Chapter 33

ACCELERATION EFFECTS ON FIGHTER PILOTS

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INTRODUCTION

Acceleration (G) is one of the major physical stresses associated with combat flying. More than 10% of pilots of fighter aircraft reported experiencing unexpected loss of consciousness (LOC) while flying aerobatic maneuvers[1]; the real incidence is probably higher because such events often induce amnesia. While such loss of consciousness resembles ordinary syncope, the consequences can be fatal, and the US Air Force cited sudden unconsciousness as the cause of 18 fatal accidents during the years 1982 through 1990.[2]

LOC during steep turns was first reported in 1918 as "fainting in the air" and became a problem during early air races.[3] Significant acceleration peaks became common experience for pilots flying improved aircraft between World War I and World War II, although the combination of high aerodynamic drag and low engine thrust in aircraft of that period made such acceleration a transient phenomenon. Nevertheless, concerns related to pilot blackout and loss of consciousness led to operational restrictions on the turn rates of some aircraft during the 1920s.

Aggressive dive-bombing techniques that were developed during the 1930s produced severe acceleration during the pull-up at the end of the bombing run.[4] Sporadic reports began to appear of blackout during these maneuvers as well as concern about acceleration-induced loss of consciousness (G-LOC). These problems were correctly attributed to "cerebral anemia produced by centrifugal action," and the Royal Air Force determined that 4 G (acceleration 4-fold greater than the force of gravity) was the limit of human acceleration tolerance.[5] In 1934 the US Navy developed a pneumatic "acceleration belt" consisting of an abdominal bladder, which the pilot inflated prior to the dive-bombing run, but this device probably had only marginal effect on acceleration tolerance.

Laboratory research on responses to acceleration was made possible by the development of human centrifuges, machines that produce acceleration by rotating an arm 20 to 30 ft long, at the end of which is mounted a capsule in which the subject sits or reclines. Although centrifuges had existed in earlier times, the first machines designed for aviation-related research were built in Germany and the United States during the 1930s, followed later by centrifuges at institutes of aviation medicine in Japan, the Soviet Union, Australia, and several European countries. Extensive research at the Mayo Clinic, Rochester, Minnesota, during the 1940s led to the development of both the five-bladder pneumatic anti-G suit (also called "G trousers") and the straining maneuvers (Exhibit 33-1) that significantly increased human ability to withstand acceleration. These techniques were adopted by military pilots worldwide over the next 3 decades, a period during which fighter aircraft remained capable of only limited periods of acceleration at peak levels of about 7 G.

The current challenge to pilot acceleration tolerance began in the 1980s with the introduction of fighter aircraft with greatly increased engine thrust and wingload capacity that allowed sustained accelerations of 9 G or more. LOC again became a problem and was identified as the cause of a number of fatal crashes. For the first time since the 1920s, the pilot's limitations began to restrict aircraft maneuverability, a serious problem in aerial combat situations where ability to turn hard and climb fast may be the key to survival. Furthermore, sudden onset of high acceleration can reduce the pilot to unconsciousness without warning. In response to these problems, during the 1990s research centrifuges have been upgraded to achieve the rapid onsets (6 G/s) and high accelerations (12 G) found in new aircraft. Recent developments include extended-coverage anti-G suits and systems for balanced pressure breathing to better counteract the circulatory effects of high acceleration. In addition, several nations now use centrifuge training to ensure that each fighter pilot makes optimal use of straining maneuvers. With these improvements, most pilots can now maintain vision and consciousness for extended periods at acceleration levels of 9 G.

Readers need to understand certain conventions and terminology that are used in discussing acceleration and its physiological effects (see Exhibit 33-1). Acceleration vectors are described in relation to three body axes (Figure 33-1), and the orientation is designated positive (+) or negative (–): Gz (head-to-foot), Gx (front-to-back), and Gy (side-to-side). The dominant acceleration for a seated pilot is +Gz, which occurs in ordinary turns and pull-ups and forces blood to pool in the legs and feet. Its reverse, –Gz, accompanies outside loops and forces blood toward the head.

Astronauts experience +Gx during launch, as do pilots in semireclining seats. Lateral (Gy) forces have been of little concern until now but may become a problem with the introduction of a new type of agile fighter aircraft, which will be able to slew its nose toward a target while continuing on its original flight path.

EXHIBIT 33-1

TERMS USED IN HIGH-ACCELERATION AVIATION

g:	Acceleration equal to gravity at the surface of Earth, 9.80665 m/s^2.
G:	A unit of convenience calculated as the observed acceleration divided by *g*; thus, acceleration of 29.4 m/s^2 is expressed as 3 G. "G" is also used as shorthand for the word "acceleration." For positive and negative directional designations and x, y, and z body axes used with the abbreviation G, see Figure 33-1.
Grayout:	Dimming of vision due to reduced retinal perfusion. It is usually accompanied by narrowing of visual fields (tunneling).
Blackout:	Loss of vision during acceleration due to insufficient retinal perfusion; it precedes loss of consciousness because eye perfusion is opposed by normal intraocular pressure.
Redout:	Reddish fogging of vision due to venous pooling and increased perfusion pressure in the eye during exposure to –Gz.
Acceleration-induced loss of consciousness (G-LOC):	Loss of consciousness during sustained acceleration due to inadequate cerebral perfusion.
Anti-G suit:	Trousers fitted with pneumatic or hydrostatic bladders over the abdomen and legs; an inelastic outer layer assures that increased bladder pressure during +Gz is transmitted to the adjacent tissues to minimize venous pooling.
Pressure breathing (PBG):	Continuous positive pressure applied to the airway during +Gz to increase intrathoracic pressure and thereby raise arterial blood pressure.
Balanced pressure breathing:	Use of a bladder contained in a vest to reduce the work of pressure breathing. The bladder is inflated to airway pressure and prevents over-expansion of the chest as well as making it easier to exhale against pressure. Also called "assisted" pressure breathing.
Straining maneuvers:	(1) Voluntary isometric contraction of major muscle groups (especially in the abdomen and legs) to prevent venous pooling and preserve cerebral perfusion during acceleration. (2) Valsalva maneuvers used to increase intrathoracic pressure and arterial pressure to preserve cerebral perfusion during acceleration.

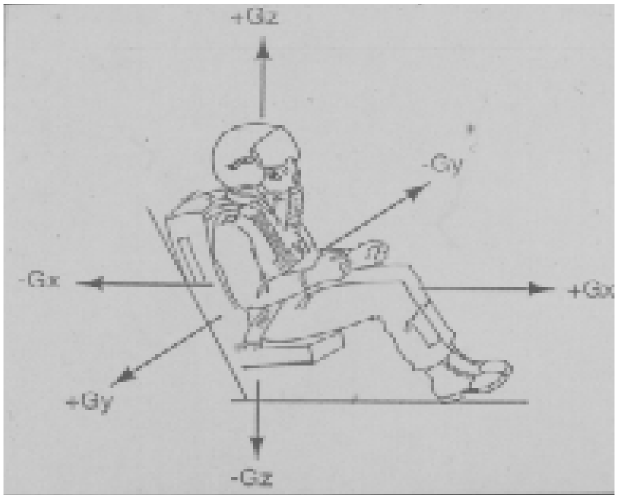

Fig. 33-1. The drawing shows the three standard axes (x, y, z) used to describe inflight acceleration (G) and their positive (+) and negative (–) directional designations. In each instance, the motion of the aircraft produces an opposite reaction in the human body. For example, for a seated pilot, the commonest acceleration is "head-to-foot," or +Gz, in which the aircraft turns sharply with the pilot's head aimed toward the inside of the turn: the headward pull of the aircraft causes soft tissue to sag downward and blood to pool in the legs. Negative Gz occurs less often when the pilot's head is pointed toward the outside of the turn. Positive Gx is commonly experienced when a powerful vehicle accelerates forward, while –Gx occurs with braking. Historically, lateral acceleration (+/–Gy) has not been a problem. Drawing: Courtesy of Mark Regna, Technical Sergeant, US Air Force.

PHYSICAL EFFECTS OF ACCELERATION

Acceleration (+Gz) has mechanical effects on soft tissues and compresses the spine. It also affects the cardiovascular and pulmonary systems, creating increased risks for visual symptoms, G-LOC, and pulmonary atelectasis. The less-common “negative” acceleration (–Gz) causes visual and cardiovascular disturbances and can also cause G-LOC.

Mechanical Effects

Acceleration causes soft tissues to sag; one obvious result is that the face appears to age remarkably—fortunately, a reversible change (Figure 33-2). Acceleration in any axis makes movement difficult. Above +2.5 G it is difficult to rise from a seat and at +3 G the limbs can hardly be raised, so that emergency escape from an aircraft requires an ejection seat. At +8 G any gross movement is impossible, but a pilot whose arms are supported can operate a properly designed control stick and buttons to +12 G and beyond.

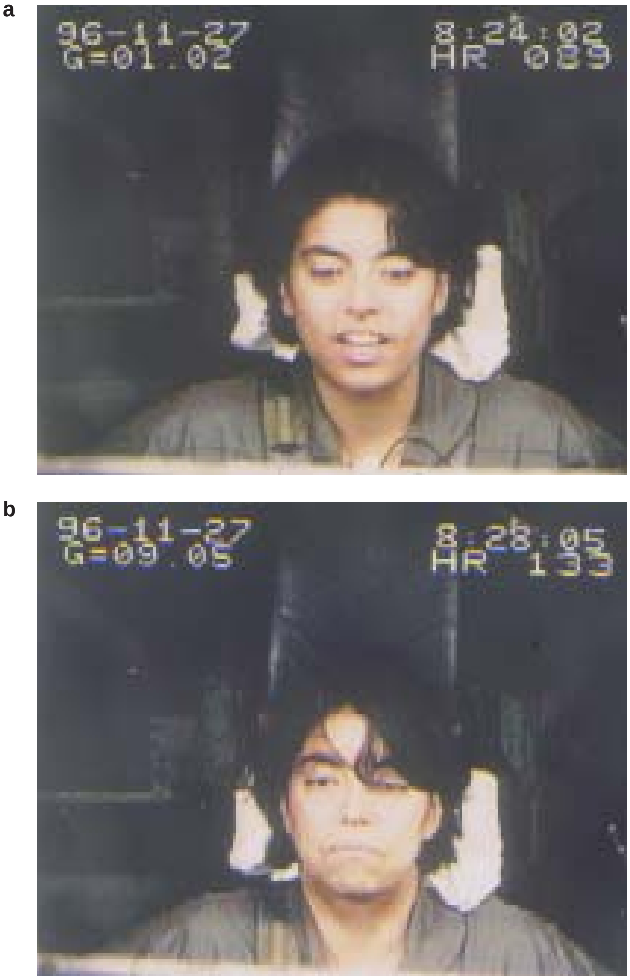

Fig. 33-2. The face of a subject exposed to (**a**) +1 G and (**b**) +9 G. Notice the aged appearance of the subject as she executes a straining maneuver at the higher level of acceleration.

Helmets and helmet-mounted equipment (Figure 33-3) create special mechanical problems because they alter the center of gravity of the head and their acceleration-magnified weight may overstress the cervical muscles. At +8 Gz a helmeted pilot can keep the head erect, but should it tip forward, the chin drops onto the chest and cannot be raised until acceleration is released.[6] Transient compression of the spinal column by up to 5 mm has been demonstrated after flights involving +7 Gz.[7]

Hydrostatic Effects and Cardiovascular Compensation

Acceleration increases the weight of the blood and so raises the pressure gradient in the hydrostatic column along the axis of acceleration. For example, the acceleration due to ordinary turns is

Fig. 33-3. A pilot wearing a Swedish-developed helmet and breathing mask system (mfg by FFV Aerotech AB, Sweden) with chemical–biological protection equipment for use in combination with assisted pressure breathing during acceleration (G). Photograph: FFV Aerotech AB, Sweden.

oriented in the +Gz direction for a sitting pilot, and so increases the pressure gradient from head to foot. Even moderate acceleration has relatively great effects on the venous circulation, greatly increasing venous pressure and therefore pooling below the heart, where "below" varies with the acceleration vector. These effects on the low-pressure side of the circulation in turn compromise venous return and therefore reduce cardiac output to regions above the heart. Heart–head distance has a significant negative correlation with acceleration tolerance, as demonstrated by studies involving a variety of seat-back angles.[3] Tall individuals have a slight disadvantage when sitting upright.

Hydrostatic effects on the arterial side of the circulation become important only at high accelerations.[8] For instance, at +9 Gz, arterial pressure in the feet of a sitting pilot might theoretically reach 630 mm Hg. Although peripheral vasoconstriction and precapillary sphincter constriction prevent some of this rise in pressure, edema and petechiae (also called "G-measles") are commonly found in dependent areas. Prolonged exposure to very high acceleration may induce hematoma in the feet, scrotum, or other dependent body regions.

Exposure to +Gz decreases arterial pressure in the head; in the absence of compensating mechanisms, perfusion to the brain would approach zero at +5 Gz (Figure 33-4). The rigidity of the skull and negative venous pressure above the heart are thought to create a siphon effect, which helps to maintain cerebral circulation, but the eyes have no such protection and are further disadvantaged by the intraocular pressure of 20 mm Hg. It is for this reason that gradual onset of acceleration typically produces visual symptoms before LOC.

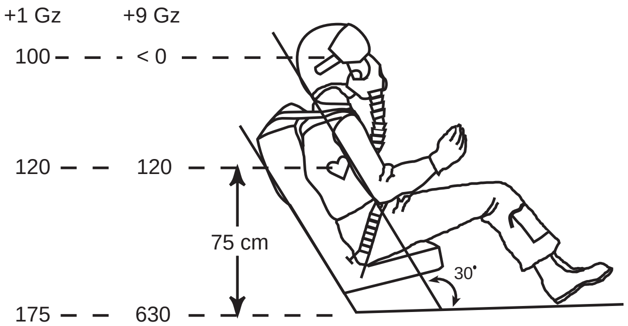

Fig. 33-4. Acceleration alters arterial blood pressure (BP, shown in mm Hg) by increasing the weight of blood and thus the hydrostatic pressure gradient along the axis of acceleration. The model shown here calculates the resulting pressures without considering physiological compensatory mechanisms. In a seated subject at +1 Gz (see Figure 33-1), if BP is 120 mm Hg at the heart, hydrostatic effects reduce the pressure to approximately 100 mm Hg at the head and raises it to 175 mm Hg at the feet. Exposure to +9 Gz increases the hydrostatic gradient: although the body maintains a BP of 120 mm Hg at the heart, pressure at the head decreases to approximately zero, while that at the feet increases to 630 mm Hg.

During exposure to high +Gz (also called high *G-loads*), when blood is forced in the head-to-foot direction, baroreflexes in the carotid and aortic regions above the heart compensate for declining blood pressure with an increased heart rate and a moderate rise in peripheral resistance. This compensation requires 5 to 10 seconds to take effect and may be too slow to affect tolerance for rapid-onset acceleration.[9] It is therefore during the first few seconds of increasing acceleration that a pilot is most vulnerable to LOC. Recent research shows that tolerance for +Gz decreases markedly in a "push–pull" maneuver, when a brief period of mild –Gz precedes the +Gz stress.[10]

Pulmonary Effects

Acceleration (+Gz) makes breathing difficult by pulling down the diaphragm and exaggerates the ventilation–perfusion mismatch in the lungs. Basal congestion tends to close off lower airways, a tendency that is increased by compression from the abdominal bladder of an anti-G suit. Should the pilot also be breathing a high percentage of oxygen for protection from hypoxia, the rapid absorption of this gas from poorly ventilated basal alveoli may lead to symptomatic pulmonary atelectasis (Figure 33-5).[11]

Negative Acceleration

A pilot is exposed to negative acceleration (–Gz) during an outside loop (ie, when the pilot's head points to the outside of the turn) or the transition from a steep climb into a dive. Increased venous pressure and pooling of the blood in the head and face cause a sensation of fullness and sometimes headache. With longer exposures, facial edema develops, along with lacrimation, blurred vision, and a red-colored visual fog. A high level of –Gz is extremely uncomfortable and the eyes may feel as if they will pop out. Various cardiac arrhythmias may occur, including bradycardia followed by asystole and unconsciousness. While a stress of –2 Gz may be tolerated for up to 5 minutes, –3 Gz can be borne for only 30 seconds, and –4 Gz for only a few seconds.

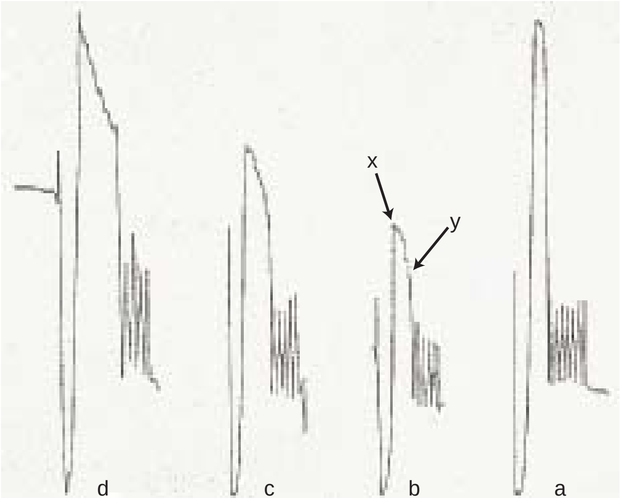

Fig. 33-5. Changes in vital capacity for a human subject (**a**) before and (**b, c, d**) after a 4-minute exposure to varied levels of acceleration while breathing 100% oxygen. Note that spirometry tracings are recorded from right to left. A sharp atelectasis-induced reduction in vital capacity occurred immediately (**b**) after the ride and (**c**) 1 minute later. The tracings reveal two components: stable atelectasis (x) and labile atelectasis (y). (**d**) The final tracing shows return to normal vital capacity after the subject took several deep breaths to clear the atelectasis. Reproduced with permission from Tacker WA, Balldin UI, Burton RR, Glaister DH, Gillingham KK, Mercer JR. Induction and prevention of acceleration atelectasis. *Aviat Space Environ Med.* 1987;58:71.

TOLERANCE TO ACCELERATION

Tolerance for high acceleration has been extensively studied in volunteers who are riding human centrifuges. Exceeding an individual's tolerance limits leads to G-LOC. Because a variety of factors help determine acceleration response, tolerance varies widely between individuals and fluctuates for the same person from day to day.

Tolerance Limits

Tolerance limits for +Gz acceleration are usually signaled by visual symptoms including tunneling, dimming, grayout, and blackout (Figure 33-6). During slow onset of acceleration, a relaxed subject not wearing an anti-G suit typically experiences initial visual symptoms at +4 Gz (range: +2 to +7 Gz) followed by blackout with a further +1 Gz; with faster onset, visual symptoms occur at lower acceleration levels. A subject can remain conscious through rapid onset to a transient high-G peak with immediate deceleration, but if the high acceleration persists, he will lose consciousness without any warning visual symptoms.

G-LOC (discussed in greater detail below) is often seen on the centrifuge, when the experimental subject fails to stop the run at onset of visual symptoms. The subject's head drops to the chest and seizure-like flailing motions may occur. Consciousness returns immediately as the centrifuge slows; the subject begins to raise the head, looks briefly confused, and then can respond to questions.[12] Subjects frequently do not remember the incident and may deny losing consciousness. Repeated episodes of G-LOC in healthy individuals appear to have no acute

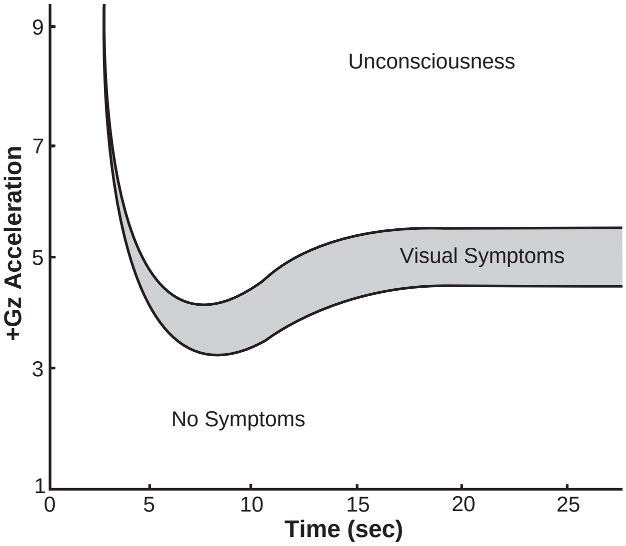

Fig. 33-6. Generalized human time–tolerance curve for +Gz acceleration (see Figure 33-1). The curves were developed from a large number of centrifuge experiments using relaxed human volunteers. The left side of the curve indicates relatively high tolerance levels for exposures that are so short that there is not enough time for development of venous pooling or cerebral hypoxia. The right side of the curve shows that tolerance is around 5 G for exposures of 15 to 30 seconds, which allow full activation of cardiovascular defense mechanisms; visual symptoms (first grayout, then blackout) precede loss of consciousness. The dip in tolerance for exposures of 5 to 15 seconds reflects the interval when venous pooling and cerebral hypoxia develop before cardiovascular defense mechanisms are fully activated. Reproduced with permission from Stoll AM. Human tolerance to positive G as determined by the physiological end-points. *J Aviat Med.* 1956;27:356-367.

or chronic aftereffects.[13]

During flight, an episode of G-LOC means that the pilot (1) unexpectedly ceases to control the aircraft for a critical period of time and (2) may not realize what has happened. G-LOC is a cause of accidents in high-performance aircraft[2]; however, because G-LOC is a transient functional state, its role in a fatal accident is always difficult to ascertain, as no evidence will be available at autopsy. G-LOC accidents are characterized by the crash of a mechanically intact aircraft that is both performing a high-G maneuver and lacks appropriate pilot response for recovery from the situation. The abrupt cessation of voluntary straining maneuvers can be detected in cockpit sound recordings and provides evidence of G-LOC.

Factors That Lower Tolerance

General fatigue, sleep deprivation, and any form of hangover or illness may significantly reduce acceleration tolerance. Pilots should therefore avoid flying high-G missions when they are ill or recovering from illness. Pilots should also be aware that their tolerance for high acceleration diminishes during any substantial layoff period during which they are not flying high-G maneuvers.

Heat stress and dehydration measurably decrease acceleration tolerance, owing to the combined effects of increased peripheral vasodilation and reduced plasma volume. A 3% level of dehydration significantly reduces tolerance for high acceleration even with the use of an anti-G suit and straining.[14] Extensive sunburn, with its peripheral cutaneous vasodilation, would likely decrease tolerance to acceleration in a similar way.

Hyperventilation due to anxiety, mental stress, hypoxia, and pressure breathing (see Exhibit 33-1) may decrease acceleration tolerance through cerebral vasoconstriction and peripheral vasodilation.

Countermeasures for Acceleration Effects

The adverse effects of high acceleration may be reduced by use of semireclining seats to the extent that they are compatible with aircraft design. Other countermeasures include voluntary straining maneuvers, anti-G suits, and pressure breathing.

Seat Configuration

The standard, chairlike seat in most cockpits has many advantages, such as easy adaptation to ejection requirements, but the upright back maximizes the length of the hydrostatic column subjected to +Gz acceleration. The change to a 30° seat-back angle in the US Air Force F-16 and French Rafale fighter planes reduces heart–brain distance and leads to a small but measurable increase in the threshold for visual symptoms.[3] Greater effects might be produced by further reclining the seat to 70° and elevating the feet; it would be even better to place the pilot in the prone position. However these more horizontal positions create difficulties in aircraft design and combat flying. Most fighter pilots crouch forward in combat, thus slightly reducing the heart-to-head distance.

Straining Maneuvers

Acceleration tolerance can be increased by 3 to 4 G through skilled use of straining maneuvers, which include (1) muscular contractions of the abdomen and legs, and (2) specialized respiratory techniques. The large-muscle component consists of strong, sustained isometric contractions of the muscles of the abdomen and limbs, producing a reflex increase in blood pressure and a mechanical decrease in peripheral pooling. The respiratory component involves use of Valsalva and related respiratory maneuvers to raise intrathoracic pressure and hence the arterial pressure at the heart.

These maneuvers must be taught to pilots, who learn to tense all major muscle groups while adopting a breathing pattern that involves straining against a closed glottis for 3 to 4 seconds, taking a quick breath and returning to straining. Regular practice is required to maximize both skill and stamina for these maneuvers, and strength training of major muscle groups has been found to significantly increase tolerance for sustained high-G profiles. Straining was formerly taught on an ad hoc basis during flight instruction, but much more consistent results are now obtained by training pilots on a human centrifuge (Figure 33-7).[15]

Physical Training

Various strength training programs have been developed in attempts to increase acceleration tolerance and stamina.[16] It appears that effective training can be accomplished without inducing muscle hypertrophy. Possible mechanisms include improved neuromuscular efficiency, which is seen during the initial phases of any strength training program. Despite the important role of abdominal

Fig. 33-7. The human centrifuge at Brooks Air Force Base, San Antonio, Texas. The closed gondola seen at the left carries one subject strapped into an aircraft seat, as well as a variety of measurement devices. The centrifuge operators, medical monitor, and investigators sit behind the windows seen above the centrifuge; they communicate with the subject by intercom and observe him or her through closed-circuit television. The machine is driven by hydraulic motors connected to an enormous "bull gear" under the center of rotation. The gondola swings on its fore-to-aft axis so that the resultant acceleration is always oriented from floor to ceiling; at rest the capsule floor is horizontal like the floor of the room, but during centrifugation it rotates out to parallel the wall. Study of different acceleration axes is accomplished by repositioning the chair within the gondola. Subjects experience significant, nauseogenic Coriolis effects during changes in centrifuge speed.

tensing in anti-G straining maneuvers, training limited to these muscles is not effective; training programs must include all of the major muscles of the legs, arms, and abdomen. Muscle biopsies of subjects trained on a centrifuge show no correlation of tolerance with the proportion of slow- or rapid-twitch muscle fibers.

A moderate level of aerobic fitness is thought to enhance acceleration tolerance and reduce overall fatigue. However, some authorities believe that excessive aerobic conditioning can reduce acceleration tolerance, perhaps because the athletic heart, with its very low resting rate, takes longer to respond to sudden acceleration stress. As a result, pilots of high-performance aircraft are now expected to follow a regular exercise program that combines moderate aerobic exercise with strength training, adding special exercises to maximize the strength of neck muscles.

Drugs

Pharmacological modalities have been examined for their potential to improve tolerance to acceleration but without much success. They usually have only marginal, transient effects and many have undesirable side effects. Ephedrine and amphetamine sulfate may reduce the fatigue caused by repeated fighter sorties, but their adverse effects outweigh any benefit and make their use inappropriate during ordinary high-performance aircraft operations.

Anti-G Suits and Positive-Pressure Breathing

As stated above, anti-G suits were initially developed during World War II and changed little over the ensuing 40 years. These suits consist of trousers made of two layers of nonstretch material, with rubber bladders inserted at the calf, thigh, and abdomen (Figure 33-8). The bladders are interconnected, and the abdominal bladder is fitted with an umbilical hose that is connected to a special regulator (the G-valve), which provides gas pressure to the anti-G suit in proportion to the +Gz level. The suit pressurizes automatically when the G-valve senses acceleration; this inflation tightens the trousers around the limbs and abdomen and thus reduces dependent pooling. In addition, the abdominal bladder enhances the return of blood from the

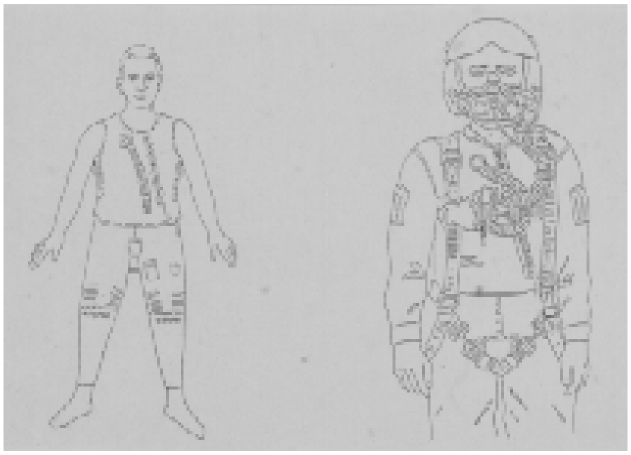

Fig. 33-8. An example of a modern US Air Force anti-G system. A pneumatic valve automatically inflates the bladders covering the legs to reduce venous pooling and delivers positive pressure to the mask to elevate intrathoracic pressure and hence blood pressure. The use of a counterpressure vest reduces the work of exhalation associated with positive pressure breathing. The valve delivers pressure that is proportional to the G load; pressure in the vest and mask is always slightly lower than that delivered to the leg bladders.

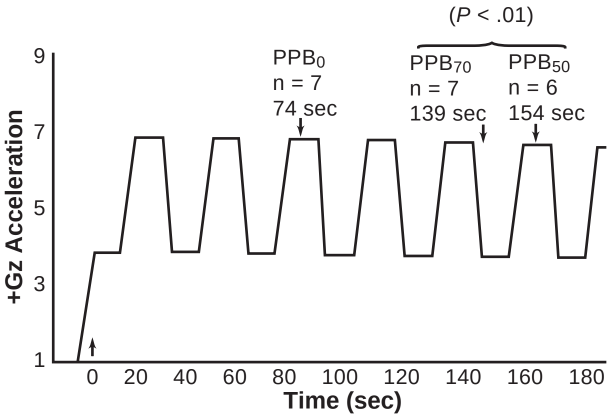

Fig. 33-9. Acceleration profile for a simulated air-combat maneuver on the centrifuge at Brooks Air Force Base, San Antonio, Tex. Alternating 5- and 9-G intervals of 10 seconds represent the acceleration experienced by a pilot engaged in a dynamic dogfight with another aircraft. Volunteer subjects were highly trained to become accustomed to the centrifuge; they wore anti-G suits and performed straining maneuvers to maintain consciousness while riding the repetitive profile to the point of exhaustion or impending blackout. Marks indicate mean endurance time without pressure breathing (PPB$_0$) and with pressure breathing levels of 50 and 70 mm Hg (PPB$_{50}$ and PPB$_{70}$). Note that PPB significantly lengthens endurance by reducing the need for voluntary straining. There is a significant advantage for the higher level of PPB. The arrows represent times and do not coincide with plateaus. Reproduced with permission from Burns J, Balldin UI. Assisted positive-pressure breathing for augmentation of acceleration tolerance time. *Aviat Space Environ Med.* 1988;59:229.

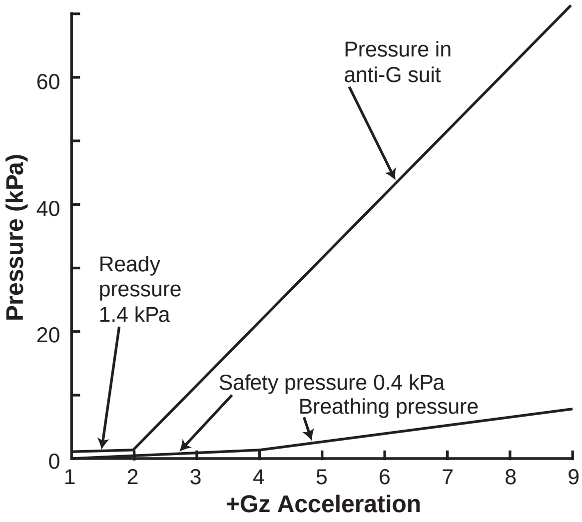

Fig. 33-10. A schedule for automatic delivery of pressure to an anti-G suit and positive-pressure breathing system. A slight residual pressure is maintained in both mask and leg bladders in normal flight (1–2 Gz) to allow instantaneous delivery of increased pressure on sudden onset of high acceleration (G). The profiles shown are for the life support system of the Swedish Air Force Gripen (Griffin) fighter aircraft; US Air Force equipment and pressure schedules are similar. Reproduced with permission from Balldin UI, Dahlback G, Larsson L-E. *Full Coverage Anti-G Suit and Balanced Pressure Breathing.* Stockholm, Sweden: FOA Report C50065-5.1; 1989. ISSN 0347-7665.

abdomen to the thorax and reduces the downward movement of the diaphragm and heart at high acceleration.

As explained above, the development of advanced fighter aircraft during the 1980s created a demand for improved anti-G protection. Anti-G valves were modified to provide faster inflation profiles. Experimental suits were made to produce sequential pressurization of bladders, and other variations were explored. However, the major improvement came with the development of full-coverage anti-G suits, in which the bladders entirely surround the legs.

Recent experimental work on human centrifuges[17] showed that balanced positive-pressure breathing during acceleration (PBG), can be substituted for respiratory straining maneuvers (Figure 33-9). The advantages of PBG include substantially diminished fatigue as well as restoration of ability to talk at high acceleration. Because inspiratory pressures during PBG usually exceed 30 mm Hg and can reach 60 mm Hg, a counterpressure bladder over the chest is used to ease the work of expiration. The resulting combination of positive-pressure breathing and chest counterpressure is sometimes termed "assisted PBG." New anti-G valves were required to control the differing but related pressures needed in the anti-G suit and the mask–vest system (see Chapter 32, Pressure Changes and Hypoxia in Aviation). A typical pressure schedule used for PBG appears in Figure 33-10.

The combination of full-coverage suits and assisted PBG increases the maximum level of acceleration that can be tolerated.[18] A major effect of this combination lies in reducing fatigue. Centrifuge subjects can ride relaxed at up to +8 to +9 Gz, and their endurance time for continuous sequences of high-G maneuvers increases 4-fold or more. Experienced fighter pilots have endured more than 12 minutes on a centrifuge-simulated aerial combat profile consisting of alternating 10-second periods at +5 and +9 Gz.

ACCELERATION-RELATED PHYSIOLOGICAL PERTURBATIONS

Acceleration effects on pilots may include motion sickness, cardiovascular and pulmonary effects, and neck and back pain. Protective equipment such as anti-G suits and pressure-breathing systems may produce unwanted side effects. Although men and women have similar tolerance levels, anatomical differences can produce gender-specific problems. Medication of various types can reduce G tolerance.

Motion Sickness

Rapid changes in acceleration stimulate the semicircular canals and may be accompanied by spatial disorientation, vertigo, and motion sickness, especially if the subject makes simultaneous movements of the head. This topic is discussed more completely in Chapter 35, Motion Sickness.

Cardiac Dysrhythmias

There is no scientific evidence that acute or chronic acceleration exposure damages the heart. Mild acceleration, like exercise, often eliminates the occasional premature ventricular contractions seen in healthy individuals. On the other hand, high acceleration on the centrifuge often stimulates more-serious dysrhythmias, including frequent premature atrial contractions and premature ventricular contractions, and, more rarely, ventricular tachycardia.[19,20] An electrocardiograph used with a centrifuge may also record relative bradycardias that proceed to asystole. Any of these arrhythmias may lead to LOC; fortunately, they routinely revert to normal as the centrifuge is brought to a halt (Figure 33-11).

These arrhythmias are not a result of pathology but reflect functional problems caused by displacement of the heart and diminished blood supply to the cardiac muscle and nodes. Medical observers are trained to immediately halt any centrifuge run in which a subject exhibits relative bradycardia, prolonged ventricular bigeminy or trigeminy, multiple paired or multifocal PVCs, or more than three beats of ventricular tachycardia. Pilots should be discour-

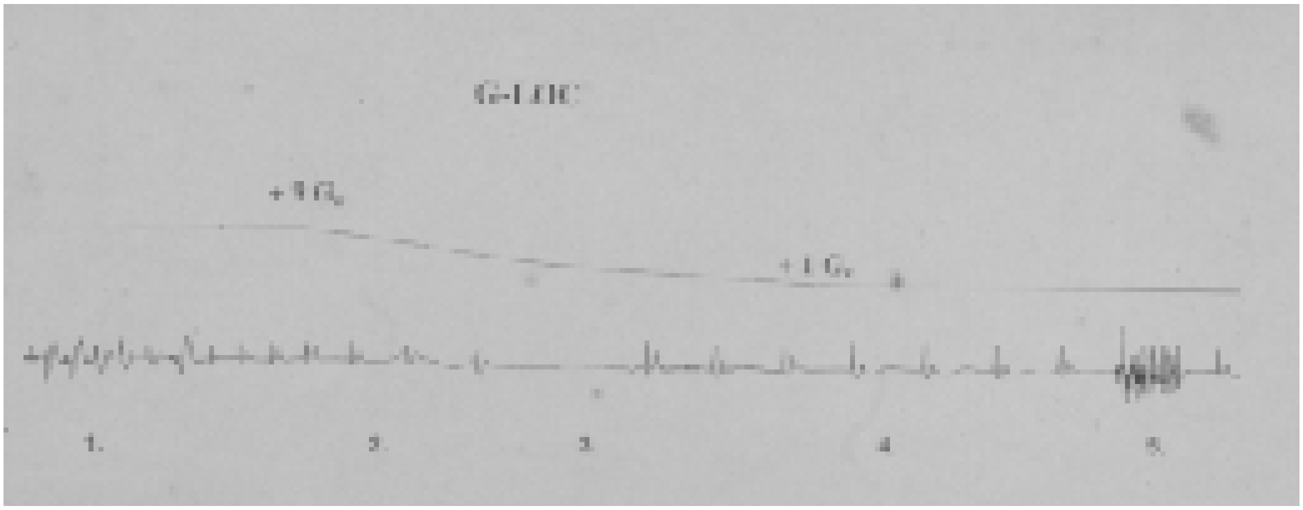

Fig. 33-11. The electrocardiogram for a human subject during and after a centrifuge run that peaked with several seconds at +9 Gz (see Figure 33-1) and was terminated when the subject suddenly lost consciousness (G-LOC). The upper line shows the decreasing acceleration (G) level as the centrifuge was slowed and stopped. Note (**1**) the onset of ventricular tachycardia at +9 Gz followed by (**2**) bradycardia of 45 beats per minute, (**3**) asystole lasting 7 seconds and (**4**) a further period of bradycardia at 35 beats per minute as the level of acceleration fell. (**5**) The subject regained consciousness and a normal cardiac rhythm on return to +1 Gz and had no sequelae. Although occasional premature ventricular contractions are a common occurrence at high acceleration, the response shown here is rare. Acceleration-induced arrhythmias correct themselves when the stress is discontinued but could still prove fatal to the pilot of a single-seat aircraft.

aged from using caffeine because of its tendency to produce arrhythmias.

Pulmonary Shunts and Atelectasis

The redistribution of blood in the lungs during acceleration amplifies ventilation–perfusion mismatching and reduces oxygen saturation.[21] During typical +Gz acceleration, blood pools at the base of the lungs, causing edema and constriction of the distal airways, reducing local ventilation. The acceleration also displaces lung tissue, stretching and expanding the apical alveoli. This displacement can occasionally be sufficient to cause pneumothorax and mediastinal emphysema. Pilots who breath an oxygen-rich mixture ($> 70\%$ O_2) during high-G maneuvers may experience bronchial irritation, substernal pain, cough, and shortness of breath. Laboratory studies have demonstrated a decrease in vital capacity under such conditions, and it has been shown[11] that the underlying problem is pulmonary atelectasis due to the rapid absorption of oxygen from closed-off, highly perfused alveoli near the base of the lung. Usually these symptoms diminish and disappear following several deep breaths. The problem can be prevented by keeping at least 30% nitrogen in the inspired gas unless altitude exposure dictates otherwise.

Pain, Petechiae, and Edema

Fit problems with helmets, anti-G suits, and vests, which seem minor on the ground, may lead to painful pinching, friction, and bruising at high acceleration. The increased intravascular pressures in the body during high G-loads, straining, and pressure breathing may cause petechiae, edema, and even hematoma formation in unprotected areas below the heart, including the arms, hands, crotch, and feet. Prolonged exposure to high G-loads can cause severe arm pain, especially when PBG is used in aircraft with a control stick placed well below the heart. Proteinuria may be seen following severe acceleration exposures.

Disorders of the Back and Neck

Fighter pilots often complain of acute neck pain, especially following aerobatic maneuvers accompanied by rapid head movements.[6] Chronic problems may also develop, especially in crew members who wear helmets loaded with electronic devices. The lower cervical spine seems to be most vulnerable to injury, especially in navigators or weapons officers who are subject to unexpected acceleration. Regular strength training of the neck muscles seems to diminish the number of complaints; nevertheless, serious injuries can occur; documented acceleration-induced injuries include torn ligaments as well as fractures of the cervical vertebral bodies and spinous processes.

A slight possibility for cervical disc problems exists when a fighter pilot moves his head during lower but more sustained acceleration. A fully loaded helmet (ie, a helmet mounted with displays, sights, laser eye protection, night vision goggles, etc) adds to the weight and increases the probability for neck injuries. Neck pain is reported in more than one third of the pilots who fly high-performance fighter aircraft.[6,7] Magnetic resonance imaging occasionally shows bulging cervical discs among symptomatic fighter pilots, and there are indications of an increased risk of degenerative changes with chronic exposure.

Back pain has also been reported[8,16] among fighter pilots, but this condition is so common in the nonflying population that it is difficult to relate it to acceleration exposure. A study[22] using magnetic resonance imaging (MRI) investigated two groups: 22 asymptomatic males who had previously been subjects in Gz centrifuge experiments and 19 age-matched, asymptomatic, nonaccelerated controls. Individuals of both groups were seen on MRI to have disc bulges, herniated nucleus pulposus, disc degeneration or desiccation, and Schmorl's nodule. Most of the abnormalities occurred from the mid-thoracic through the lumbar spine (one subject from each group had a bulge or a herniated nucleus pulposus in the cervical spine), but no significant differences were found between the two groups. Thus, exposure to acceleration per se does not appear to result in spinal column abnormalities. In extreme cases, spinal column trauma has been seen after exposures to high acceleration in aircraft as well as in centrifuges. The severe +Gz acceleration on the spine during ejection with gun-type seats exceeds +25 G for 0.12 to 0.15 seconds and is known to cause compression fractures of the vertebral bodies and herniated intervertebral discs. With rocket-assisted ejection seats, the acceleration peak is reduced to +15 G or less during 0.2 to 0.5 seconds, thus reducing the risk for spinal injuries. In addition, windblast during high-velocity ejections may cause injuries when the arms and legs are flailing.

Continuing improvements in aircraft performance have produced a need to look at acceleration up to +12 Gz. To minimize the risk to human subjects, several laboratories sought improved methods for documenting the integrity the vertebral column. However, neither conventional methods nor magnetic resonance imaging shows a good correlation between disc pathology and subjective symptoms.[22]

Side Effects of Using Acceleration-Protective Equipment

While new anti-G equipment increases acceleration tolerance to match current flight profiles, it will also likely lead to expectations for further increases in aircrew tolerance for long-duration, high-G exposure. These more-severe exposures to acceleration will likely lead to the reappearance of known problems as well as create new ones. For instance, prolonged centrifuge experiments reveal the need for anti-G suits that include pressure socks to control pain, petechiae, and edema in the feet. Other problems include arm, neck, and back pain; motion sickness; and generalized fatigue. Many of these symptoms persist long after flight and will become troublesome challenges for commanders and flight surgeons as they accumulate during prolonged flights or surge operations.

Gender-Specific Medical Risks

The risks for women exposed to high G-loads are not particularly well studied but are generally similar to the risks for men.[23] However, the need for correct fitting of protective equipment is an important issue; anti-G suits must be tailored to fit women to prevent the abdominal bladder from compressing the lower ribs, causing pain and restricting breathing.[24] Men, on the other hand, may have a slight risk of high-G-related discomfort to their genitalia, such as scrotal pain and hemorrhage.

Women may experience increased menstrual flow or bleeding (spotting) between menses during acceleration stress.[25] The effects of acceleration on a fetus are also mostly unknown, and the potential for fetal injury, malformation, spontaneous abortion, or fetal death cannot be excluded. Rarely, oral contraceptives may cause formation of thrombosis, which might become dislodged and advance to the lungs with possible fatal results. If there is an augmented risk of dislodging thromboses during increased G-load, it is currently unknown; however, the lower hormone content of modern oral contraceptives may have substantially minimized this risk.

ACCELERATION-INDUCED LOSS OF CONSCIOUSNESS

G-LOC develops gradually during slow onset of acceleration. The subject usually experiences dimming or tunneling of vision followed by blackout before actual unconsciousness occurs (see Figure 33-6). However, with sudden onset of acceleration and high G levels, G-LOC may occur without warning. In centrifuge experiments in which the machine is immediately slowed to a halt, unconsciousness typically lasts 10 to 15 seconds and is followed by an equal or longer period of mental confusion that is often accompanied by convulsive movements.

Subjects may report having vivid dreams during this period.[13] Amnesia is also a frequent occurrence, so that subjects deny that they lost consciousness and are dumbfounded when shown video tapes of the episode.

MEDICATIONS FOR PILOTS OF HIGH-PERFORMANCE AIRCRAFT

Few systemic medications are acceptable for pilots of high-performance aircraft, as drugs might interfere with the flying and mission capabilities. Exceptions include single doses of aspirin, antacids for mild epigastric distress, hemorrhoidal suppositories, and bismuth subsalicylate for mild afebrile diarrhea. Decongestant nasal sprays may be used to treat ear block for get-me-down purposes (see Exhibit 32-8 in Chapter 32, Pressure Changes and Hypoxia in Aviation). Oral antibiotics and topical acyclovir (Zovirax, mfg by Burroughs Wellcome, Research Triangle Park, NC) may also be allowed, if prescribed by a flight surgeon.

Other drugs may be approved after a waiver has been received from the appropriate command level when the potential for idiosyncratic reactions is excluded and with certain restrictions:

- malaria prophylaxis,
- scopolamine and ephedrine for airsickness in flying trainees,
- doxycycline for mild diarrhea (after 72 h ground testing),
- completion of oral antibiotics for asymptomatic streptococcal pharyngitis and other specified infections,
- vaginal creams or suppositories, and
- some medications for treatment of acute urinary tract infection or prostatitis (after symptoms have abated).

Waivers may also be obtained for use of other, less commonly indicated medications such as chlorothiazide or hydrochlorothiazide for controlling hypertension, and triamterene, probenecid, and allopurinol for gout.

SUMMARY

Crews of fighter aircraft encounter severe physical stress due to the acceleration produced by aerobatic maneuvers. G-LOC was first recognized early in the development of military aviation and has reemerged as a problem with the recent introduction of increasingly powerful, agile aircraft. Acceleration effects include increased weight of head and extremities, sagging of soft tissue, spinal compression, and amplified hydrostatic gradients in the cardiovascular system. With slow onset of acceleration, cardiovascular reflexes provide some protection, and visual changes precede loss of consciousness. For rapid onset and higher acceleration levels, voluntary straining maneuvers and protective clothing are used to increase tolerance. Relaxed tolerance for head-to-foot acceleration (normally about 4 +Gz) can be substantially increased by tensing the limbs and abdominal muscles combined with respiratory maneuvers to increase intrathoracic pressure. Introduction of PBC, combined with extended-coverage anti-G suits, has improved acceleration tolerance by reducing the fatiguing effort required.

Crews who fly fighter aircraft are expected to engage in regular physical training to increase neck strength and improve the efficacy of limb contractions; regular acceleration exposure in flight or on a centrifuge are required to optimize the combination of limb tensing, abdominal contractions, and respiratory maneuvers. Many factors can reduce acceleration tolerance, including fatigue, loss of training effects, illness, and medication or hangover.

Medical problems associated with exposure to acceleration include skin manifestations (petechiae or bruising), dependent edema, back and neck pain, and muscle strains. In addition, cardiac arrhythmias may occur during exposure, although these normally disappear when acceleration abates.

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