′40″ Bo	1′35″ Bo	—	24′ Ft	—	7′50″ Er	4′ AL	—
5	60′ AL	45′10″ Ft	20′ AL	9′ Er	4′ AL	—	22′20″ Ft	—	4′50″ Ft	4′ AL	1′ Ft
6	40′45″ Er	60′ AL	19′25″ Ft	11′ AL	4′ AL	—	60′ AL	—	10′ AL	4′ AL	—
7	60′ AL	14′25″ Ft	16″ Bo	3′20″ Bo	22″ Bo	60′ AL	—	12′35″ Ft	10′ AL	3′15″ Bo	1′45″ Bo
8	60′ AL	30′ Ft	3′30″ Bo	20″ Bo	23″ Bo	36′ Ft	—	—	3′35″ Bo	2′35″ Bo	30″ Bo
9	—	—	—	—	—	—	—	—	—	—	1′10″ Er
10	—	—	—	—	—	—	—	—	—	—	15″ Bo
11	—	—	—	—	—	—	—	—	—	—	45″ Bo

AL—Arbitrary limit Ft—Fatigue Bo—Blackout Er—Run stopped in error

Much of the centrifuge investigation of positive g accomplished previously has utilized loss of vision or blackout as the predominent endpoint. In this study at low accelerations of 3.0 and 3.5 g blackout did not occur. The experiment usually proceeded until either an arbitrary endpoint in time was reached or the subject could go no further because of general fatigue. At higher levels of acceleration, however, blackout became the limiting symptom. About half of the subjects experienced loss of vision prior to reaching the arbitrary cut-off points at 4.0, 4.5, and 5.0 g.

No limit of tolerance to 3.0 g could be reached within the sixty-minute arbitrary termination of the experiment. All subjects appeared able to tolerate an acceleration of 3.0 g for one hour, except one, whose run was halted in error at forty-five minutes. Two other subjects, similarly halted, completed this time in subsequent experiments: one subject tolerating an hour at 3.0 g in an anti-G suit which, as noted below, offers little advantage at low levels of acceleration, and the other, tolerating an even higher level of acceleration (3.5 g) for one hour.

This last-mentioned subject was the only one to complete the experiment at 3.5 g to the arbitrary limit of one hour. The seven other subjects in the study halted their runs after varying periods because of generalized fatigue and musculo-skeletal pain. The shortest duration of tolerance was fourteen minutes. The musculo-skeletal pain, confined principally to regions along the spine, was a continuous, dull, aching sensation. It was particularly severe in the neck and low back areas, increasing in intensity with time until the subject was forced to conclude the experiment.

In the 3.0 and 3.5 g runs, duplicated to compare the duration of tolerance with anti-G suits, no significant change in tolerance was observed. At 4.0 g three subjects were able to reach the arbitrary limit of twenty minutes; three more experienced blackout at sixteen seconds, three minutes thirty seconds, and nine minutes ten seconds, respectively, and two terminated the experiment because of fatigue, one subject stopping only thirty-five seconds short of the arbitrary limit due to feelings of warmth and nausea.

At 4.5 g only two subjects reached the cut-off point of ten minutes; one was stopped in error at nine minutes, and five experienced blackout. The shortest run to blackout was twenty seconds. At 5.0 g three subjects reached the limit of four minutes while five experienced blackout, the shortest duration being twenty-two seconds.

In the 4.5 and 5.0 g runs, duplicated with the subjects wearing anti-G suits, the results indicated that tolerance could be prolonged in those subjects who had experienced blackout in the non-suit runs at the same levels. Three of the five subjects who experienced blackout at 5.0 g were able to continue to the arbitrary limit of four minutes with no difficulty and the remaining two had their duration of tolerance to blackout greatly prolonged. The anti-G suit appears to lengthen tolerance time only in those higher g experiments where blackout is a problem. The garment is uncomfortable when worn inflated for long intervals; hence, during the longer low g runs in which the subjects stopped because of fatigue and not blackout, the anti-G suit contributes little if anything to tolerance and may in some cases actually constitute a negative influence.

In the series of experiments at 6.0 g, all runs were made with anti-G suit protection. Only one subject reached the arbitrary limit of two minutes; another stopped at one minute because of the severe discomfort of his anti-G suit, and the other six subjects experienced blackout. The shortest duration to blackout was fifteen seconds.

The experiments were exhausting ones for the subjects, particularly the long low g runs. Each subject required from one to three hours to recover from post-run symptoms of malaise and dizziness. No abnormalities of cardiac rhythm were observed in the continuous electrocardiograms taken on each subject. Pulse rate showed large variation however. Usually the rate increased at the start of centrifugation although there were some subjects who did not demonstrate this increase. At 3.0 g most subjects maintained rates between 80 and 90 beats per minute. This low level of acceleration incited little marked increase in the pulse rate during the sixty-minute time limit placed on the experiment.

At acceleration levels of 3.0 to 4.0 g some subjects maintained lower pulse rates during the later portion of the experiment than they reached during the initial phase of acceleration. In this instance the pulse rate increased until the centrifuge reached peak acceleration, proceeding then to decrease to a level which was maintained until the experiment was terminated. There appeared to be no correlation of pulse rate with blackout. Some subjects experienced blackout with rates as low at 112 per minute while other subjects were able to maintain vision with rates as high as 196 per minute.

At high acceleration levels of 4.0 to 6.0 g, a gradual increase in pulse rate was usually seen as the acceleratory stress was prolonged. Occasionally, however, a subject would maintain a low rate of 100 to 110 per minute even after four minutes at a 5.0 g acceleration. Petechiae, rare below 3.5 g, were increasingly common at higher levels, appearing in dependent parts of the body, particularly about the ankles, elbows, and forearms. The petechiae were more numerous after the subject wore an anti-G suit, and were located in areas distal to the inferior border of the compressing bladder.

DISCUSSION

Because the cardiovascular system is adapted for the force of 1 positive G (gravitational attraction) any change in this force upsets the mechanisms controlling homeostasis. The effects resulting from an increase in positive acceleration have been fully described in the literature as early as 1937.[1] The progression of symptoms—loss of peripheral vision, loss of central vision (blackout) and unconsciousness—is well known. Failure of an adequate blood supply to the retina and to the brain is generally agreed to cause blackout and unconsciousness with increasing magnitude of acceleration.

The average blackout level for accelerations of rapid onset (rates of 1 g per second or greater) has been determined by most studies to lie somewhere between 3.5 and 4.0 g. Gradual rates of onset such as the one used in this study, which provide time for the cardiovascular reflexes to compensate for the increased acceleration, afford an increase in the average blackout level in the order of 2.0 to 2.5 g.[5,7]

In this study none of the subjects experienced blackout at low acceleration levels of 3.0 and 3.5 g even with exposures as long as an hour, a fact clearly indicating the cardiovascular reflexes were adequate to maintain sufficient blood pressure to the head despite the continued stress. It was conceivable that with acceleration continuing over a long period, circulatory embarrassment and blackout might occur, perhaps as a result of a progressive decrease in circulating blood volume, or from fatigue or adaptation of vasoconstrictor reflexes, but no evidence of such decompensation was seen within the time limits investigated. Instead of blackout, generalized fatigue and pain supervened to limit the duration of these low g experiments. Apparently musculoskeletal in origin, the pain—a continuous, dull aching sensation, located particularly in the muscle groups along the spine—gradually increased in intensity and necessitated termination of the experiment. Some temporary relief could be obtained by various postural maneuvers (squirming) on the part of the subject, but with time the discomfort became of such intensity that the subject could no longer tolerate its continuance.

The subjects complained particularly of cervical pain, located in the region of the first and second cervical vertebrae. Anterior and posterior, as well as rotational movements of the head, did little to relieve this pain. The low back area was another region where pain localized for many of the subjects. Pain in the lower extremities, however, was a complaint made less often than one might have expected. Some tingling sensations about the ankles were the only observations of note.

After centrifugation, there were no overt signs of a fluid shift into the dependent tissues. Previous investigation has indicated that there is some decrease in the volume of circulating plasma as evidenced by hematocrit changes during centrifugation.[3] Certainly some escape of fluid from the vascular bed seems likely; however, it does not appear to be progressive. Evidently a new dynamic equilibrium is rapidly achieved between the increased hydrostatic effect in the blood vessels and those forces in the immediate tissue environment, which tend to move fluid back into the vessels.

Continuous electrocardiograms were recorded on all subjects. The report of Zuidema and his associates,[10] who found cardiac abnormalities occurring in four of five subjects exposed to prolonged accelerations in the magnitude of 5.0 g for one minute, made this aspect of the study particularly interesting. In none of the electrocardiographic tracings of the eleven subjects, who made a total of seventy-three runs with accelerations as high as 5.0 g for four minutes and 6.0 g for two minutes, did there appear evidence of an abnormal cardiac rhythm. The incidence of arrhythmias during prolonged acceleration does not seem as high as previously estimated.

The effect of acceleration upon cardiac rate, however, proved extremely variable; so much so that in selection of personnel who might be best suited to undergo stress situations of this nature it would be difficult to assign great significance to the reaction of the pulse rate to the stress of acceleration. Usually the pulse rate rose gradually with increasing duration of acceleration; especially was this observed in the higher g experiments of 4.0 to 6.0 g. The phenomenon of blackout concluded approximately one-half of these experiments prior to attainment of the arbitrary time limit. At the time of blackout the pulse rate generally had reached its highest point. Yet in some, blackout occurred at a time when the subject had a relatively low pulse rate (112 per minute), a pulse rate that had decreased from a previously higher point; whereas in others, vision was maintained even while the pulse rate rose to alarming heights (196 per minute). In the first case one might be tempted to conclude that the subjects who experience blackout with low pulse rates have cardiovascular systems with reflexes less responsive than those subjects who maintain good vision and have concurrently higher pulse rates.

If this is true how is one then to choose between two subjects, one of whom has a lower pulse rate than the other, while both undergo the same acceleration with seemingly the same results? If both do equally well, and one has a lower pulse rate, could not a conclusion be that his cardiovascular system has compensated for the acceleration with less effort than the subject who has a higher rate? Would it then be safe to suppose that the subject with the lower pulse rate is the more superior physically of the two? Obviously we do not have the evidence to support either view. In any event it may be stated that correlation between pulse rate, physical fitness, and blackout will be difficult to prove. This is in agreement with the findings of Zarriello and his co-workers.[9]

Another report[8] in the literature has cited the occurrence of "residual damage to vision" in a subject who experienced blackout during a run of 5.0 g for three minutes. The authors do not state how long the subject was in blackout. No visual damage has thus far been observed in our subjects, nor would any damage have been expected as the retinas was not ischemic for more than momentary periods. The centrifuge was stopped immediately at the onset of blackout.

The most favorable position in which to tolerate prolonged high accelerations has been shown to be a position transverse to the vector of acceleration.[2] In this position the prospect of blackout is greatly decreased, or at least a wider latitude of acceleration is provided before loss of vision supervenes. However, it is clear that if the acceleration be kept below 3 g the position of the body in headward acceleration is not entirely unfavorable. It is also readily apparent that low accelerations maintained for long periods of time allow the attainment of high linear velocities. For example, a rectilinear acceleration of 3.0 g for one hour (a force-time period similar to that experienced in this study) would result in a final velocity of 235,000 miles per hour, almost ten times escape velocity.

SUMMARY

Human tolerance to prolonged positive accelerations of sub-blackout magnitude has been investigated in eleven subjects who made a total of seventy-three runs on the human centrifuge at g levels of 3.0, 3.5, 4.0, 4.5, 5.0, and 6.0. A gradual rate of onset of acceleration was used (0.07 g per second). At low accelerations of 3.0 and 3.5 g a sharp limit of tolerance could not be reached within the design of the experiment. All subjects ap-

peared able to tolerate an acceleration of 3.0 g for one hour with no ill effect beyond fatigue and a certain amount of post-run malaise. Loss of vision (blackout) limited approximately one-half of the high g experiments (4.0, 4.5, and 5.0) but three of eight subjects were able to tolerate 5.0 g for four minutes without experiencing blackout. The anti-G suit effectively prolonged tolerance to blackout in low g tolerance subjects, but even the benefit of g protection did not allow all low g tolerance subjects to perform as well as do high g tolerance subjects without the protection of anti-G suits. Except for tachycardia no abnormalities were observed in the continuous electrocardiograms recorded on all subjects. Man apparently is able to withstand the forces of positive g for durations much longer than previously supposed.

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Family Doctor of the Flyer

Only through close personal association can the flight surgeon influence those factors which will prevent the conditions that are the causes of suspension and noneffectiveness. The flight surgeon, to successfully accomplish his mission, must have knowledge of the housing condition, living habits, and emotional problems of the flying personnel and their families. These are all interrelated, one to the other, and to flying effectiveness. Much of the job of the flight surgeon depends on his capability as a sympathetic advisor and educator rather than the actual practice of clinical medicine. However, in fulfilling his function as an advisor and educator, a broad and comprehensive knowledge of medicine is absolutely essential.—USAF Medical Service *Digest,* Jan., 1956.