Gs and Aerobatic Pilots

DISCLAIMER — There is a current joke in the medical research community that has to do with using white rats for research. In the future, so the joke goes, lawyers will be used because they're more plentiful and you don't get so attached to them. These are litigious times, and anyone giving advice on the life threatening pastime of flying high G maneuvers must of necessity do so with caution. The material presented in this work is, of necessity, general in nature and is by no means complete. Individuals with disease states or metabolic conditions that are not discussed are warned, along with all other readers, to consult an Aviation Medical Examiner prior to applying any of the material contained in this article.

INTRODUCTION — The lore of competition aerobatic flying is full of anecdotes concerning pilots who died because they could not maintain consciousness as a result of the high sustained accelerations developed in the sport. The purpose of this article is to discuss the factors that influence the individual's ability to tolerate Gs and to suggest methods for the enhancement of acceleration tolerance that might be useful to aerobatic pilots.

Tolerance to sustained acceleration varies widely from individual to individual and from day to day for a single individual. The primary factors that determine acceleration tolerance are as follows:

Anatomy, Physiology and Physics
Body orientation with respect to the G vector
Magnitude of Gs
Duration of Gs
Rate of change of Gs
Proficiency in performance of self-protection (straining) maneuvers
Somatotype (the individual's build)
Physical fitness/type of exercise
Age
Blood pressure
Fatigue/rest status
Diet/nutrition
Dehydration
Ambient temperature
Altitude
Illness
Medications

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To provide a foundation of understanding at the outset I will discuss the physics, anatomy and physiology of acceleration. The role of some of the factors listed above will then be self-evident.

ANATOMY, PHYSIOLOGY AND PHYSICS OF G TOLERANCE — In aerospace medical acceleration research the effects of acceleration on human physiology are separated according to the body axis through which the acceleration acts. Pilots with a background in aerodynamics should keep in mind that when an acceleration physiologist talks about Gs he is talking about the INERTIAL EFFECTS of the acceleration ($F = -ma$). Three physiological axes are defined using (+) and (-) signs to denote the direction of the inertial force in a given body axis. These axes and their directions are defined as follows:

+Gz: Headward acceleration (vernacular "eyeballs down")
-Gz: Footward acceleration ("eyeballs up")
+Gy: Lateral acceleration ("eyeballs left")
-Gy: Lateral acceleration ("eyeballs right")
+Gx: Transverse acceleration ("eyeballs in")
-Gx: Transverse acceleration ("eyeballs out")

A few examples: inside loops produce +Gz, outside loops produce -Gz, sideslips produce (+) or (-) Gy, abrupt forward acceleration in the aircraft's longitudinal axis produces +Gx, and abrupt deceleration produces -Gx.

The necessity for all of these definitions in acceleration physiology depends basically upon human anatomy. Human tolerance to acceleration is lowest in the +Gz direction and, in order to understand why this is true, refer to ***Figure 1.*** The left-hand drawing in this figure indicates that the vertical distance (in a pilot seated upright) from the aortic valve in the heart to the retina of the eye is, on the average, a distance of 32.5 centimeters (350 millimeters). Sitting in a chair in normal earth gravity your heart must pump this column of fluid (with a density roughly equivalent to sea water) up to the eyes and brain.

In order to determine what that pumping pressure means in terms of blood pressure, we divide the height of this "water" column by the density of mercury (13.6) and find that (at one G) this amounts to a pressure head of about 24 millimeters of mercury (mmHg). Pulling +2Gz makes that fluid column twice as heavy (or twice as high, depending on how you choose to look at it), which means that the heart must increase its pressure output by another 24 mmHg in order to keep the eyes and brain perfused with blood in the normal manner. At +5Gz, the heart must pump a pressure of about 120 mmHg additional (5 x 24) in order to keep you conscious. For the average relaxed and unprotected man subjected to gradually increasing acceleration in the +Gz direction, dimming of vision commences in the range of 3.0-3.5G and continues to peripheral vision loss in the range of 3.5-4.5G.

Tolerance, however, is a tricky word to define when you're dealing with acceleration because different kinds of tolerance endpoints are used. The symptoms of slowly applied +Gz acceleration are primarily visual (aside from the sensations of increasing body heaviness). The earliest symptom is loss of peripheral vision and this becomes increasingly worse as the stress is sustained. The vision eventually (or quickly) collapses to tunnel vision, followed by graying or dimming of vision, followed by blackout, followed by unconsciousness.

These symptoms are caused by the decreasing effective blood pressure at the level of the eyes. Because of this decrease in effective pressure, the heart is unable to fill the arteries in the retina and, as this process goes on, the eyes cease to be perfused at all and you are then "blacked out." The pressure of fluid within the eyeball (the intra-ocular pressure) is equal to about 20 mmHg, which means that when the man is in blackout, there is still about 20 mmHg pressure left to perfuse the brain, or at least some of it.

For this reason it is possible to be in blackout and still be conscious. If the stress is continued unconsciousness will result. A G-induced loss of consciousness (GLOC) results in a period of absolute incapacitation which lasts, on the average, about 15 seconds (range 9 to 30) if the acceleration is reduced to near normal earth gravity. This period of absolute incapacitation is followed by a period of relative incapacitation in which the individual is nominally conscious but not capable of purposeful action ("the lights are on, but nobody's home") which may last another 30 seconds.

When reading papers on acceleration research it is necessary to understand what exact endpoint was being used to define tolerance. Current practice in at least three military laboratories is to use peripheral light loss (PLL) as the endpoint. The exposure is terminated when the subject's peripheral vision (which he tracks with a control stick and a ring of peripheral light emitting diodes) collapses to an included angle of 30 to 60°.

THE EFFECT OF G ONSET RATE — Human tolerance to rapid onset rate acceleration is less than tolerance to gradual onset acceleration. During gradual onset rate (GOR) acceleration (arbitrarily defined as a rate of less than one G/second increase in Gs) tolerance is increased by cardiovascular compensatory reflexes. Sensors in the circulatory system detect the changes in flow and blood pressure and respond by narrowing the diameter of the blood vessels in the peripheral circulation, by increasing the strength of contraction of the heart muscle, and by increasing the heart rate (the number of heartbeats per minute). These latter two effects increase cardiac output, which is measured in liters per minute of blood pumped by the heart.

The mean arterial blood pressure is defined as the product of peripheral vascular resistance and the cardiac output. As the body reflexively increases the peripheral flow resistance by narrowing the blood vessels and increases cardiac output, the result is an increase in blood pressure which is exactly what is required to increase G tolerance. This process requires ten to fourteen seconds to develop fully and increases tolerance about one G.

Figure 2 shows the tolerance curve to GLOC of relaxed subjects with no anti-G suit protection. Notice that the time to GLOC decreases dramatically when the rate of onset is above one G/second. Notice that at higher onset rates, the curve becomes asymptotic; further increases in onset rate cause only very small decreases in tolerance time. This is true because the limiting factor is the blood oxygen reserve of the brain which maintains consciousness for three to five seconds irrespective of the onset rate. The reality of the brain's blood oxygen reserve is responsible for the anecdotes you hear around the bar to the effect that so-and-so pulled 12Gs without blacking out. Sure he did, but not for long!

Through training and experience, pilots of high performance aircraft learn to fine tune their G tolerance by observing the changes in their peripheral vision as it progresses toward tunnel vision, grayout and blackout. It is common for pilots to add and unload Gs to maintain a maneuver short of actual blackout.

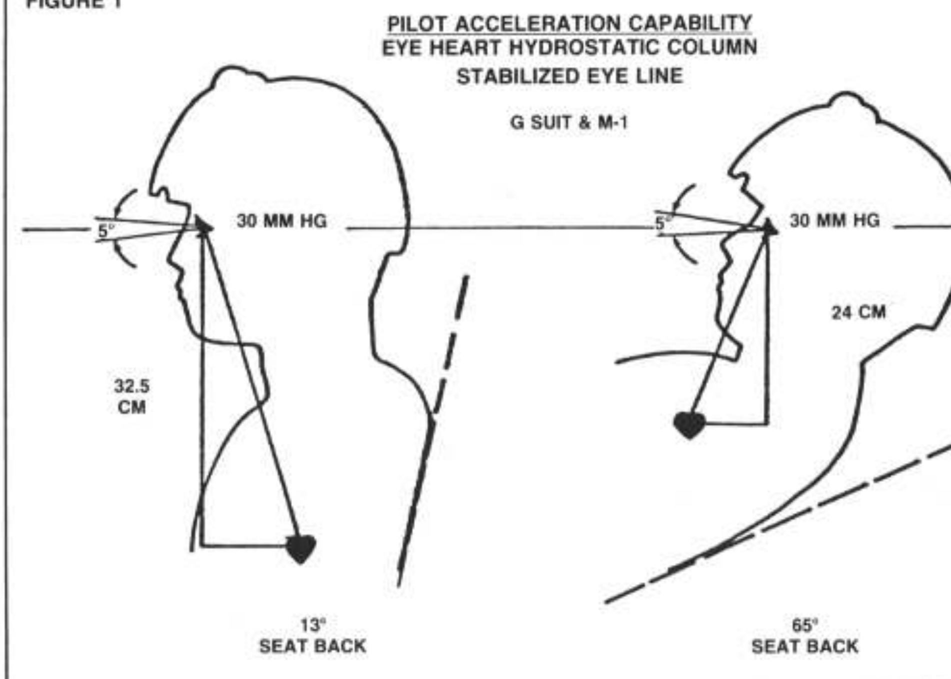
When performing a rapid onset run (ROR) in a snap maneuver to a sustained high G level there is a very real danger of an abrupt GLOC without any of the warning symptoms because there is no time for cardiovascular compensation and the individual is running on the brain blood oxygen reserve. The straining maneuver can, to a degree, alleviate the rapid drop in blood pressure and is critical in maneuvers of this sort.

Accordingly it is important that the unprotected (aerobatic) pilot be skilled in the straining maneuver, performing it immediately and well, when flying in this manner. Should the brain blood oxygen reserve be exhausted because of rapid onset G and inadequate straining, a GLOC is certain. Considering the low altitudes at which aerobatic pilots fly, the result could well be fatal.

PHYSIOLOGICAL EFFECTS OF -Gz — In aerobatic flying -Gz is almost as common as +Gz, though it is seldom used in air combat maneuvering. Human tolerance to -Gz is primarily limited by discomfort and visual effects and is usually specified as around -3Gz for sustained exposures. Unpleasant sensations of fullness of the neck and head with accompanying pain are common in -Gz exposures and vision is usually compromised by the lower lids partially covering the pupil of the eyes. This results in a phenomenon called "redout" and has, to this writer's knowledge, no relationship to seeing red because of blood in the eyes despite the occasional occurrence of burst blood vessels in the eyes as a result of excessive -Gz exposure.

The cardiovascular effects of -Gz are opposite to those experienced in +Gz. The compensatory reflexes operate on the fact that the blood pressure in the head is far too high. Consequently the reflexes operate to expand the peripheral blood vessels, reduce the heart rate, reduce the strength of contraction of the heart and thereby reducing pressure. This situation can result in a very great hazard as will be discussed in the next section.

FIGURE 1



UNIQUE HAZARD OF ALTERNATING (+) AND (-) Gz — The foregoing discussion of the cardiovascular reflexes and their role in G protection leads to the special hazard involved in aerobatic maneuvers involving sustained -Gz maneuvers followed immediately by sustained +Gz maneuvering. A -Gz maneuver has the effect of altering the cardiovascular system so as to reduce blood pressure as much as possible. If a -Gz maneuver is followed by a high sustained +Gz maneuver there is a very real hazard of an abrupt loss of consciousness because the body is totally unprepared for this stress. An aerobatic pilot must be well aware of this phenomenon and prepare for it with a straining/crouching maneuver in order to combat the effect.

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PROTECTION AGAINST +Gz — Military pilots in high performance aircraft have as their baseline protection the anti-G suit and anti-G valve. The anti-G suit is a cutaway trouser-like garment containing air bladders over the abdomen, the thighs and the calves. These bladders are pressurized in accordance with the Gs on the aircraft by a special valve (the anti-G valve) which admits compressed air into the bladders as necessary. The anti-G suit has the effect of increasing the resistance to the flow, or pooling, of blood into the legs and the abdomen, and provides about one to two Gs of protection depending upon its design and the type of valve being used.

Since aerobatic pilots do not have the assistance of the anti-G suit and valve and since they frequently expose themselves to acceleration levels higher than the average relaxed tolerance level, some other means of protection must be used.

Referring once more to ***Figure 1*** it can be seen in the right-hand drawing that a radically reclined seat can assist in increasing G tolerance. The reclined posture reduces the height of the hydrostatic column between the heart and the eye, and thus reduces the arterial blood pressure necessary to perfuse the brain and eyes at high Gs. At some cost in terms of space and weight, a 65° seatback angle may be a worthwhile idea to pursue for aerobatic aircraft. Crouching forward is a useful countermeasure because this posture is nearly as effective as is a reclined posture in reducing the heart-to-eye distance. Depending upon the characteristics of the aircraft it may be even more effective than a reclined posture since the normal acceleration vector on the aircraft may sometimes be inclined aft of the true perpendicular. An extreme crouching posture could conceivably raise relaxed tolerance by two Gs to a total value of six Gs.

A tolerance of six Gs is not sufficient for really high G maneuvering and so an additional protective measure must be used. The straining maneuver can add the necessary tolerance margin. Recall that increasing peripheral vascular resistance can help increase G tolerance. A voluntarily produced increase in the resistance can be accomplished by isometrically straining the muscles of the legs, the arms and the abdomen. The muscular straining can be augmented by respiratory straining.

The least complicated version of this maneuver involves doing the muscular straining and simultaneously inhaling, closing the glottis, and bearing down hard with the chest muscles. You can learn to control the glottis, which is the little trapdoor in your throat that keeps foreign materials out of your windpipe, by practicing coughing. The little explosive sound you hear is the glottis opening and allowing a gust of air, compressed by the chest muscles, to be expelled.

This respiratory straining maneuver increases the pressure inside the lungs/chest and, in effect, supercharges the pressure on the "inlet" side of the heart. A well-trained pilot can raise his blood pressure around 100 mmHg with this technique so it is recommended that you not practice heroic straining maneuvers in your easy chair.

THE RESPIRATORY STRAINING MANEUVER MUST NOT BE HELD UNTIL YOU TURN BLUE IN THE FACE. In terms of G protection this is counterproductive. The respiratory straining maneuver should be "cycled" every three to five seconds. Take a breath, strain, hold the strain for three to five seconds, forcefully expel the air from your lungs and QUICKLY take another breath commencing a new straining episode. Repeat as needed and beware of stopping your strain as you unload Gs from the aircraft until you reach a low enough level to be safe. Remember to maintain the isometric muscular straining along with the respiratory straining.

WARNING:
IF YOU DO NOT UNDERSTAND THE FOREGOING DESCRIPTION OF THE STRAINING MANEUVER CONSULT AN AVIATION MEDICAL EXAMINER WHO WILL BE ABLE TO DRILL YOU ON THE TECHNIQUE
AND
NEVER, REPEAT N-E-V-E-R, DO A STRAINING MANEUVER WHILE PULLING NEGATIVE Gs.

EXPOSURE INCREASES TOLERANCE — The gist of this section is that "pulling Gs makes you good at pulling Gs." Although structured research has yet to be done, on this issue it has been observed repeatedly that a long layoff from pulling Gs reduces your ability to tolerate the stress. Frequent exposure to high sustained Gs probably causes an increase in reactivity in the cardiovascular system, or it may simply be that frequent exposure begets better straining technique. When you resume aerobatic flying after a layoff of more than two or three days you should always commence with a few "G awareness" maneuvers at levels well below your usual tolerance level; work up gradually until you're satisfied that you know how your body is reacting.

INFLUENCE OF BODY TYPE ON TOLERANCE — There are three basic body types or somatotypes. Pure somatotypes are rare; most of us are mixtures of types. The mesomorph: short, stocky, heavily muscled is the ideal body type for pulling Gs. The mesomorph usually has a short, thick neck which reduces the heart-eye distance and has the well developed musculature for a good straining maneuver.

INFLUENCE OF PHYSICAL FITNESS ON TOLERANCE — There is some evidence that a systematic program of weight training enhances acceleration tolerance. The evidence is felt to be sufficiently strong that the Swedish Air Force has commenced a program of installing weight training equipment at all fighter squadron bases. The isometric muscle straining maneuver tends to increase peripheral vascular resistance and it follows, therefore, that better muscular development would enhance the effectiveness of straining and thus enhance G tolerance.

There is also evidence indicating that extreme aerobic training is not necessarily a good thing for G tolerance. Aerobic training, such as jogging, tends to develop a lower heart rate and to increase the (volumetric) capacity of the large blood vessels. Extreme aerobic training (in excess of 15 miles per week) is thought to reduce G tolerance because of these factors. The current consensus on this issue is that a balanced program of weight training combined with moderate aerobic training is probably best, although there is some controversy over the validity of the results and effects that have been reported.

INFLUENCE OF AGE ON G TOLERANCE — The aging process is accompanied by decreases in the elasticity of tissues, including cardiovascular tissues. The loss of elasticity may be accompanied by deposits of fatty tissue in the arteries and may also be accompanied by high blood pressure. There is at least one study on this topic that concluded that the older, overweight, slightly hypertensive individual exhibits a higher G tolerance. The stiffness of the arteries no doubt contributes to this phenomena by increasing vascular resistance which is accompanied by high blood pressure. However, attempts at premature aging or adoption of a lifestyle that leads to hardening of the arteries and high blood pressure is not a course recommended for any pilot.

INFLUENCE OF LIFESTYLE ON G TOLERANCE — This is a catchall category. Fatigue is likely to lead to a loss of tolerance because of its generally debilitating effect. (He who hoots with the owls by night cannot scream with the eagles by day.) Diet is important. A taste for junk food can lead to decreased tolerance and one of the worst offenders is refined sugar (sucrose).

When sucrose is eaten it goes directly into the bloodstream. When this happens, the pancreas is stimulated to release insulin in order to reduce the blood sugar level. In addition, the adrenal glands are stimulated to secrete adrenaline so that you'll be jittery and active to help in burning off the sugar calories and reduce the blood sugar level. This process can result in what is called rebound hypoglycemia. This low blood sugar condition can make you weak and dizzy and drive you to reach for another cup of sugar-laced coffee or a syrupy soft drink and, thus, start the whole cycle over again. A balanced diet, high in complex carbohydrates (fresh fruits and vegetables, whole grain cereals) is recommended prior to G exposures.

Dehydration (low tissue water level) will result from an insufficient intake of fluids. Dehydration leads to a reduction in the circulating blood volume, which leads to decreased G tolerance. Dehydration can lead to loss of electrolytes, such as sodium, calcium and potassium all of which are essential to proper heart muscle function.

When flying in hot weather it is better to drink your fill frequently even if you don't have urgent feelings of thirst. If you do feel thirsty, you are already dehydrated to some extent. Salt tablets are not recommended under high heat stress since they can cause stomach irritation and may lead to nausea and vomiting. Appropriate use of one or another of the commercially available drink preparations intended for use by athletes in hot environments should take care of your electrolyte needs.

INFLUENCE OF TEMPERATURE AND ALTITUDE ON G TOLERANCE — Cool temperatures cause blood vessels to contract, especially in the skin, in order to reduce the rate of heat loss from the body. For this reason an individual's G tolerance is higher when the individual is cold. Conversely, high temperatures dilate the circulation in order to improve the rate of heat loss. For this reason high temperatures tend to reduce your G tolerance.

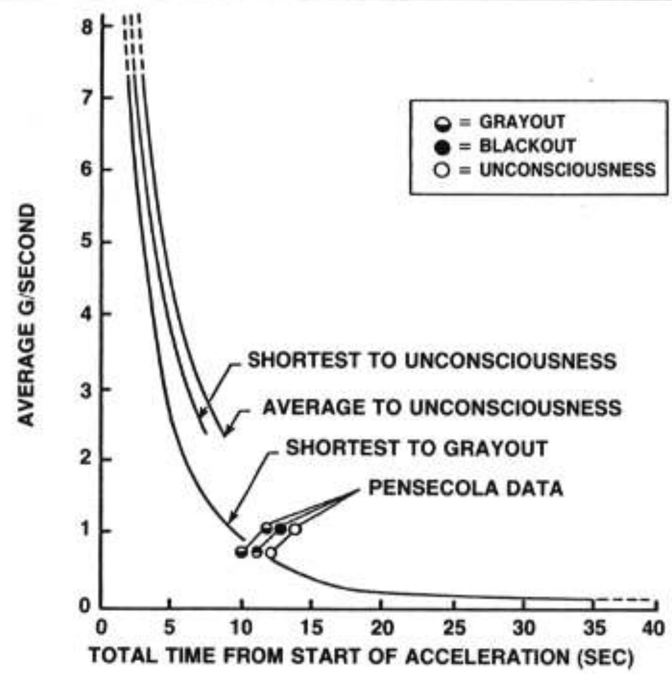
Altitude tends to reduce G tolerance because of the reduced partial pressure of oxygen in the atmosphere. Since aerobatic flying is ordinarily done at altitudes below 5,000 feet this should not be a problem. Be cautious, however, if you're accustomed to operating from a sea level airstrip but are flying in a meet located at a significantly higher altitude above sea level. You may find your tolerance somewhat reduced and your endurance compromised.

EFFECT OF MEDICATIONS ON G TOLERANCES — Flying and medications don't mix. Generally this is true because of the underlying health problems that require the medications. If you're on any kind of medication you must inform yourself of the effects that medication is likely to have on your G tolerance. Consultation with your Aviation Medical Examiner is strongly recommended.

A drug as innocuous as aspirin may not necessarily affect your tolerance but, because it tends to "thin" the blood, may cause you to be inappropriately peppered with "high G measles." These little red spots on the buttocks, backs of the thighs, and on the legs and feet are caused by the rupturing of tiny blood vessels in the skin brought on by high acceleration. The medical name for these is petechiae (pronounced peh-tee-kee-eye). They're essentially harmless and usually disappear within a few days. A close cousin to the petechiae are the "splinter" hemmorhages which appear under the finger and toenails. Their name derives from the dark splinter-like appearance they present. These also are harmless and disappear in a relatively short time.

EFFECT OF ILLNESS ON G TOLERANCES — Those of you who have done high G aerobatic flying know that it can be an exhausting business. Consequently, it does not make sense to attempt high G aerobatics when you are in anything other than perfect health. Even the common cold can lead to painful and even disabling effects with changes in altitude affecting the ears and sinuses. Illnesses, such as intestinal flu or food poisoning, are accompanied by vomiting and watery bowel movements, both of which can lead to rapid dehydration, not to mention the other generally rotten-feeling symptoms they present. Accordingly, this type of illness is especially threatening in terms of reduced G tolerance. The bottom line is simple: don't fly when you're sick.

FIGURE 2



CORRELATION OF ACCELERATION RATES TO PHYSIOLOGICAL ENDPOINT
FROM: STOLL AM, HUMAN TOLERANCE TO POSITIVE G AS DETERMINED BY PHYSIOLOGICAL ENDPOINTS. AVIATION MEDICAL ACCELERATION LABORATORY, JOHNSVILLE, PA, NADC-MA-5508 (DTIC ADN 75326)

CONCLUSION — An overview of techniques and principles useful in the attainment of higher tolerance to sustained acceleration has been presented. The essential components of high G tolerance are: an understanding of the physiological effects of G, proficiency in using postural and straining maneuvers for tolerance enhancement, attention to appropriate physical fitness, adoption of an appropriate lifestyle involving adequate rest, nutrition and fluid intake, and recognition of the possible effects of age, drugs, illness, blood pressure and altitude.

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