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NASA Technical Memorandum 104753

Issues on Human Acceleration Tolerance After Long-Duration Space Flights

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October 1992

NASA

(NASA-TM-104753) ISSUES ON HUMAN ACCELERATION TOLERANCE AFTER LONG-DURATION SPACE FLIGHTS (NASA) 55 p

N93-29651

Unclas

G3/52 0176442

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SUMMARY

This report reviewed the literature on human tolerance to acceleration at 1 G and changes in tolerance after exposure to hypogravic fields. It was found that human tolerance decreased after exposure to hypokinetic and hypogravic fields, but the magnitude of such reduction ranged from 0% to 30% for plateau G forces and 30% to 70% for time tolerance on sustained G forces. A logistic regression model of the probability of individuals with 25% reduction in +Gz tolerance after 1 to 41 days of hypogravic exposures was constructed. The estimated values from the model showed a good correlation with the observed data (r=0.99; p-value for goodness-of-fit=0.58), and the model was as below:

$$\text{Probability of 25\% reduction in +Gz tolerance after Hypokinesia} = \frac{e^{0.295 + 0.076\,(\text{Duration of Exposure})}}{1 + e^{0.295 + 0.076\,(\text{Duration of Exposure})}}$$

A brief review of the need for in-flight centrifuge during long duration missions was also presented. Review of the available data showed that the use of countermeasures (such as anti-G suits, periodic acceleration, exercise) reduced the decrement in acceleration tolerance after long duration space flights. Areas of further research include quantification of the effect of countermeasures on tolerance, and methods to augment tolerance during and after exposures to hypogravic fields. Such data are essential for planning long duration human missions.

I. INTRODUCTION

Acceleration occurs whenever there is a change in the velocity and direction of motion of a body. The physiologic responses to altered acceleration fields limit man's exposure to acceleration. A great deal of research was conducted on human tolerance levels before 1960, and the physiologic effects of acceleration on the human body have been summarized in various monographs (9, 15, 18, 19, 36).

The proposal of long term space flights to Mars and beyond (44) has provided a renewed interest in the various issues related to human acceleration tolerance. The ***objective*** of this report is to provide the designer of spacecraft systems with a summary of available information on human acceleration tolerance, and to outline areas where research is needed, before extrapolating these results to long term space flights. Detailed information on several of these issues is available from many sources referenced throughout this report.

II. ACCELERATION

A. TERMINOLOGY

Acceleration is a vector quantity with both magnitude and direction, denoting rate of change of velocity. It is possible to distinguish between various accelerations:

- ***linear accelerations***, when the direction of movement is constant and there is change in the velocity of a mass
- ***radial accelerations,*** when the direction of movement changes
- ***angular accelerations,*** when the axis of rotation passes through the body.

However, accelerations often occur due to several forces acting on a moving body, resulting in composite accelerations (e.g. coriolis phenomena). The acceleration applied should be considered with respect to the following:

- ***axis*** of acceleration
- ***magnitude*** of accelerations
- ***rate of onset*** and ***time duration*** for which they are applied
- ***site*** and ***area*** of application

The nomenclature for the various terms used in this report is given in Table 1, and follows widely accepted terminology (also refer to Fig. 1).

The body is considered to be a fluid-filled, hydraulic system responding to changes in acceleration fields, and limiting human tolerance. Generally, accelerations acting greater than 60 msec are called ***sustained*** accelerations, while those below 60 msec are called ***transitory*** accelerations or impact.

B. EFFECTS OF LINEAR ACCELERATION

The following is a brief description of the effects of acceleration fields on the human body. Detailed reports are available in a number of references (6, 8, 9, 16, 18, 19, 36).

1. Positive Gz

The effects of upward acceleration are primarily due to the hydrostatic pressure changes in the cardiovascular system. Under +1Gz, the heart-brain distance is approximately 30 cm and this column of fluid exerts a hydrostatic pressure of 22 mmHg. With each additional +Gz, the blood pressure at the brain level is reduced by 22 mmHg and at the foot level is increased by 55 mmHg. The effects of +Gz are limited by visual symptoms and loss of consciousness. The common symptoms due to +Gz are listed below:

+1 Gz	Erect/seated terrestrial posture
+2 Gz	Increase in weight; increased pressure on the buttocks, drooping of face and soft body tissues; movement against acceleration is difficult
+3 to 4 Gz	Difficult to raise arms and legs; impossible to rise; Dimming of vision after 3-4 sec; progressive tunneling of vision; arterial oxygen saturation falls to 93% ; unaided escape from aircraft impossible
+4.5 to 6 Gz	Progressive blackout after 5 seconds; hearing and then consciousness lost if continued (G-induced loss of consciousness [G-LOC]); mild to severe convulsions in about 50% of subjects during or following unconsciousness, frequently with bizarre dreams; occasionally parasthesias and confused states; widening of arterio-venous oxygen differences; tension and congestion of lower limbs with cramps and tingling; transient loss of orientation post-acceleration; difficult to hold feet on rudder pedals; at +8 Gz, body and limbs cannot be lifted above.

The effects of G-LOC vary depending on the ischemic/hypoxic insult to the central nervous system. It is dependent on rate of onset of +Gz, peak levels attained, length of time at peak, offset rate and individual tolerance to +Gz (43).

Exposure to high +Gz, and repeated exposures to +Gz are very fatiguing (6, 11). Microtrauma including petechial hemorrhages, scrotal hematoma, hernia, cardiac dysrhythmias, pneumothorax and vertebral body compression fractures have been seen after +Gz exposures (6). Tolerance to +Gz could be increased by physiologic techniques like centrifuge training, protective straining maneuvers (such as M-1 and L-1), positive pressure breathing, and mechanical devices like tilt-back seat, and anti-G suits (11, 19, 36).

2. Negative Gz

Response to -Gz are hydrostatic in nature and human tolerance is considerably lower, compared to +Gz (18, 36).

-1 Gz	Sense of pressure and fullness in the head; congestion of eyes
-2 to -3 Gz	Throbbing headache, edema of eyelids; petechial hemorrhages in the face and neck; bradycardia; redout due to conjunctiva pulled up over eyeball
-4 to -6 Gz	Seldom tolerated beyond 6 seconds; causes mental confusion and unconsciousness

Initially during -Gz acceleration, the arterio-venous oxygen difference is maintained, but with increasing loads and headward fluid shift, increased carotid sinus pressure causes bradycardia and fall in arterial pressure, while venous pressure is still maintained. This results in fall of arterio-venous oxygen difference, leading to the tolerance limiting symptoms such as confusion and unconsciousness.

3. Positive Gx

Forward acceleration is primarily limited by respiratory problems, although minimal hydrostatic effects persist. In general, human tolerance to gravitational/inertial forces in the transverse direction are much higher than other axes (19, 36).

+1 Gx	Slight increase in abdominal pressure; respiratory rate increases
+2 to 3 Gx	Difficulty in spatial orientation; 2 Gx tolerable up to 24 hours
+3 to 6 Gx	Mechanical compression of the chest wall; progressive tightness of chest; difficulty in breathing; reduction in pulmonary volumes; blurring of vision; difficulty in speaking; extrasystoles and cardiac rhythm disturbances

+6 to 9 Gx	Body and limbs cannot be lifted at +8 Gx; head cannot be moved at +9 Gx; blurring and tunneling of vision; decreasing oxygen uptake during acceleration; pulmonary vascular pressures increase towards the dorsal part of chest and fall in alveolar pressure on the ventral part; arterial oxygen saturation falls below 85%;
+9 to 12 Gx	Reduced peripheral vision and dimness of central vision; ventilation-perfusion inequalities in the lungs increase further;
> +12 Gx	Breathing extremely difficult; pain in the chest; loss of vision

4. Negative Gx

The response to backward acceleration are similar to +Gx, but the respiratory problems are less severe. The hydrostatic effects that occur in +Gx are reversed (19).

-6 Gx	No deterioration of lung vital capacity; blurring of vision, probably due to mechanical effects
-8 Gx	Bradycardia and other cardiac arrythmias; abundant lacrimation; restraint of human body difficult; Position of head influences the hydrostatic effects

5. Positive/Negative Gy

Very little work has been done regarding the effects of +/-Gy forces. Petechiae and hemorrhages in the dependent limbs occur around +/-5 Gy (19).

C. EFFECTS OF RADIAL/ANGULAR ACCELERATION

The physiologic changes associated with combined accelerations are primarily due to hydrostatic pressure differences along the various axes. They are commonly encountered in spinning and tumbling, during escape ejections from aircraft or free-fall from heights. The effects of these combined rotary accelerations are dependent on the following:

- ***Axis*** of rotation
- Position of the ***center of rotation***
- ***Rate of rotation***

Movement of the center of rotation towards the head, increases the effects of +Gz, while movement towards the feet increases the effects of -Gz.

Depending on the center of rotation, various magnitudes of positive and negative G result along the different axes. Under such conditions, the pooling of blood in dependent portions of the body are responsible for the various symptoms resulting from these forces (17, 47).

1. Slow Rotation (1 to 15 rpm)

Most individuals can tolerate rotation rates up to 6 rpm in any axis without any untoward effects. Increases in heart rate follow the rate of rotation, but arrythmias are generally not seen. Evidence of performance decrement is apparent in some individuals even at rotational rates of 6 rpm. At rates above 6 rpm, arterial oxygen saturation begins to fall, probably due to pulmonary ventilation-perfusion inequalities during combined Gy/Gz acceleration. The fall in arterial oxygen saturation leads to disorientation at these rotational rates.

2. Moderate Rotation (16 to 60 rpm)

Rotation rates of 60 rpm around the pitch axis (y-axis) and yaw axis (z-axis) are tolerable up to 4 minutes.

3. Severe Rotation (>60 rpm)

During combined Gy/Gz accelerations, effects of +Gz are prominent above rotations of 60 rpm at the heart level and intolerable above 120 rpm. Spatial disorientation, headache and nausea are increasingly apparent. With the center of rotation at the iliac crest, unpleasant symptoms of -Gz are evident at 70 rpm. Pain and discomfort are evident at rotations above 80 rpm, largely because of swelling of tissues. At rates of 160 rpm, unconsciousness would result after 3 to 10 seconds, when the center of rotation remained at the heart level, or around 180 rpm when the center of rotation occurred at the iliac crest. Bradycardia, EKG abnormalities and petechial hemorrhages are evident at these rapid rates of rotation. Rates of rotation above 195 rpm are associated with frank bleeding in experimental animals.

Another major effect of ***angular acceleration*** is on the vestibular system, resulting in nystagmus, nausea and symptoms of motion sickness (21).

D. EFFECTS OF TRANSIENT ACCELERATIONS (IMPACT)

Short duration accelerations are encountered in crash, parachute opening, landing and free-fall situations. The severity of injuries with short term, transient accelerations on humans are dependent on the magnitude, duration and axis of impact. In addition to the various factors mentioned in section 2.1., the effects of transient accelerations are also influenced by the type and method of body restraint .

Human tolerance to impact improves when the contact area between the restraint system and body is greater (14,15). In the absence of proper restraint, whipping and submarining injuries of the spinal column are encountered (14). The injuries sustained during impact are highly variable – tolerable, debilitating or traumatic. Various studies have shown that injury of extremities, unconsciousness, dislocation, compression fractures of the spine, multiple fractures, and life-threatening injuries occurred with impact (15,19,38,41).

Impact injuries due to ***free fall*** are dependent on the height of the fall, orientation of body at impact, area and distribution of forces and duration of impact (38, 40, 41). In general, head-first (-Gz) or feet-first (+Gz) impact on water provide greater chances of survival compared to lateral (Gx/Gy) impacts. Majority of survivals after impact at terminal velocity (53.6 $m.sec^{-1}$ or 175.8 $ft.sec^{-1}$), occurred after falls into water or snow (39). The rate of onset of G and duration of G are very important in determining the survivability of such impacts. Following is a summary of physiologic effects:

Impact force	Effects
5 to 15 +Gx, 12 +Gy	Bradycardia
>15 +/-Gx, +Gy	Faint, pallor
>16 +Gz/-Gx	Vertebral compression fractures
>20 -Gx	Shock, involuntary movements

III. HUMAN TOLERANCE LIMITS

The term "physiologic tolerance" implies no debilitation or traumatic injury to the individual. However, it is not possible to provide accurate and proven figures for such limits. Many of the investigators use the information from animal experiments to extrapolate the data, where none is available (15, 18, 36).

A. TOLERANCE TO LINEAR ACCELERATION

There are several factors which influence the tolerance to sustained linear acceleration along the various axes. Detailed information on these factors are readily available from several monographs (8,15,18,19,36). Since the tolerance to acceleration is probably nonlinear with time, the limits specified by Fraser (18) from observed data serve as a general guideline (Fig. 2).

The rate of onset of G influences the total time on peak acceleration before manifestation of symptoms. This is illustrated by the curves on human tolerance to +Gz in Figure 3. The tolerance to +Gx as a function of seat back angle is given in Figure 4.

B. TOLERANCE TO RADIAL/ANGULAR ACCELERATION

Human tolerance to rotational acceleration, with the center of rotation at the heart level and iliac crest (hip bone) are given in Figure 5a, and allowable tumbling rate around the pitch axis in Fig. 5b, respectively. It is estimated that unconsciousness would occur at 160 rpm at the heart level and 180 rpm at the iliac crest after 3 to 10 seconds (38, 47).

There is extreme variability with regard to perception of angular motion, ranging from 0.035 $deg \cdot s^{-2}$ to 8.2 $deg \cdot sec^{-2}$ in humans (10). There is a time lag between perception of angular acceleration and response (e.g. nystagmus). The relationship between angular acceleration and time for which it is tolerable is log-linear (17).

C. TOLERANCE TO IMPACT ACCELERATION

Impact tolerance curves given in Figures 6 through 10 are that of seated and well-restrained individuals. Eiband proposed impact tolerance curves in 1959 based on both animal and human exposures, and it is interesting to note that no new information has been added to these curves (15). These curves were based on tolerance along each axis separately. Using such observed data, single-degree-of freedom tolerance indices have been generated for spine, head and chest. These mathematical models include Wayne State curves, Dynamic Response Index, Gadd's Severity Index, and Effective Displacement Index (12). The Dynamic Response Index (DRI) model was recently used to estimate the probability of compression fractures in the lower spine due to upward acceleration, and in the design of ejection seats (4, 14). Further efforts are under way to incorporate complex whole-body accelerations along each orthogonal axis in a single ***Dynamic Response*** (DR) model (4, 5, 14). Preliminary design criteria for acceleration exposure limits using this model have also been published for low, moderate, and high risk of injury (4, 5). This method merits further follow-up and could be used in design criteria for impact limits of space vehicles, as well as escape devices. However, due to the preliminary nature of this work, and the limited verification on humans, it is not considered further in this paper.

Few experiments have been conducted on off-axis impacts and combined accelerations (29, 35, 38, 42). These results indicate that off-axis impacts of 20 G could be tolerated up to 60 msec (38, 42). Experimental information on free-fall impact is also very limited and much have been obtained from analysis of accidents. Human free-fall water impact velocities were survived as below (38, 39):

-Feet-first (+Gz axis): up to 35.4 $m \cdot sec^{-1}$ (116.1 $ft \cdot sec^{-1}$)
-Head-first (-Gz): 29.6 $m \cdot sec^{-1}$ (96.1 $ft \cdot sec^{-1}$)
-Supine (+Gx): 28.4 $m \cdot sec^{-1}$ (93.2 $ft \cdot sec^{-1}$)
-Prone (-Gx): 26.8 $m \cdot sec^{-1}$ (87.9 $ft \cdot sec^{-1}$)
-Laterally (+/-Gy): up to 26.5 m·sec-1 (86.9 $ft \cdot sec^{-1}$)

Terminal velocity (53.6 $m \cdot sec^{-1}$) impacts on snow have been tolerated without serious injuries by humans (39).

IV. ACCELERATION ENVIRONMENTS IN SPACE

A. ACCELERATION STRESS DURING SPACE FLIGHT

During space operations, **linear accelerations** may be encountered during the following operations:

- launch
- entry
- abort
- transorbital flights
- on land (earth, moon, Mars)

Angular accelerations may occur during the following:

- orbital maneuvers, extravehicular activities
- launch, entry, abort operations
- on land (earth, moon, Mars)

Impact accelerations may occur during

- escape (ejection seats)
- landing (crash, parachute opening)
- on land (earth, moon, Mars)

These levels do not include the low G levels seen on Moon (approx. 0.17 G), Mars (approx. 0.38 G) and during interplanetary travel (approx. 10^{-3} to 10^{-6} G).

The following sections describe the factors influencing the acceleration loads and levels seen in the past and present U.S./Soviet space missions (22, 23, 34, 45).

B. ACCELERATION LEVELS - PAST AND PRESENT

1. Effective Physiologic Angle

In addition to the various individual factors affecting acceleration tolerance, crew vehicle design and orientation also influence the magnitude of such forces on the members. Human tolerance to acceleration is greater in the transverse axis, compared to upward or downward. The tolerance to acceleration in space flights is increased by providing an inclined seat back, thereby reducing the Gz vector and increasing the Gx vector. The term ***"Effective Physiologic Angle"*** (EPA) is used to indicate the sum of the seat angle, aorta-retina angle and the angle between the acceleration vector and vertical line of spacecraft (Fig. 11a). An EPA of 8 to 12 degrees (Fig. 11b) is considered to be optimal to reduce the effects of +Gz component during space flight (3, 45).

2. Launch

In order to place a rocket into orbit about 200 Km (125 miles) above the Earth, a velocity of about 8.0 Km·sec^{-1} (4.97 miles·sec^{-1}) is required (19, 22). In the Mercury-Atlas and Gemini projects, two major peaks of 6.4 G for 54 sec and 6 G for 35 seconds in the +Gx axis were encountered during launch (Fig. 13a). The liftoff accelerations in Apollo and Skylab programs were around 4 G (Fig. 14a), while that of the Space Transportation System (STS) were around 3 G (Fig. 15a), considerably lower than the initial flights.

3. Re-entry/Landing

The re-entry accelerations are generally greater than launch operations and depend on the re-entry angle of the spacecraft (Fig. 12). By reducing the angle of entry to less than 1 degree, the peak acceleration attained during this phase of space flight could be reduced (19, 45). The re-entry accelerations were in the range of 7.6 to 11.1 +Gx in the Mercury, 4.3 to 7.7 +Gx in the Gemini projects (Fig. 13b), and 3.3 to 6.8 +Gx in the Apollo (Fig. 14b), with slightly higher values during lunar missions. Due to its unique re-entry profile, the acceleration in the STS is 1.2 +Gz for a period of 17 minutes (Fig. 15b).

The landing forces in the Mercury spacecraft were considered to be higher, and were reduced from about 50 +Gx to 15 +Gx by adding air cushions. The landing impact forces in the Apollo ranged from 6 to 8 +Gx. The maximum impact landing force in the STS is estimated to be about 6.8 +Gz. The Soviet re-entry profiles yielded 8 to 10 +Gx during the earlier Vostok missions, and 3 to 4 +Gx during the Soyuz missions (22). Emergency systems were designed to provide less than 20 +Gx during the escape sequences for brief periods in the U.S./Soviet missions.

C. THE FUTURE - LONG DURATION SPACE MISSIONS

1. Mission Profiles

The **Space Exploration Initiative (SEI)** describes various design options and opportunities for interplanetary space flight, including return missions to the Moon and exploration of Mars (44). In earlier missions, the Apollo crew traveled to the moon in three days and the delta-v (velocity change for the spacecraft) for the trip averaged 5.6 Km·sec^{-1}. The delta-v for a Mars mission is expected to be approximately in the range of 8.2 to 24 Km·sec^{-1}. Exactly similar launch opportunities to Mars would occur only once in every 15 years, due to the orbital planes of the Earth and Mars. Further, the entry velocities are expected to be >13 Km·sec^{-1} during Mars entry, considerably greater than Apollo entry velocities. The various possibilities envisaged for a Mars mission are one of the following (44):

- ***Long Duration Mission:*** The mission trip duration is of the order of 1,000 days, with a typical stay time of 500 days at Mars.

- ***Short Duration Mission:*** Typically of 500 days total trip time, with a 30 to 100 day stay at Mars.

The SEI Synthesis Report outlines that, by reducing the trip time, the hazards of space radiation and long duration exposure to hypogravic conditions could be minimized (44). This report does not advocate the use of an in-flight centrifuge, and forecasts that reduced trip times are possible by incorporating advanced designs in the launch vehicles. Long duration missions involving 1000-day trip times are possible with existing technologies. However, it would require extensive research and development of rocket technology to achieve shorter trip times to Mars.

2. Concerns for Acceleration Tolerance

The acceleration tolerance levels discussed in earlier sections are applicable only to unit gravity conditions of the Earth. The major concerns for human tolerance to acceleration forces during, and on return from, long duration space flights are

- The effects of altered ***gravitational conditions*** on the Moon (0.17 G)/Mars (0.38 G)
- The effects of exposure to long periods of time spent under ***hypogravic conditions of interplanetary travel***

Although short-duration exposures to hypogravic conditions have not produced significant reduction in human acceleration tolerance, the effects of long exposures are not clear.

If man is considered predominantly to be under the influence of 1 +Gz on Earth, then the reduced gravity under space flights could be considered as a continuum of that state (36, 37, 45). Under such assumptions, it is understandable that the ***physiologic changes associated with hypogravic states are similar to that of -Gz***. The headward fluid shift, facial suffusion, and altered baroreceptor mechanisms (23, 34) all provide evidence to the above hypothesis. The similarity between the physiological changes with nominal levels of -Gz and that of hypogravic conditions need to be examined further.

Some work has been done on the effects of hypergravic fields applied for a long duration of time (called ***"chronic acceleration"***) on animals (37, 45). Smith refers to the pathophysiologic states associated with chronic acceleration as ***"acceleration sickness"*** (35). Animals exposed to low intensity accelerations (1-1.5 G) showed relative increases in proportional body size, mostly skeletal size, and increase in extensor muscle groups after exposures for 6 months. The maximum work capacity was three-fold greater in these animals, compared to controls. Chronic hypergravic stimulation also increased metabolic requirements and feed intake. The acceleration tolerance so acquired was only lost slowly, over a period of 3-6 months, on return to unit gravity (37, 45). These results have been used as evidence for positive effects of hypergravic fields on the detrimental effects of hypogravic fields seen in space flight (7, 30, 36, 37, 50).

D. ACCELERATION TOLERANCE AFTER EXPOSURES TO HYPODYNAMIC CONDITIONS

Early experimenters evaluated tolerance to headward acceleration after a short duration (6 to 24 hours) of water immersion. They found a small (0.50 to 0.62 G), but significant reduction in human tolerance to +Gz after water immersion (1, 2, 20). Tolerance to +Gx accelerations (similar to Gemini profile) was determined on individuals bed rested for 2 weeks and 4 weeks in another study (28). Although these levels were tolerated, there was 38% increase in heart rate. Visual symptoms at peak +Gx were similar to that of pre-bed rest runs. However, tolerance to +Gz was reduced with gradual onset rates and cardiac arrhythmias were also noted.

A preliminary study by White et al. examined the therapeutic effects of intermittent +Gz acceleration on post-bed rest acceleration tolerance (50). This study administered 68 minutes of physical exercise and 45 minutes of centrifuge exposures to either +1Gz or +4 Gz for 45 minutes every day during the second half of a 41-day bed rest. There was no significant difference in acceleration tolerance between the control group with only exercise as a preventive measure, and the experimental groups with exercise and a daily dose of acceleration. Further, they found that acceleration tolerance was not related to performance on the tilt table after bed rest. In another study, these investigators found that even with exercise and +1.75 Gz for 20 minutes/four times a day, there was a 12 to 38% reduction in peak +Gz tolerance after 10 days of bed rest (49). However, sustained acceleration (+2.5 Gz for 20 minutes) was well tolerated without any symptoms, but with higher heart rates. In general, exercise with periodic centrifugation appeared to provide only partial protection against the expected losses in plasma and blood volumes after bed rest (36, 49, 50). These investigators opined that about 60 minutes a day in the centrifuge would help to alleviate the cardiovascular instability produced by bed rest (49).

Newsom et al. found about 67% reduction in tolerance time to low level, +Gz exposure (+3 Gz) after 14 days of bed rest in women (32). Comparison of this data with time tolerance on +Gz exposures of men from another study showed that women recovered better after bed rest than men (Fig. 17). Natelson et al. found a 52% reduction in tolerance time to +3 Gz exposure after 9 days of bed rest in men aged 55 to 65 years (31). There was also a 13% reduction in maximal oxygen uptake (VO_{2max}) in these individuals. In general, the reductions in tolerance times were similar to that of younger individuals.

Soviet ground-based studies examined tolerance to +Gx, following bed rest duration varying from 3 to 100 days (25, 45). These studies showed that there was a reduction in tolerance to +Gx by about 2.2 G (seat back angle=10 degrees), following 7 to 20 days of hypokinesia. However, after 20 days, there was no further reduction in +Gx tolerance, indicating relative stabilization of cardio-vascular parameters (Fig. 18). The use of preventive measures such as physical training and medications (caffeine, phenamine) were found to reduce the overall changes in tolerance (25). However, the magnitude of such changes is not clear from these reports.

Kotovskaia et al. evaluated +Gx tolerance from operational space flights in the Soviet cosmonauts (26). The flights were divided into short term (less than one month), and long term (>1 month and up to 12 months) exposures to hypogravity. The re-entry accelerations after short term flights (n=14) were tolerated with higher heart rates (about 48% increase), cardiac rhythm disturbances (14%), and increases in respiratory frequency (62% higher), compared to preflight centrifuge values. After long term flights (n=24), there was about 95% increase in heart rate and about 92% increase in respiratory frequency, compared to preflight centrifuge values (Fig. 19). These results were in general agreement with the ground-based studies.

There was considerable improvement in G tolerance after physical training inflight, and use of anti-G suits (AGS) during re-entry (Fig. 20). The use of physical training methods in flight and AGS during return were proposed by these investigators as preventive measures for lowered +Gx tolerance after long-term exposures (26). Table 2 summarizes the available evidence on G tolerance after hypokinesia.

E. CASE FOR IN-FLIGHT CENTRIFUGE

There has been some advocating of the use of in-flight centrifuge or a rotating space vehicle to prevent cardiovascular deconditioning in man during long-term space flights (7, 50). The only studies that specifically looked into the advantage of periodic centrifugation over exercise were that of White et al. (49, 50). Based on preliminary results, they opined that about 60 minutes per day of periodic acceleration would be beneficial. However, the observed data showed only partial protection against losses in plasma and blood volumes. On the other hand, increases in body mass, relative skeletal size and work capacity were observed in experimental animals after centrifugation for six months under hypergravic fields (37). The reconditioning potential of the centrifuge needs to be explored in controlled trials comparing the effects of exercise alone, exercise plus periodic acceleration and periodic acceleration alone on post-hypokinetic tolerance.

The use of an in-flight centrifuge poses challenging problems in spacecraft design, as well as poses problems to humans due to angular accelerations (21, 27, 33, 36). Arm radius of greater than 40 feet is required to produce gravity gradients below 15% in a rotating space vehicle, (36) as shown in Fig. 16. It is estimated that tolerable coriolis forces need to be less than 0.25 times the applied torque, and cross-coupled angular accelerations below 2 rad·sec^{-2} in a rotating space vehicle (33).

V. ACCELERATION LIMITS FOR LONG-TERM SPACE MISSIONS

A. THE ISSUES

The studies described above showed clearly the decrement in peak G tolerance after hypokinetic states. Operational evidence from long-duration Soviet space flights also indicated similar results. However, the magnitude of such decrement is still not clear (13). Various countermeasures have been used in short- and long-duration space flights, such as fluid and electrolyte loading and anti-G suits, to prevent orthostatic intolerance on return to unit gravity (23, 34, 45). During long-duration space flights up to 12 months, the cosmonauts used anti-G suits on re-entry and return accelerations. It was estimated that the use of AGS (in conjunction with in-flight physical training) reduced the heart rate by 50%, compared to flights without AGS (Fig. 18).

These results suggest that such preventive measures should be actively pursued for use in long-term space flights. At the same time, it should be kept in mind that aerobic conditioning is associated with greater periods of incapacitation during +Gz exposures, and increased susceptibility to motion sickness (24, 48). There are two important points that need to be considered in proposing acceptable acceleration levels during long duration missions:

- There is a definite ***decrement in peak G tolerance*** after hypokinesia of long-duration (>1 month), but the decrement may not be linear.
- Use of ***protective measures***, such as anti-G suits, may reduce the detrimental effects of acceleration during return to unit gravity.

The levels proposed in this report should be considered as preliminary, and need to be modified with accumulation of more information.

B. MODELING THE REDUCTION IN ACCELERATION TOLERANCE

Based on the data available (Table 2), it is estimated that there would be a ***reduction in plateau accelerations by about 25%*** (similar rates of onset), while there would be ***about 50% reduction in tolerance times of sustained accelerations,*** after long duration of hypokinesia and hypogravia. However, it should be remembered that these are ball-park estimates (n=147 from Table 2), and the observed reductions varied from 0% to 40% for peak G levels and 25% to 75% for time tolerance limits.

In order to estimate reductions in acceleration tolerance in a group of individuals after exposure to hypokinesia, we used epidemiologic modeling by logistic regression analysis techniques. The logistic regression model was designed to estimate the **probability of developing 25% reduction in peak +Gz tolerance**, compared to preflight centrifuge values, **in a group of individuals** after exposure to hypokinesia. The data on +Gz tolerance from 7 tests (Table 2) involving 57 individuals exposed to hypokinesia was examined. Those individuals who showed less than 25% reduction in tolerance were coded as one, and those with greater than 25% reduction as two (binary responses).

The independent variables used in the regression were duration of exposure (1 to 41 days [continuous variable]) and acceleration end-point (1=peripheral light loss, 2=central light loss, 3=blackout). There was insufficient information for including individual factors such as age in the regression. The analysis was carried out by using maximum likelihood method, and only those variables contributing significantly ($p<0.05$) were included in the final model.

The results of this analysis showed that the duration of exposure to hypokinesia (DURATION) was a significant predictor of the probability of 25% reduction in tolerance among a group of individuals. The model is represented as below:

$$\text{Probability of 25\% reduction in } +G_z \text{ tolerance after hypokinesia} = \frac{e^{0.295+0.076\,(\text{DURATION})}}{1+e^{0.295+0.076\,(\text{DURATION})}}$$

The estimated probabilities from the above model are given in Fig. 21. It is seen that the probability of 25% reduction in tolerance rose higher with longer duration of exposures in the group. The model was satisfactory for our purposes (p-value for goodness-of-fit=0.58) and there was high correlation between observed data and predicted probability from the model (Fig. 22). These findings indicate the robustness of the model to estimate reduction in tolerance in a group of individuals.

The above model, however, is limited by the fact that it represents only the unaided decrement in +Gz tolerance and less than 41 days of hypokinesia. It is interesting to compare this model (Fig. 21) with the observed data from Soviet experience in Fig. 18. As more detailed data becomes available, it is possible to construct robust epidemiologic models to estimate the effects of extended duration of hypokinesia, and/or specific countermeasures on acceleration tolerance.

VI. DESIGN RECOMMENDATIONS

Review of available information indicates that there is incomplete understanding of the effects of long periods of hypokinesia and hypogravia on human acceleration tolerance. Although there is a reduction in tolerance after hypogravic exposures, the magnitude of such reduction varies widely between individuals and is probably nonlinear. Studies examining acceleration tolerance and methods to augment tolerance after hypokinesia are urgently required before specifying limits for long duration missions. Table 3 presents some of the acceleration design limits currently specified in various reports and some **initial estimates** for long duration hypogravic missions, based on the principles proposed above. All impact tolerance limits are for seated and properly restrained individuals. It should be emphasized here that Table 3 provides only general guidelines.

Based on current evidence, the ***reductions in G tolerance after hypokinesia are estimated to be about 25% of plateau G forces or about 50% of time tolerance under sustained G forces***.

The magnitude of changes in ill/injured crew members (compared to deconditioned crew members) and the need for two separate limits (one for deconditioned, and another for ill/injured crew members) is still not clear. The present evidence indicates that such a delineation may not be required, if methods to augment acceleration tolerance were employed (25, 45). This is an important aspect of long-duration missions, and should be investigated at the earliest. Due to lack of information, no separate limits are envisaged for these groups of crew members at this time. The initial recommendations for ***design requirements*** with regard to long-term space missions based on these principles are as below:

LINEAR ACCELERATIONS

- Launch and entry operations

G-axis	**Peak G**	**Duration (sec)**
+Gz	12	0.04
	5	0.1
	3	180.0
-Gz	6	0.02
	5	0.1
	2	30.0
+Gx	25	0.04
	15	0.2
	8	150.0
-Gx	25	0.04
	15	0.2
	6	60.0
+/-Gy	6	0.1
Off-axis	15	0.01

ANGULAR

• Orbital maneuvers:	$< \pm 1.5$ deg·sec^{-2}
• Cross-coupled angular accelerations in rotating vehicles:	< 2 rad·sec^{-2}
• Coriolis forces:	< 0.2 times the applied torque

All launch and entry operations may need to be carried out with additional protection from anti-g suits.

The above limits are arbitrary and should be reviewed and modified with the addition of further information on acceleration tolerance after hypokinesia. The information in Table 3 could be used as a general guideline. Although the limits described in this report may be adequate for a 500-day mission to Mars, the requirements for a 1000-day mission need to be examined more carefully.

VII. AREAS FOR FUTURE RESEARCH

It is apparent that the information on acceleration tolerance after hypokinesia is very limited. Several important aspects of hypogravic exposures are evident from this review:

- That the physiologic effects of hypogravic exposures are similar to that of -Gz acceleration
- That there is definitive decrement of acceleration tolerance after exposure to hypogravic and hypokinetic fields, but the reduction is probably nonlinear, reaching asymptotic levels after about 20 to 30 days of exposure
- That hypogravic conditions for less than 30 days may be considered as short-duration exposures, while greater than 30 days as long-duration exposures
- That the conditioning effects of exercise and/or periodic centrifugation are unclear and appear to be minimal
- That the use of protective measures such as anti-G suits during exposure to acceleration after hypogravic conditions reduce the decrements in tolerance

Further investigations are required in the following areas:

1. Investigation of the ***magnitude of reduction*** in acceleration tolerance (various axes and time-duration) after increasing periods of exposures to hypokinetic and hypogravic fields, including ***ill or injured crew members***
2. Investigation and quantification of the effects of countermeasures (such as exercise, periodic centrifugation, anti-g suits), ***during the various stages of hypokinesia***, on acceleration tolerance
3. Investigation of new (e.g. pulsed AGS) and optimization of available ***methods to augment acceleration tolerance*** of individuals after hypokinesia

4. Further efforts to predict changes in acceleration tolerance by using various modeling approaches

5. Further examination and development of ***unified approaches to acceleration tolerance limits*** (such as combined acceleration levels, Dynamic Response, etc.); based on such work, acceleration tolerance limits may be ***redefined*** in the future

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Table 1. Acceleration Nomenclature.

Motion		Acceleration Descriptive	Inertial Descriptive	Physiologic Descriptive
1. Linear Motion:				
Forward		+Ax	-Gx	Back to chest G
Backward		-Ax	+Gx	Chest to back G
Upward		-Az	+Gz	Positive G
Downward		+Az	-Gz	Negative G
To right		+Ay	+Gy	Left lateral G
To left		-Ay	-Gy	Right lateral G
2. Angular Motion:				
Roll	- right	+ax	-Rx	
	left	-ax	+Rx	
Pitch	- up	+ay	-Ry	
	down	-ay	+Ry	
Yaw	- right	+az	+Rz	
	left	-az	-Rz	

Table 2. Human Acceleration Tolerance After Hypokinesia.

Number of Subjects (1)	Age (Years) (2)	Duration of Hypokinesia (3)	Change in G Tolerance (4)	Change in Heart Rate (5)	Ref (6)
12 M	-	Water immersion - 18 hours	+Gz by 22% (LOMA)	-	2
4 M	23-34	Water immersion - 24 hours	+Gz; No change (Blackout)	31-56%	20
7 M	21-43	Water immersion -11 to 23 hours	+Gz; Early PLL on exposure to +4.5 Gz	-	1
22 M	17-23	Bedrest 2 to 4 weeks	+10.6 Gx peak; Gemini re-entry profile - no change; +Gz tolerance - no change (CLL)	20-22% with +Gz; rhythm changes+	28
10 M	-	Bedrest 41 days- (1) bedrest + exercise vs (2) bedrest + exercise + periodic g	+Gz tolerance; (blackout); no difference between 1 vs 2	-	50
8 M	21-26	Bedrest 10 days- exercise + periodic g	+Gz tolerance by 12-38% (blackout); tolerance to +2.5 Gz for 20 minutes unchanged	13% during sustained +Gz	49
9 M	24-35	Bedrest 1 week	Time tolerance to +4 Gz	-	32
12 F	24-35	Bedrest 2 weeks	Time tolerance to +3 Gz by 67%	-	32
8 M	55-65	Bedrest 1 week	Time tolerance to +3 Gz by 52%	-	31
17 M	-	Bedrest/ immersion 3 to 100 days	+Gx tolerance by 2.2;	Rate and rhythm changes	25
14 M/F 12 M	-	Spaceflights (1) <1 month; (2) 2-12 months	+Gx tolerance during re-entry	(1) 48% (2) 95% Bradycardia and visual symptoms during (2)	26

M=Males; F=Females; note the different endpoints used for tolerance testing: LOMA=limitation of ocular motility with acceleration, PLL=peripheral light loss, CLL=central light loss; all changes in tolerance measured within 24 hours after exposure to hypokinesia.

Table 3. Human Acceleration Tolerance Limits.

G Vector (1)	Acceleration Limits At Unit Gravity (2)	Acceleration Limits Estimated Limits After Hypokinesia (3)
1. **Positive Gz**		
a. Plateau G Limits:	4 G at 1 G•sec^{-1} for 5 sec (43); 10 G for 0.1 sec (15)	3 G at 1 G•sec^{-1} for 5 sec; 7 G for 0.1 sec
b. Sustained:	4 G sustained for 20 min (3); 3 G sustained for 60 min (3);	4 G sustained for <5 min (32); 3 G for 2 to 5 min (32)
c. Impact:	10 G at 500 G•sec^{-1} (15); 16 G for up to 0.04 sec (15)	7 G at 500 G•sec^{-1}; 12 G for <0.04 sec
2. **Negative Gz**		
a. Plateau G Limits:	-5 G for 5 sec (18); -7 G for 0.1 sec (15)	-3 G for 5 sec; -5 G for 0.1 sec
b. Sustained:	-2.5 G for up to 1 min (18)	-2.5 G <30 sec
c. Impact:	-10 G at 60 G•sec^{-1} (15); -9 G for up to 0.02 sec (16)	-7 G at 60 G•sec^{-1} -6 G for <0.02 sec
3. **Positive Gx**		
a. Plateau G Limits:	16 G for 5 sec; 20 G for 0.2 sec (15)	12 G for 5 sec; 15 G for 0.2 sec
b. Sustained:	8 G for 5 min (3)	8 G for <2.5 min
c. Impact:	35 G for up to 0.1 sec with onset rates of 500-1000 G•sec^{-1} (15)	25 G at 500 G•sec^{-1}
4. **Negative Gx**		
a. Plateau G Limits:	-15 G for 5 sec (18); -25 G for 0.2 sec (15)	-11 G for 5 sec; -18 G for 0.2 sec
b. Sustained:	-6 G for 2 min (18)	-6 G for <1 min
c. Impact:	-45 G for 0.04 sec at 500 G•sec^{-1} (15)	-30 G at 500 G•sec^{-1}
5. **Positive/Negative Gy**		
a. Plateau G Limits:	5 G for 10 sec (16);	3.5 G for 10 sec;
b. Sustained:	Not available	-
c. Impact:	9 G for 0.1 sec (16)	6 G for 0.1 sec

Table 3. Human Acceleration Tolerance Limits (cont).

G Vector	Acceleration Limits	
	At Unit Gravity	Estimated Limits After Hypokinesia
(1)	(2)	(3)
6. Critical Velocities for Free-fall Impact		
a. Water impact:	35 m•sec^{-1} for +/-Gz; 26 m•sec^{-1} for +/-Gx and +/-Gy (39)	<30 m•sesec^{-1} <20 m•sec^{-1}
b. Hard surfaces:	16 m•sec^{-1} (39)	$\leq$10 m•sec^{-1}
c. Off-axis Impact:	20 G at 1000 G•sec^{-1} up to 60 msec (42)	15 G up to 1000 G•sec^{-1} for <60 msec
7. Rotary Accelerations		
a. z- and y- axes:	60 rpm for 4 min (47);	<30 rpm
b. Threshold of angular acceleration:	1.5 deg•sec^{-2} (10)	-
c. Tolerable cross-coupled angular acceleration:	2 rad•sec-2 (21) (115 deg•sec^{-2})	-

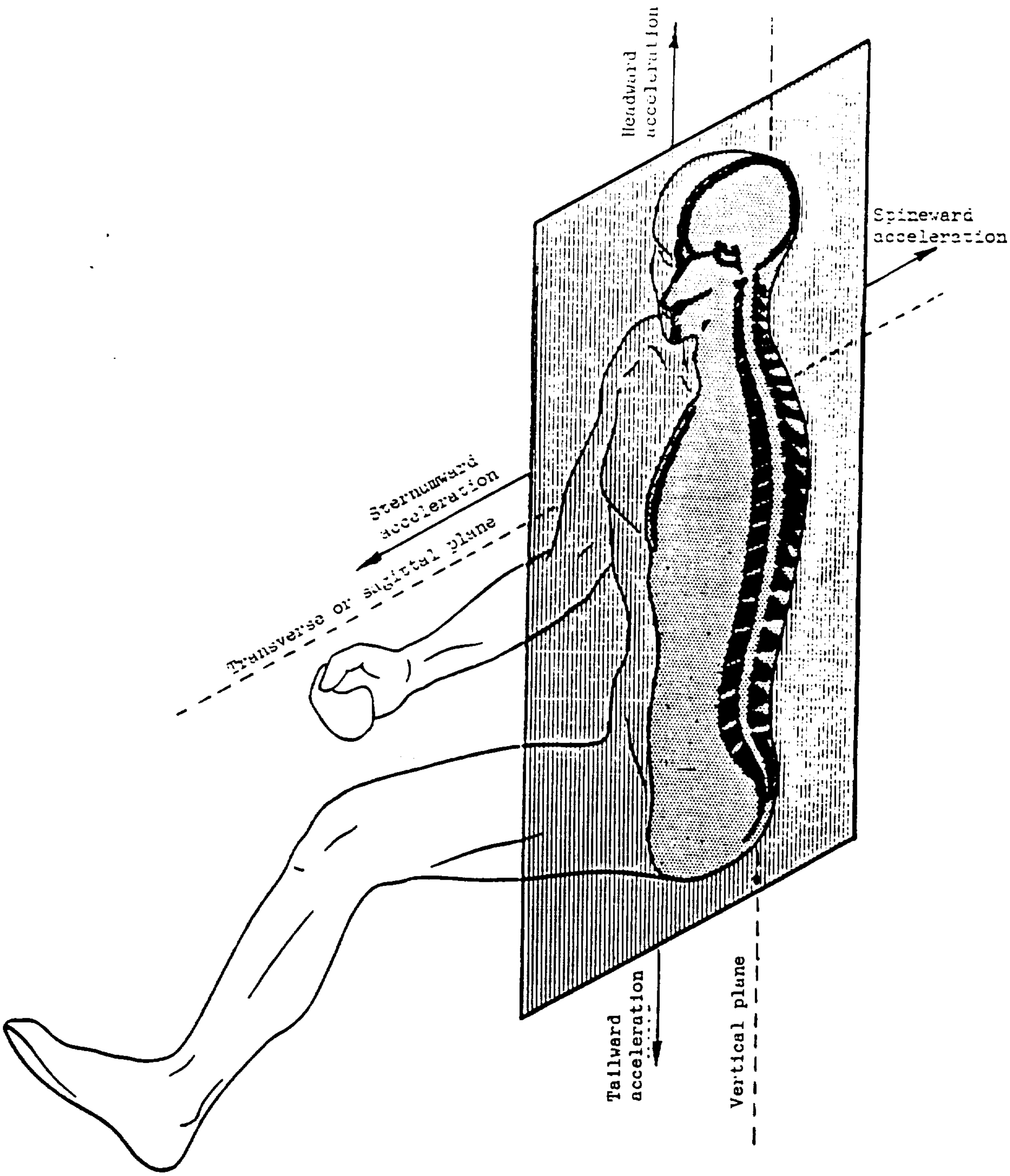


Fig. 1. Typical Nomenclature for Acceleration Components (Ref. 15; p. 57)

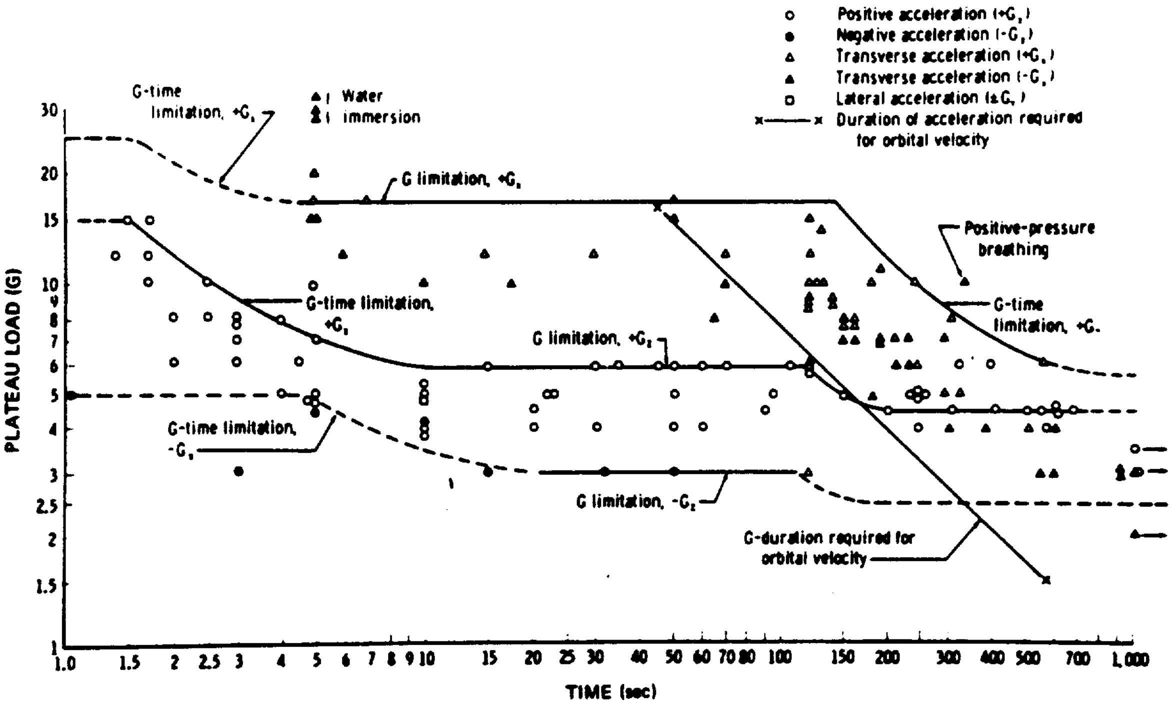


Fig. 2. Human Tolerance to Sustained Acceleration (Ref. 16; p. 173)

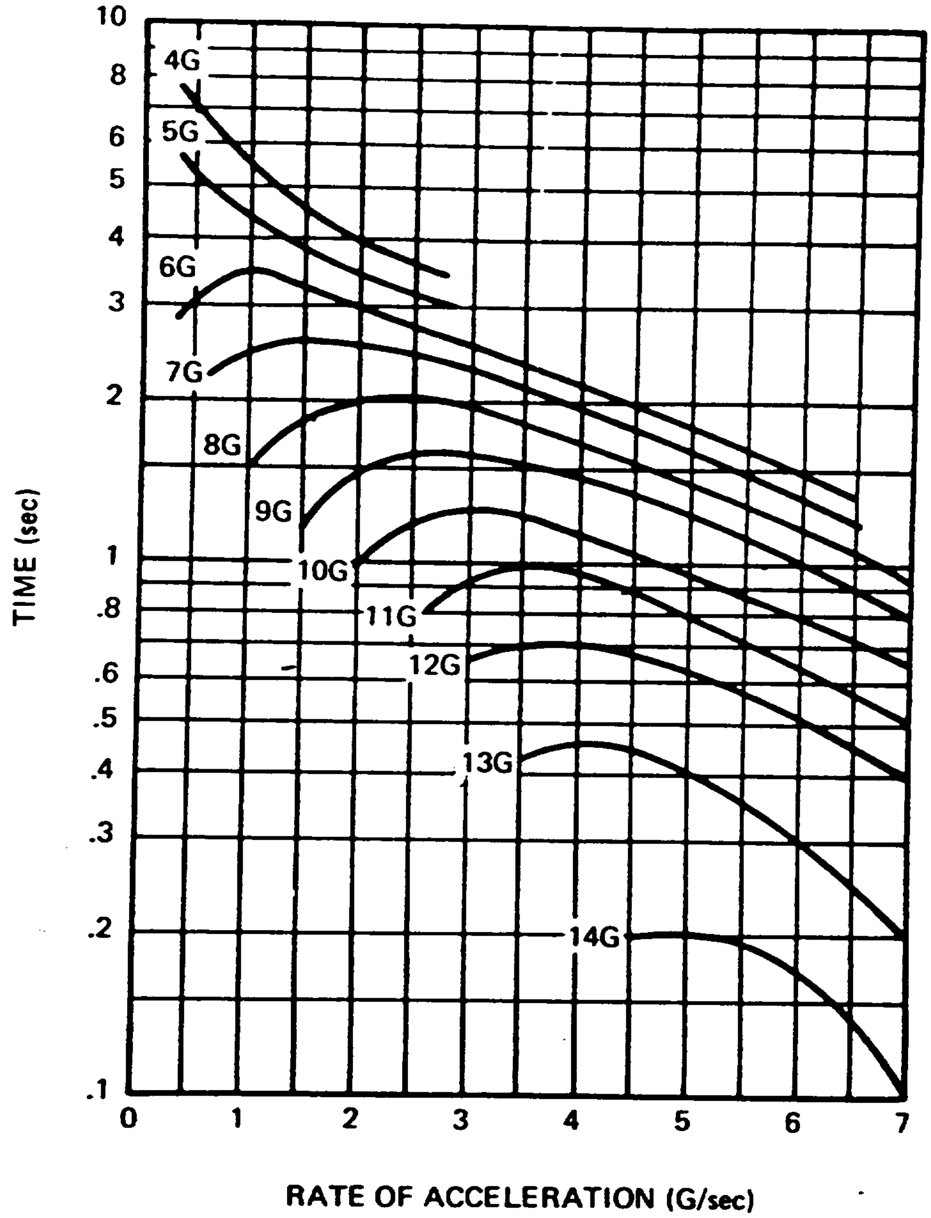


Fig. 3. Time to Grayout with Various Rates of Onset (Ref. 16; p. 175)

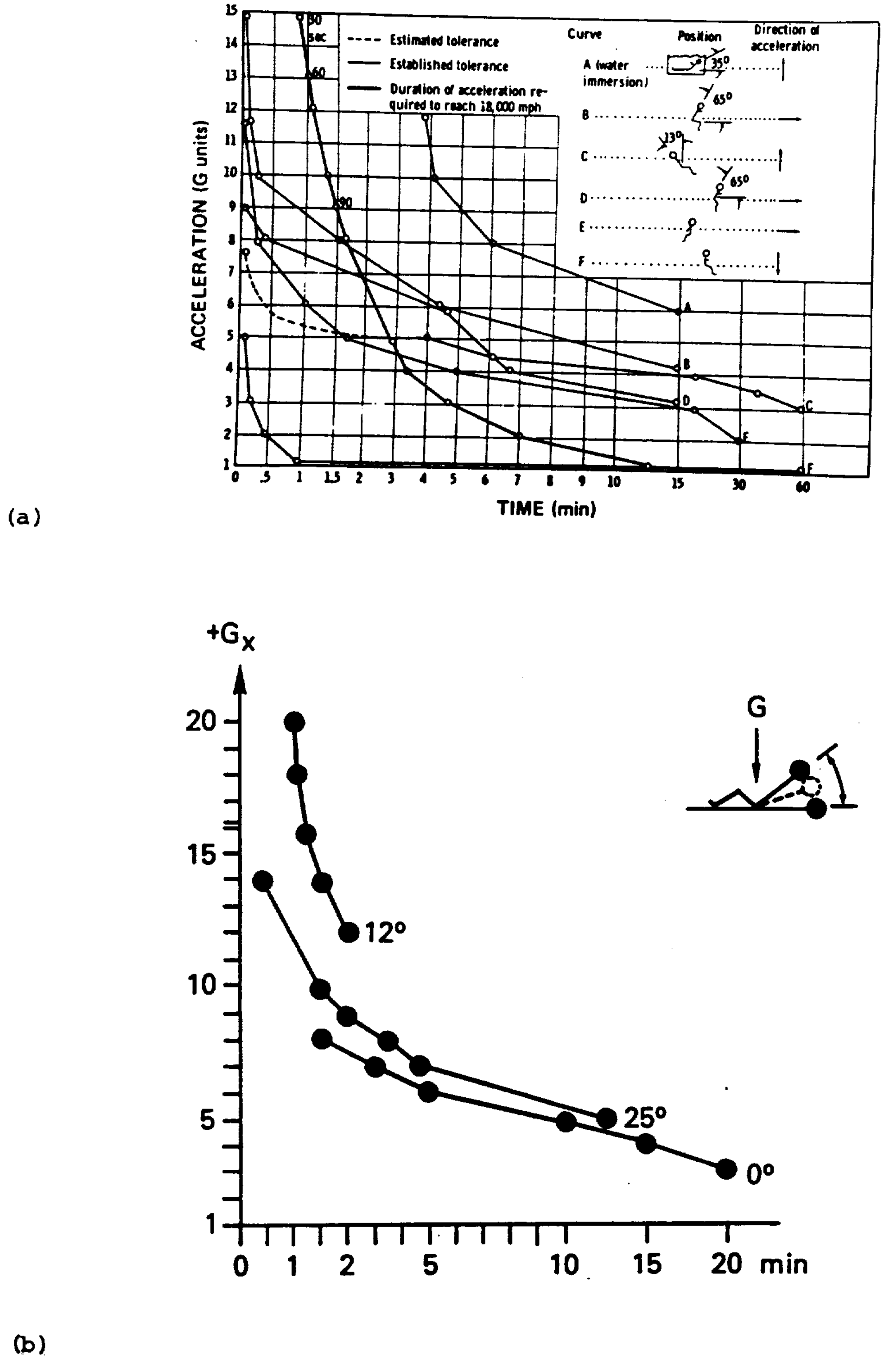


Fig. 4. Tolerance to Acceleration as a Function of (a) Body Posture (Ref. 17; p. 176) and (b) Seat Back Angle (Ref. 45; p. 169)

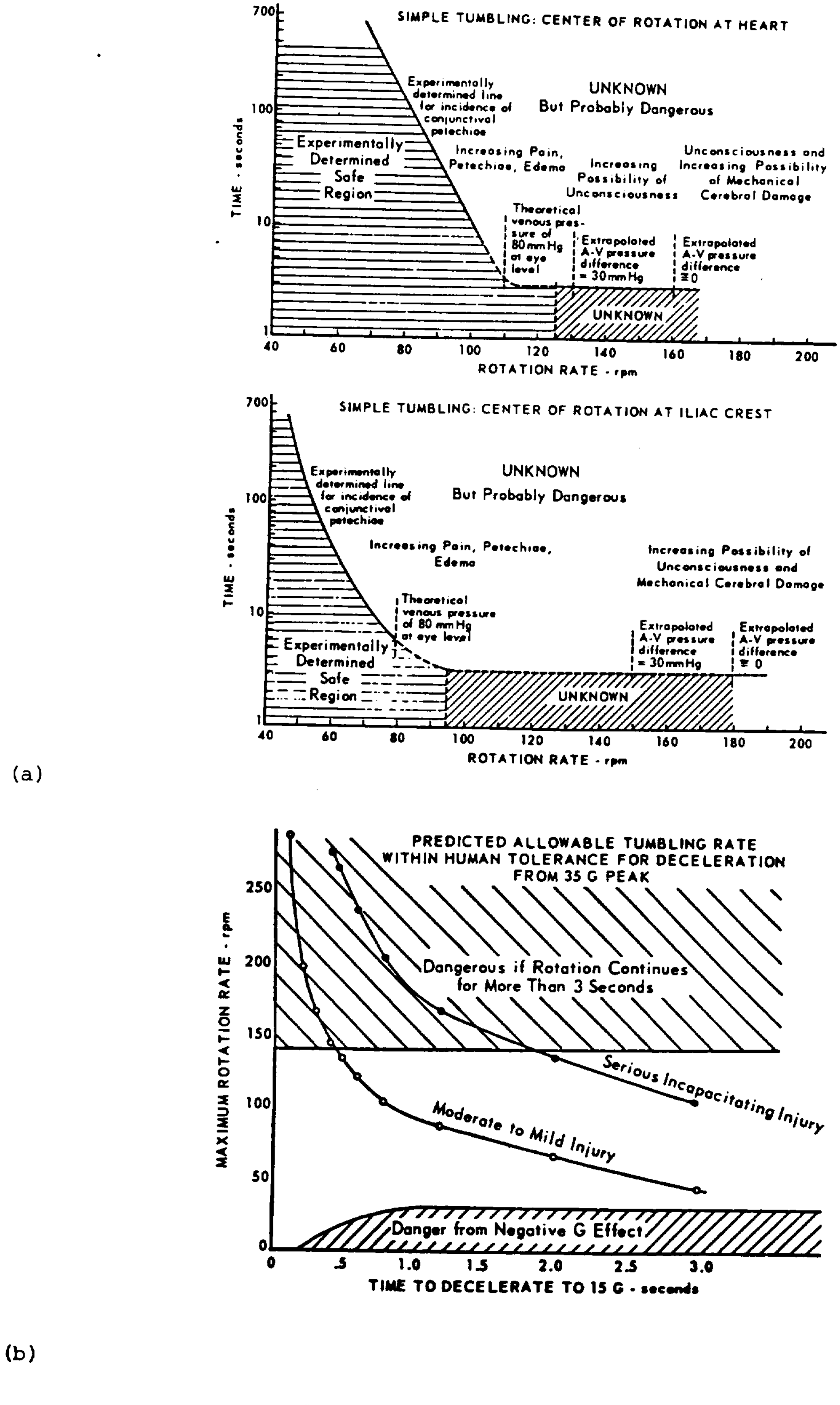


Fig. 5. Human Tolerance to Rotation around (a) Pitch Axis and (b) tolerance during a G decay from 35 to 15 G (Ref. 17; p. 193)

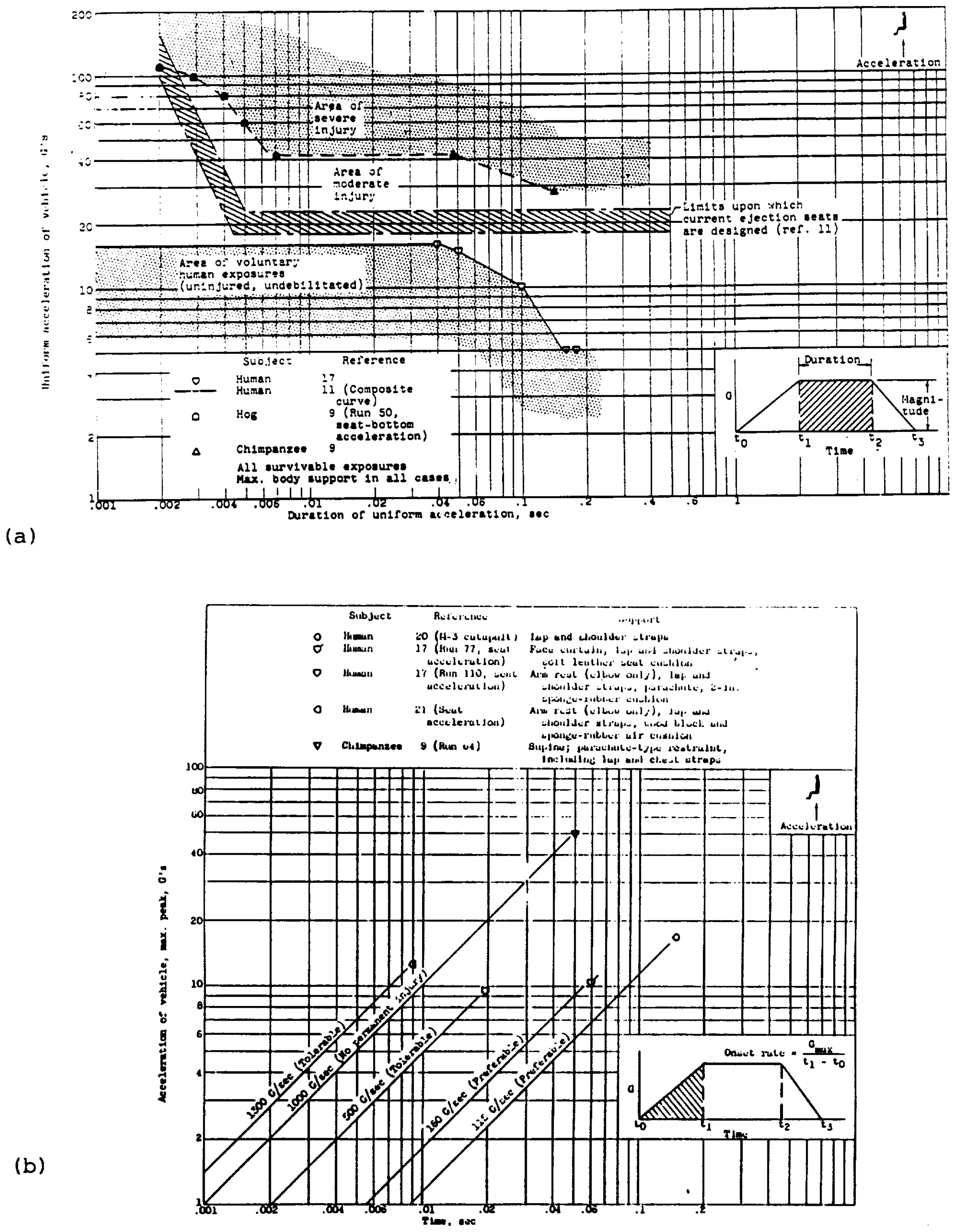


Fig. 6. Tolerance Limits for (a) headward Acceleration and (b) Changes in Tolerance with Rates of Onset (Ref. 15; p. 74, 77)

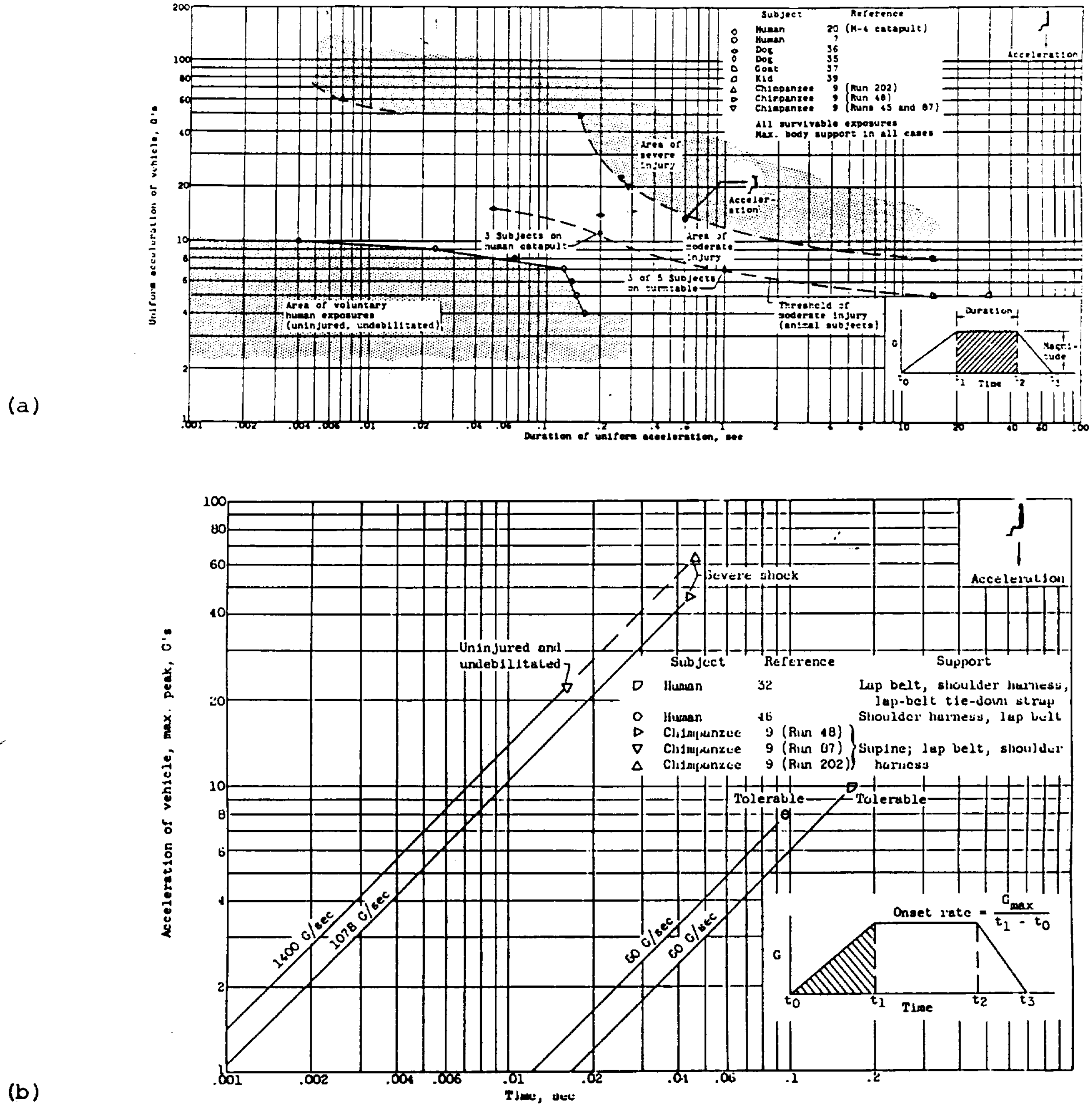


Fig. 7. (a) Tolerance Limits for Downward Acceleration and (b) Variations with Different Rates of Onset (Ref. 15; p. 86 & 87)

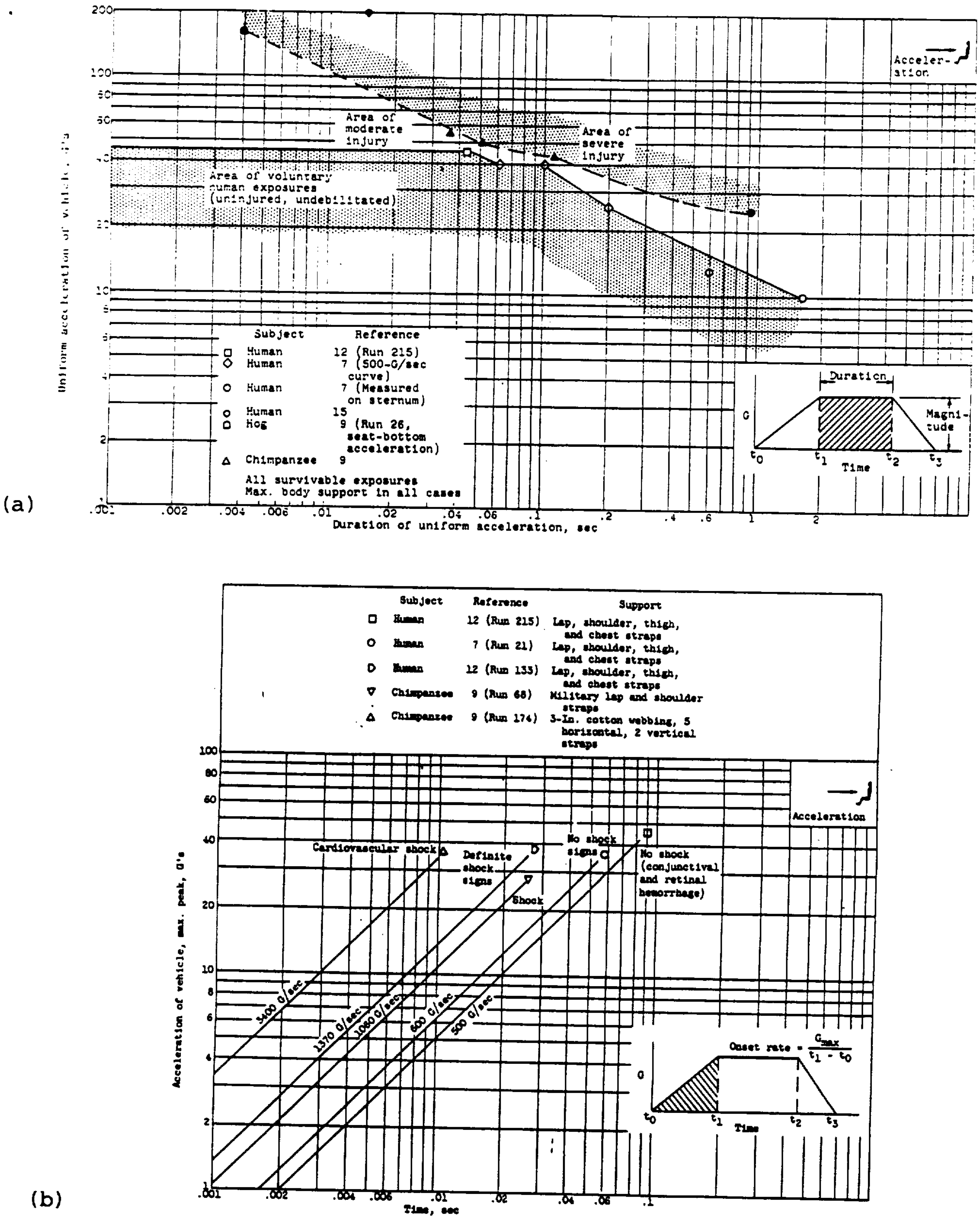


Fig. 8. Tolerance Limits for (a) Backward Acceleration and (b) Variations with Rates of Onset (Ref. 15; p. 58 & 64)

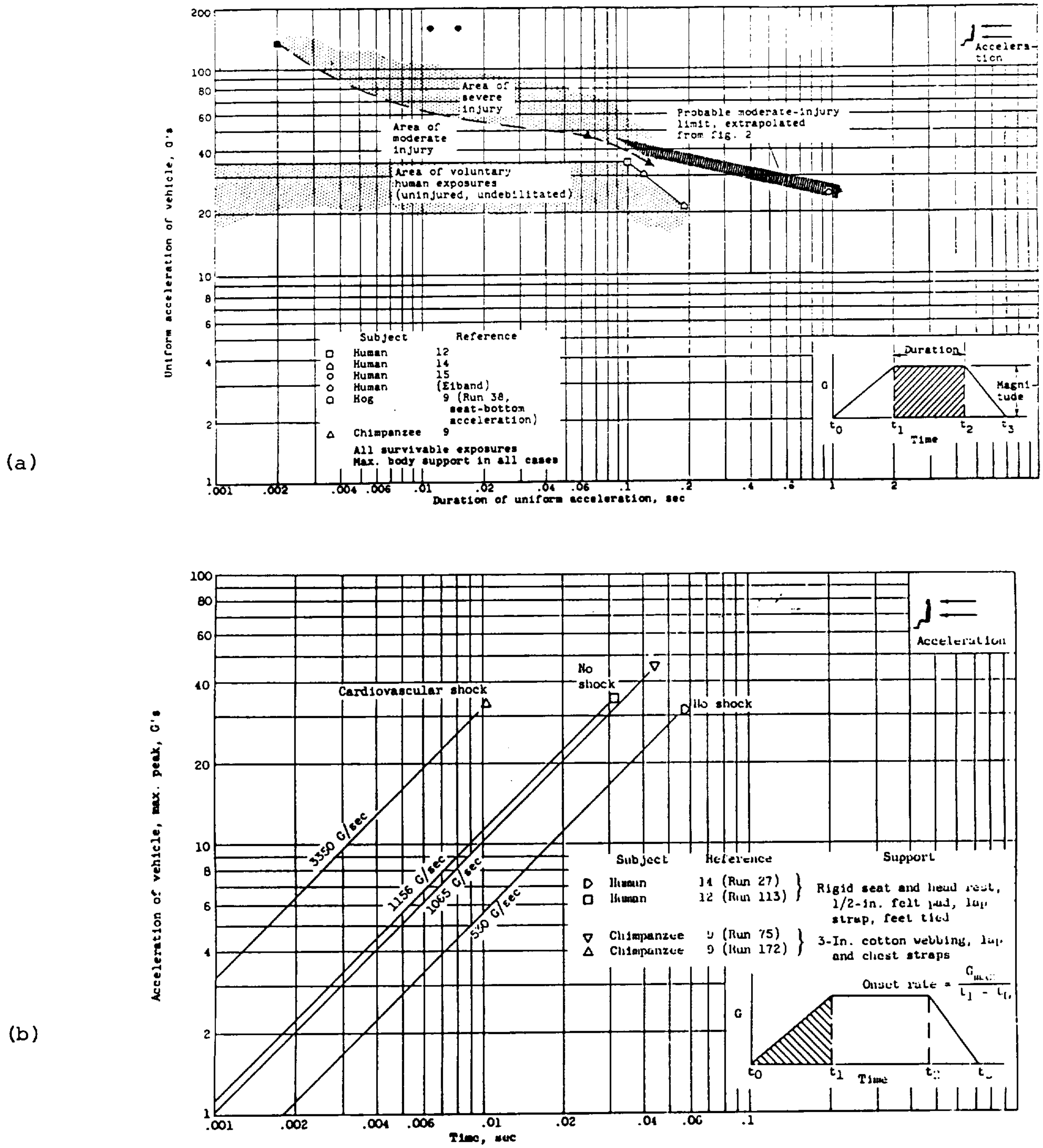


Fig. 9. Tolerance to (a) Forward Acceleration and (b) Changes with Various Rates of Onset (Ref. 15; p. 66 & 71)

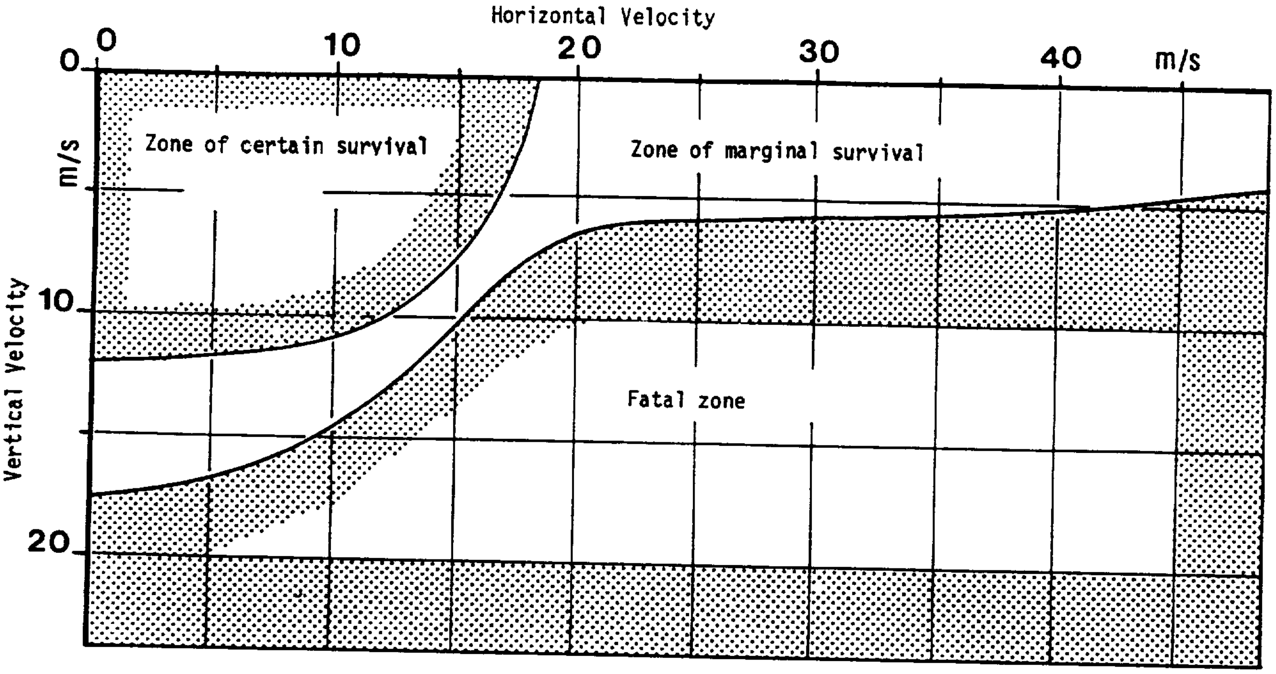


Fig. 10. Human Tolerance to Impact Velocities (Ref. 14; p. 36)

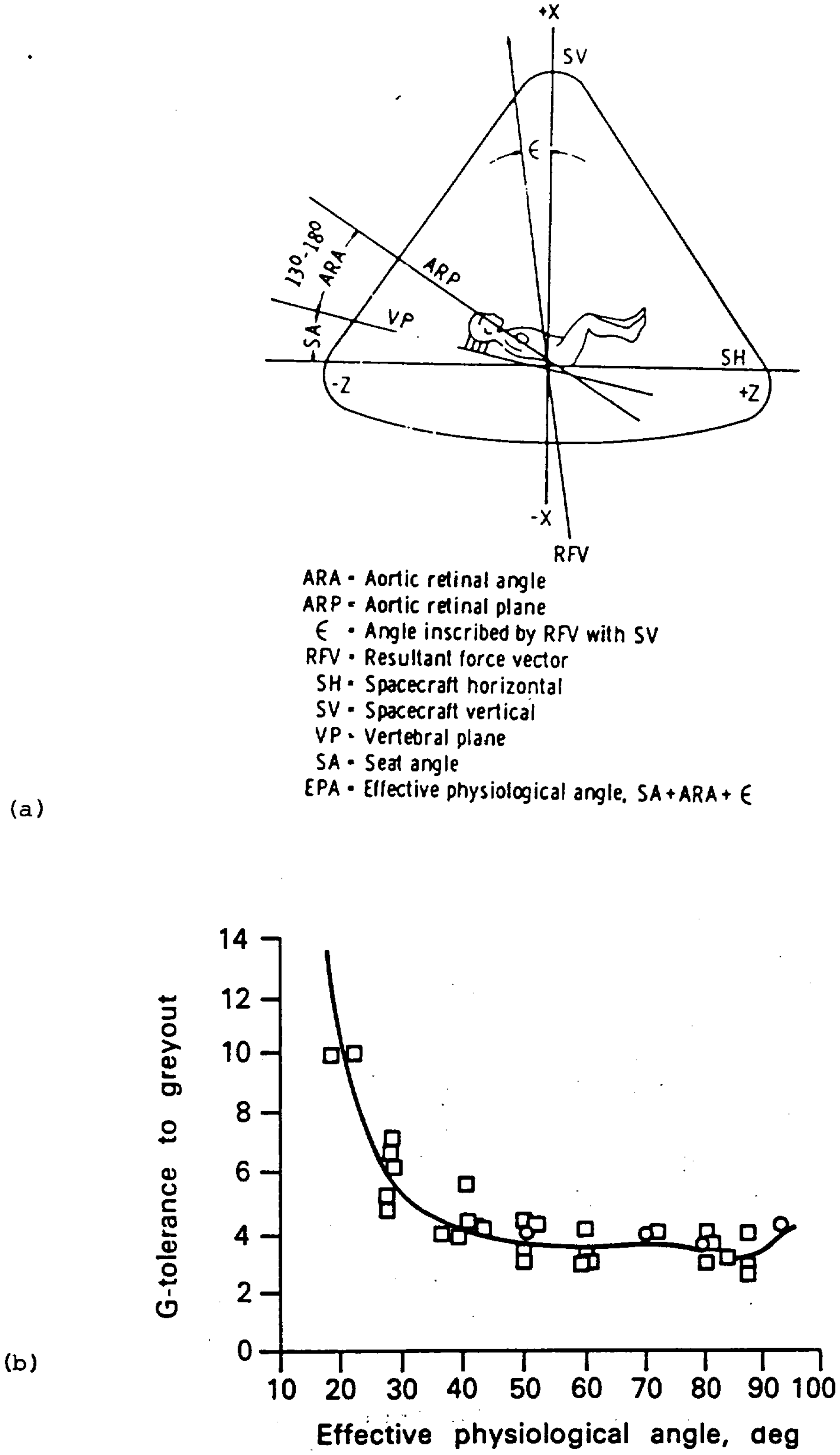


Fig. 11. (a) Effective Physiologic Angle and (b) Human Tolerance at Various Angles (Ref. 18 p. 70)

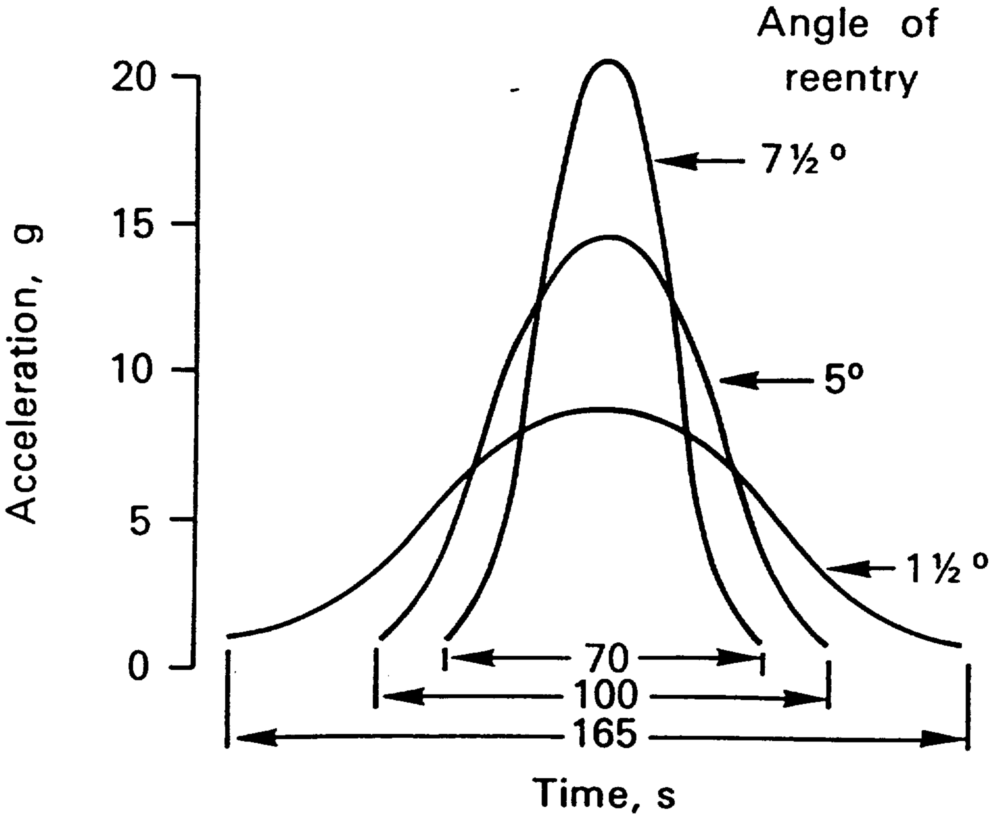


Fig. 12. Re-entry Accelerations as a Function of Angle at Re-entry (Ref. 45; p. 172)

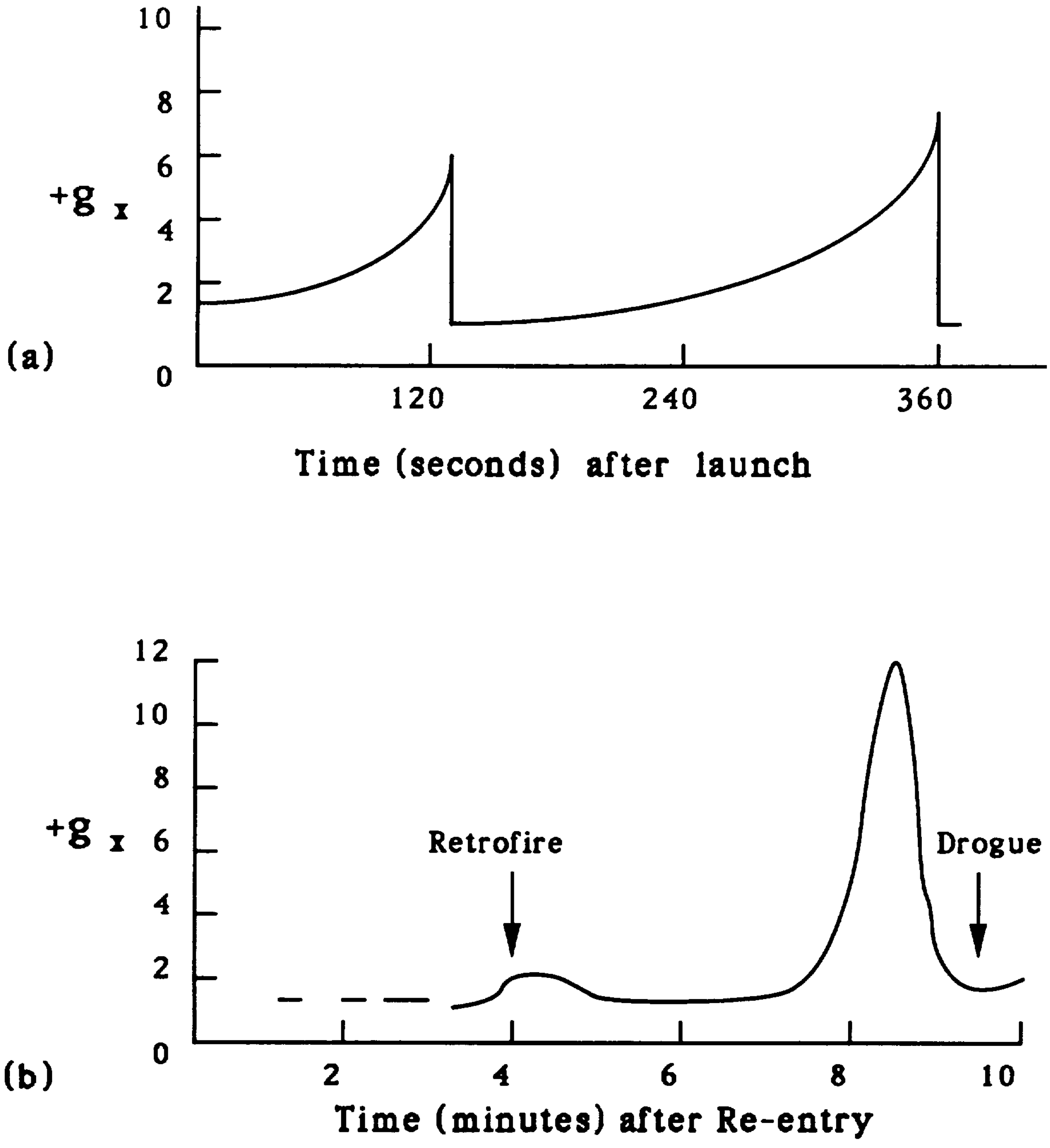


Fig. 13. Accelerations During (a) Launch and (b) Re-entry in the Mercury Program

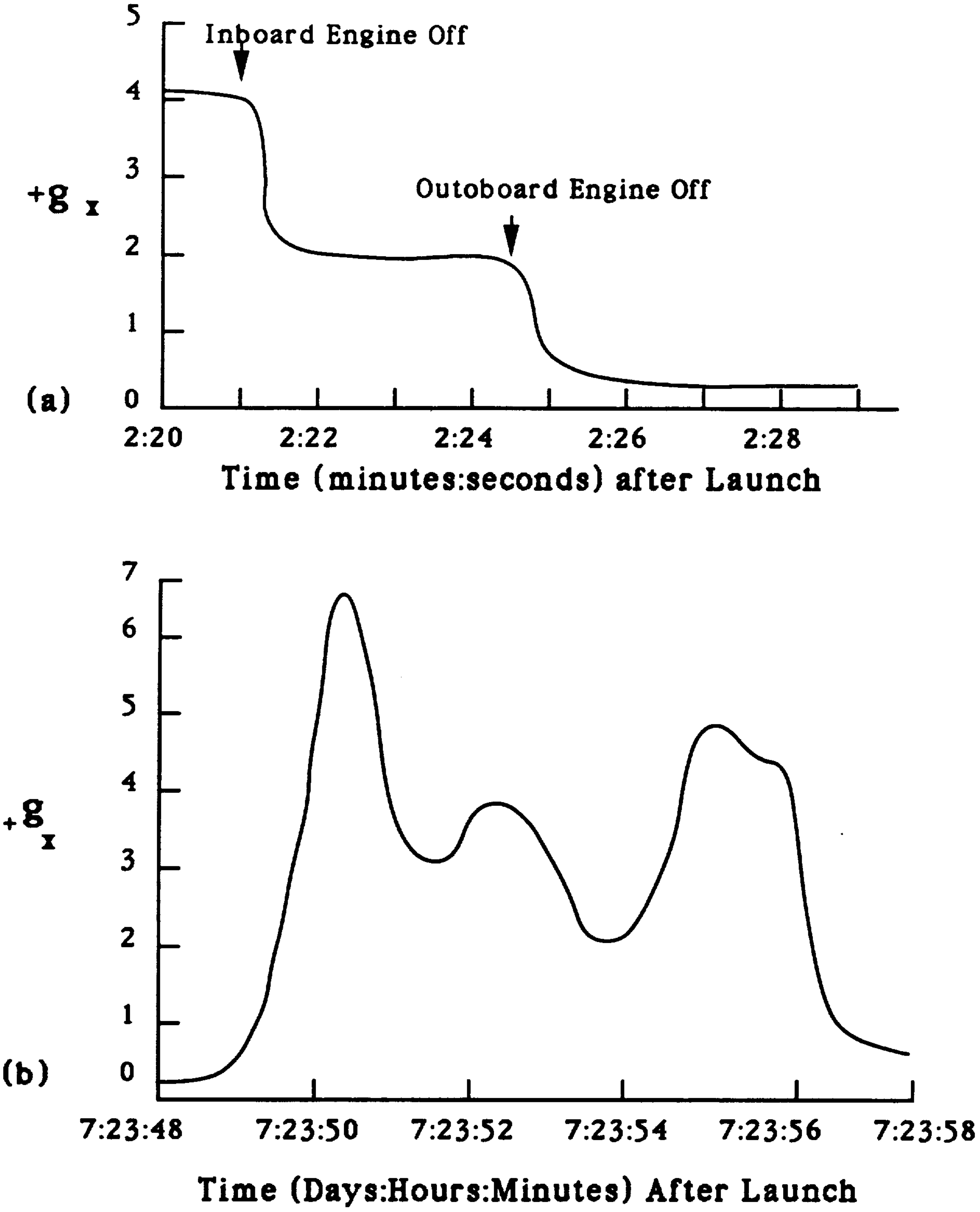


Fig. 14. Accelerations During (a) Launch and (b) Re-entry in the Apollo Program

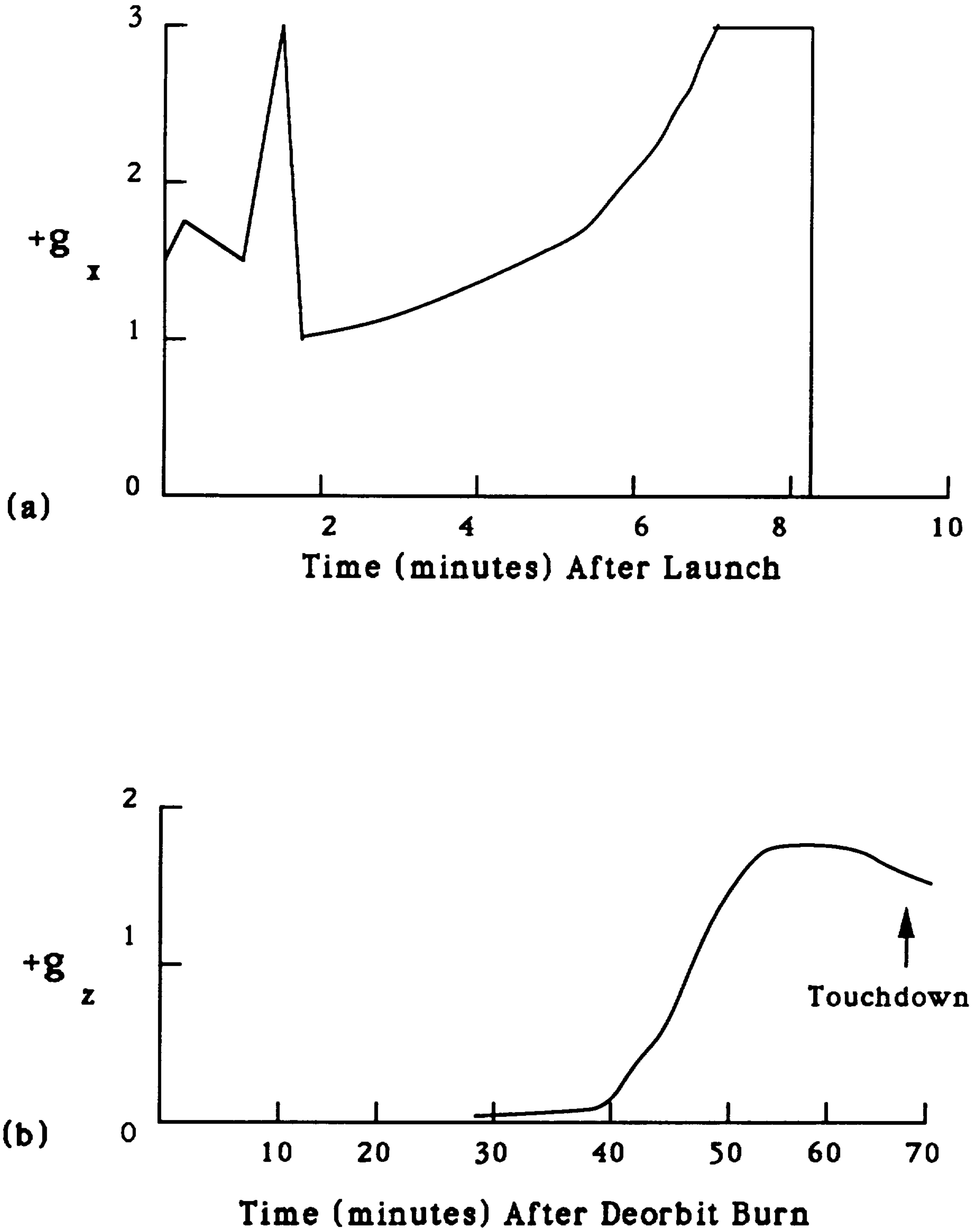


Fig. 15. Accelerations During (a) Launch and (b) Re-entry in the STS Program (Ref. 34; p. 50)

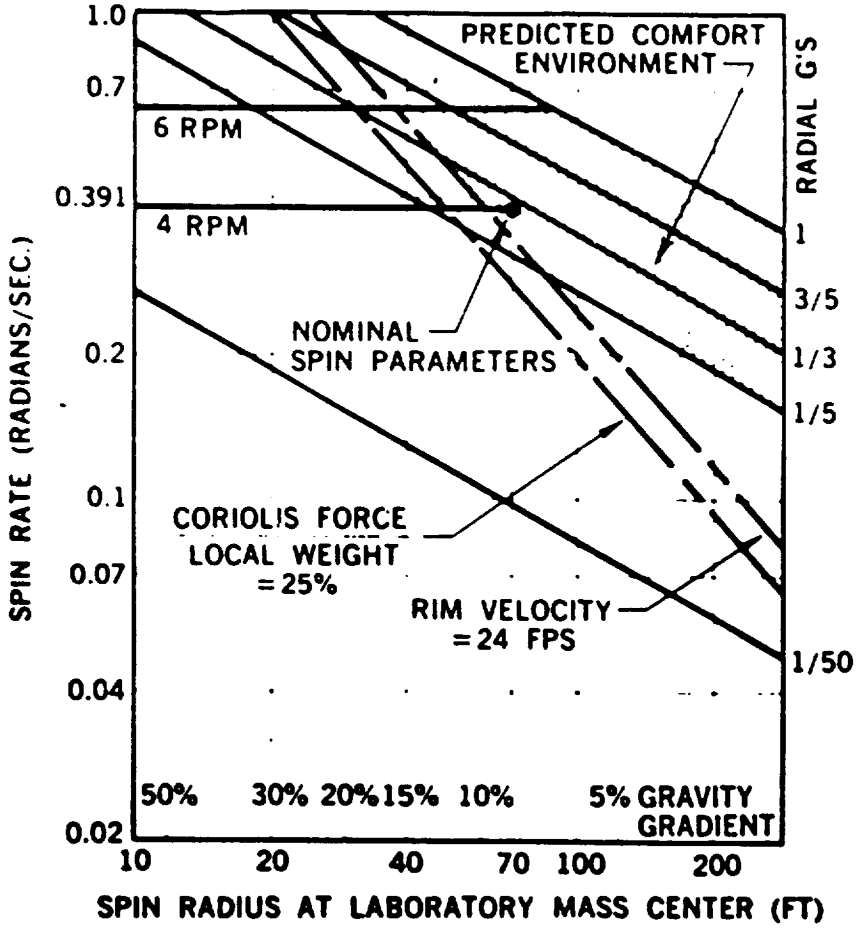


Fig. 16. Rotational Limits in Space Vehicle Design
(Ref. 36; Ch. 7 p. 108)

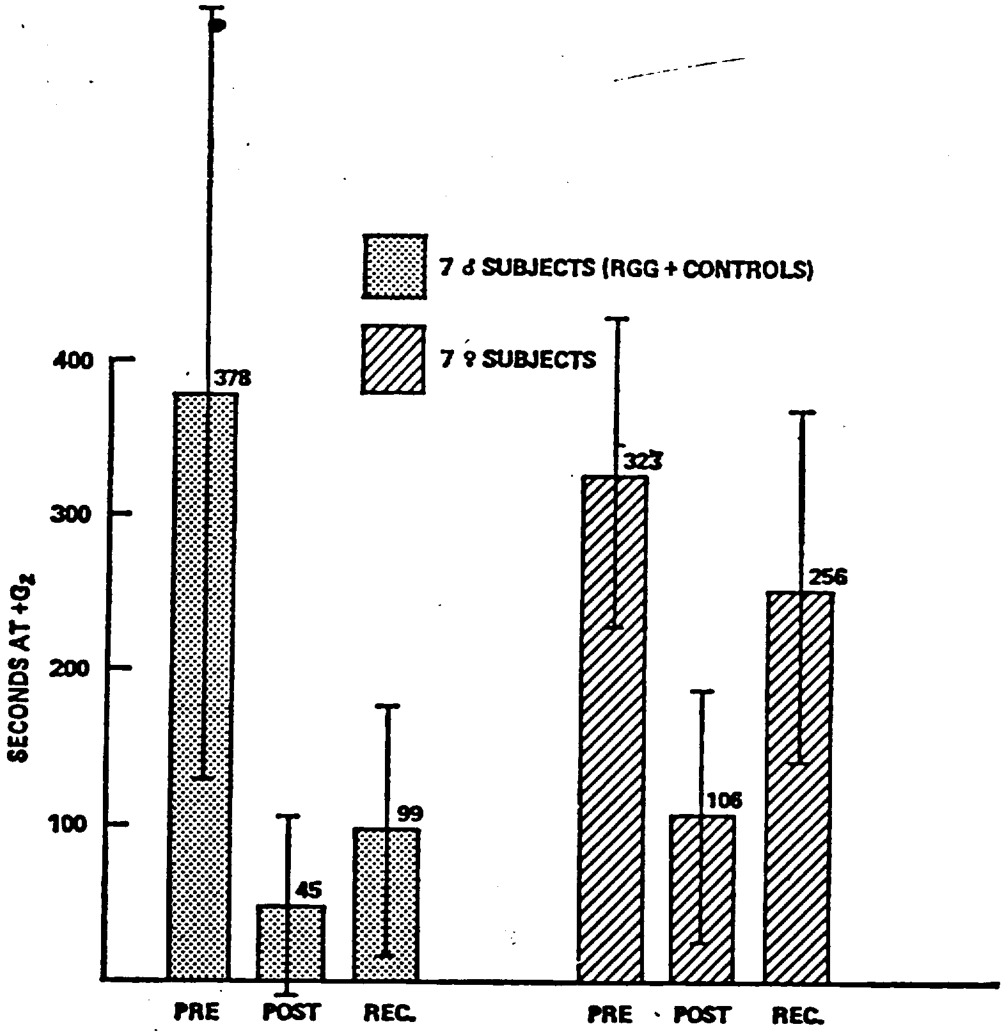


Fig. 17. Tolerance to Sustained +Gz Acceleration After Bedrest for 1 week (Ref. 32; p. 331)

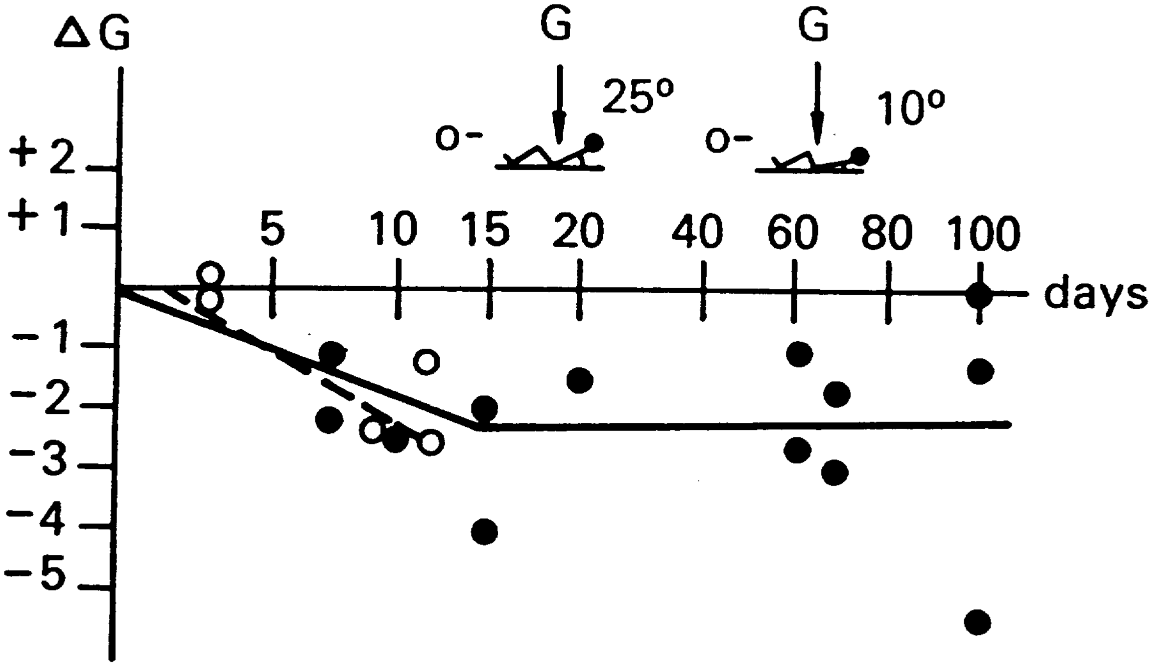
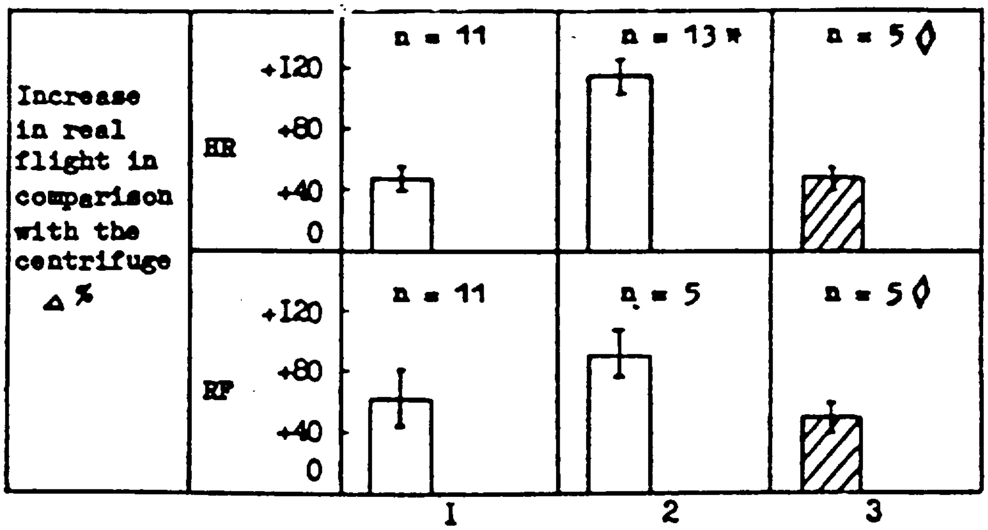


Fig. 18. Change in Human Tolerance to +Gz Acceleration with Bedrest and Different Seat Back Angles (Ref. 45; p. 173)



* $p < 0{,}05$ – in comparison with short-term flights

◊ $p < 0{,}05$ – in comparison with prolonged flights with and without AGS

n –number of observations

☐ –without AGS

▨ –with AGS

Fig. 19. Changes in Response to +Gz Accelerations (1) After less than 1 month, (2) between 2-8 months, and (3) 8-12 months of exposure to hypogravic spaceflights (Ref. 26; p. 159)

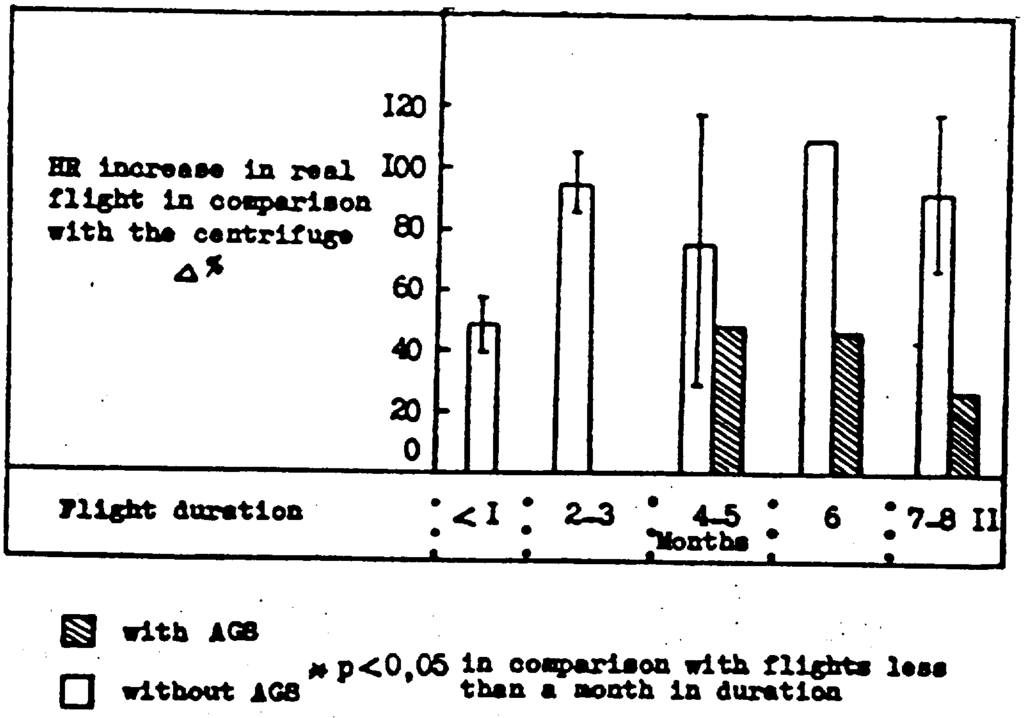


Fig. 20. Changes in Heart Rate under +Gz Accelerations After Operational Spaceflights with and without Anti-G Suits (AGS)
(Ref. 26; p. 159)

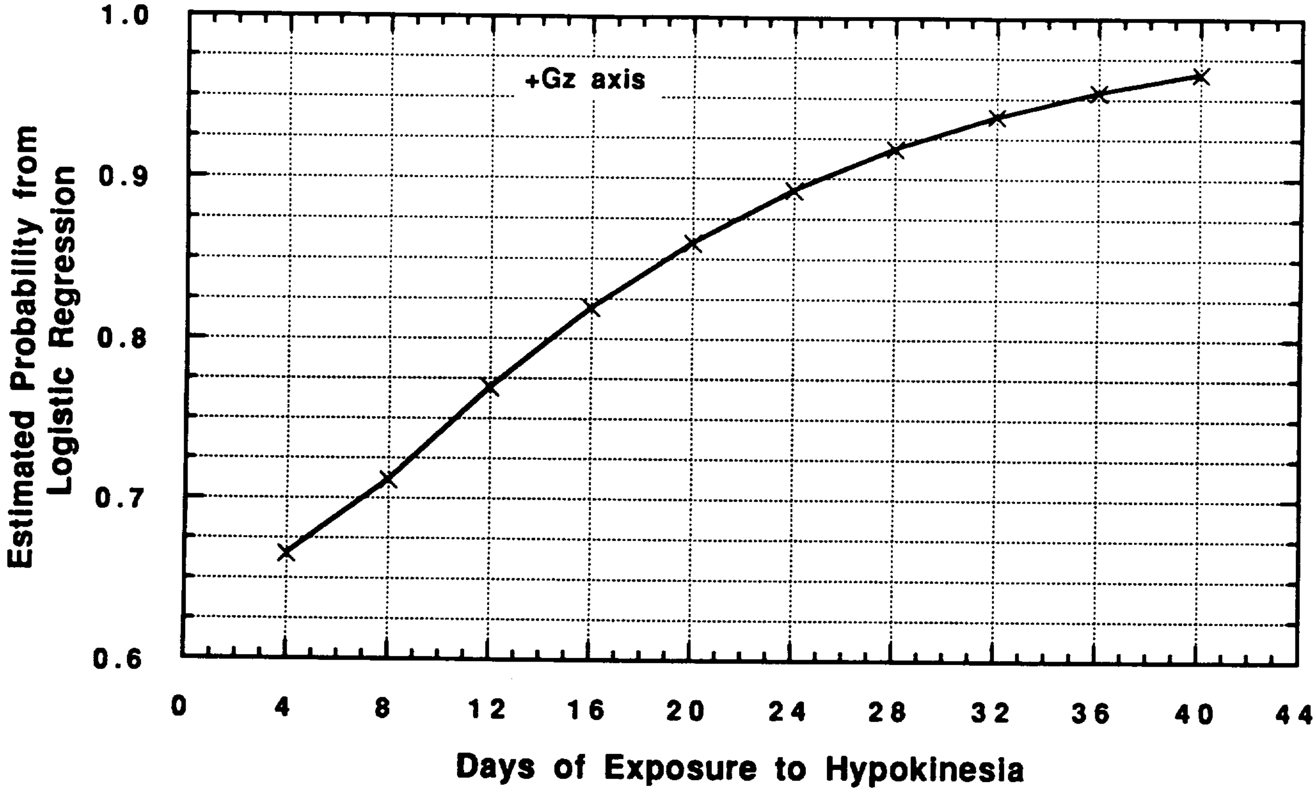


Fig. 21. Probability of 25% Reduction in Human Acceleration Tolerance

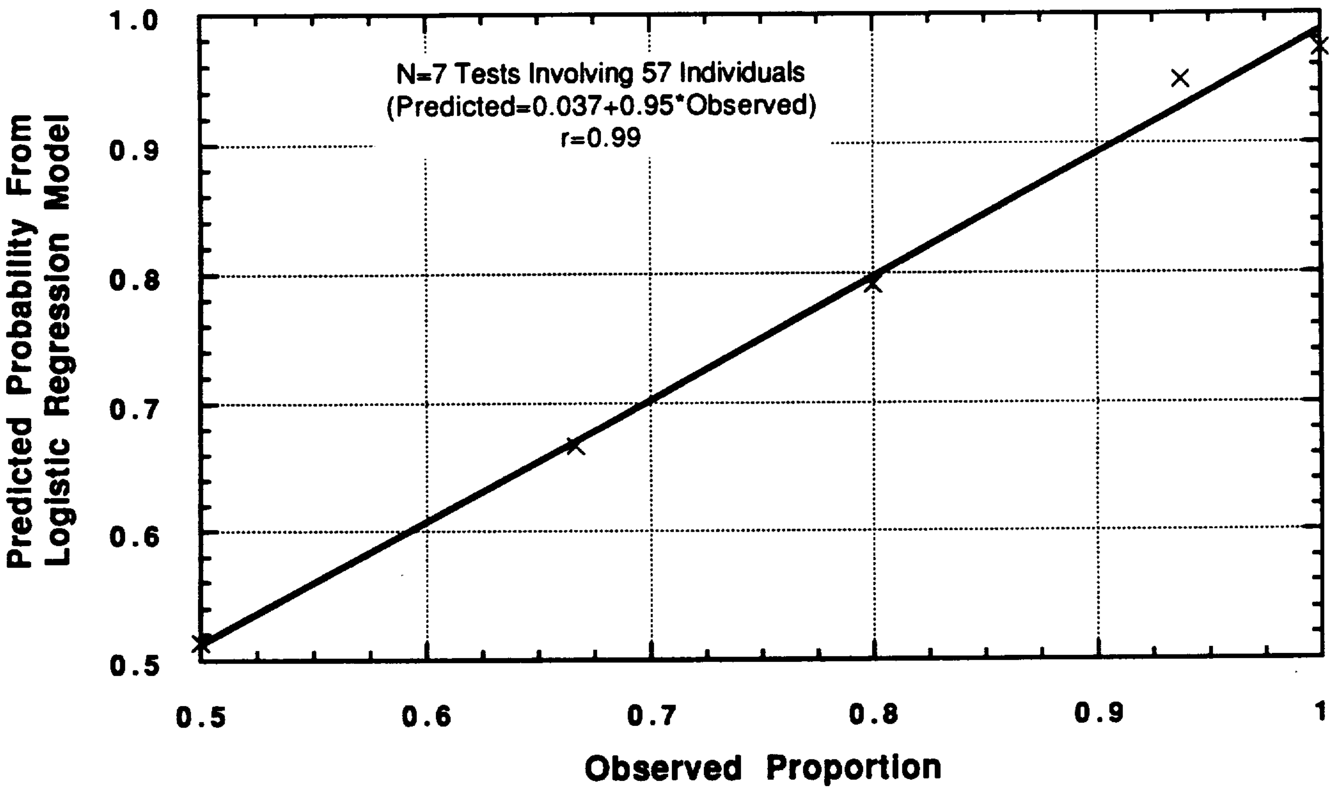


Fig. 22. Relationship Between Observed and Predicted Probabilities

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1992

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Issues on Human Acceleration Tolerance After Long-Duration Space Flights

5. FUNDING NUMBERS
NAS9-18492

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBER
TM 104753

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
S-686

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Unclassified/Unlimited

Subject Category 169

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report reviewed the literature on human tolerance to acceleration at 1 G and changes in tolerance after exposure to hypogravic fields. It was found that human tolerance decreased after exposure to hypokinetic and hypogravic fields, but the magnitude of such reduction ranged from 0% to 30% for plateau G forces and 30% to 70% for time tolerance on sustained G forces. A logistic regression model of the probability of individuals with 25% reduction in +Gz tolerance after 1 to 41 days of hypogravic exposures was constructed. The estimated values from the model showed a good correlation with the observed data.

A brief review of the need for in-flight centrifuge during long-duration missions was also presented. Review of the available data showed that the use of countermeasures (such as anti-G suits, periodic acceleration, and exercise) reduced the decrement in acceleration tolerance after long-duration space flights. Areas of further research include quantification of the effect of countermeasures on tolerance, and methods to augment tolerance during and after exposures to hypogravic fields. Such data are essential for planning long-duration human missions.

14. SUBJECT TERMS
Acceleration tolerance, in-flight centrifuge, countermeasures, human tolerance, microgravity, acceleration model

15. NUMBER OF PAGES
56

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102