Science and Technology Committee Panel

High-G Training for Fighter Aircrew

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GILLINGHAM KK, FOSDICK JP. *High-G training for fighter aircrew.* Aviat. Space Environ. Med. 1988; 59:12–9.

From 8 Jan 85 through 12 Feb 86, 744 USAF fighter aircrew from Tactical Air Command underwent high-G training at the USAF School of Aerospace Medicine, the major objectives of the training being to increase their understanding of G stress and G protection and to raise their G tolerance. The didactics centered on discussion of the G-time tolerance curve and demonstration of an effective anti-G straining maneuver (AGSM). Exposure to G stress on the USAFSAM centrifuge allowed the trainees to determine their G tolerances and to perfect and practice their AGSM. The trainees' mean relaxed and straining G tolerances on the gradual-onset run (GOR) without anti-G suit inflation were 5.2 and 8.3 G, respectively; and 41% of the trainees reached the 9.0-G run limit. All but two of the trainees completed the 8-G, 15-s rapid-onset run (ROR) with anti-G suit inflated; 94% completed the 9-G, 15-s ROR; and 93% were able to tolerate the 9-G, 10-s ROR while looking back over their left shoulder. G-induced loss of consciousness (G-LOC) occurred in 9% of the trainees, most commonly on the GOR, less often on the 9-G RORs. Motion sickness was a significant problem in less than 1% of the trainees. Critiques provided by 382 trainees revealed 73% enthusiastic or positive assessments of the training, as opposed to only 2% negative or hostile responses. We conclude that high-G training is well-tolerated by fighter aircrew and is a highly appropriate method for minimizing the potential for aircraft mishaps due to G-LOC in flight.

IT HAS BEEN SAID that G-induced loss of consciousness (G-LOC) has occurred in every fighter aircraft known to mankind. Although that specific statement might be contested, there is no doubt that the potential for G-LOC has increased dramatically in the past decade as a result of the introduction of modern, highly maneuverable, fighter aircraft into military inventories. This potential was recognized in the early 1970s by fighter development program managers and aeromedical scientists; and research efforts aimed at preventing G-LOC in flight were reinitiated in a number of laboratories, including our own. One of the most important results of that epoch of high-G research was the demonstration that experimental subjects, using the existing anti-G equipment (suit, valve), could be trained to tolerate sustained high-G loads for prolonged periods—up to +9 G_z for 45 s—in a conventional (upright) aircraft seat in a centrifuge (7). The focus of the training given the experimental subjects was on performance of an optimally effective anti-G straining maneuver (AGSM).

Impressed by the success of the centrifuge-trained experimental subjects in raising their G tolerance, Dr. Sidney D. Leverett, Jr., and his coworkers at the USAF School of Aerospace Medicine (USAFSAM) offered high-G training to the USAF Tactical Air Command (TAC) in 1971. High-G training at USAFSAM was then implemented for students in the F-4 Fighter Weapons Instructor Course conducted by the USAF Fighter Weapons School, Nellis Air Force Base, NV. Beginning in 1972, 90 F-4 aircrew (5 classes) received the centrifuge training at USAFSAM, and generally were highly complimentary of both the contents and objectives of the high-G training course (5). The need for high-G training was not perceived by TAC commanders to be great enough, however, to justify the logistical burden of sending their students to USAFSAM for the 1-day course; and TAC discontinued the high-G training in 1973.

In the mid-1970s, as the F-15 was employed in greater and greater numbers in the USAF, reports of G-LOC incidents in the F-15 began to surface. Some of those reports were of near-mishaps, and were a source of considerable concern in the aeromedical community (6). As a result of a fatal F-15 mishap in which G-LOC was listed as a possible cause, interest in G-LOC-preventive measures was expressed anew by TAC in 1978. In response, USAFSAM again

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offered to provide high-G centrifuge training for pilots of high-performance fighter aircraft. After giving it serious consideration, TAC declined the offer of centrifuge training, citing logistical problems as the primary reason. The feeling of the TAC commanders at that time was that special efforts to educate pilots about G-LOC hazards and methods of improving G tolerance, as well as frequent and regular exposure of pilots to the higher G loads generated by the modern fighter aircraft, would be sufficient measures to counter any incipient problem of G-LOC mishaps in the USAF. By the early 1980s G-LOC incidents in the F-16 began to be reported—one of which was captured on an F-16B head-up display (HUD) videocassette tape. Then in early 1983 two fatal F-16 mishaps occurred within 1 month of each other, both of which were found to have resulted from G-LOC. Consequently, the attention of TAC again became focused on the now obvious G-LOC problem and on all practicable means of solving it. Among those means was centrifuge training for aircrew, and TAC expeditiously negotiated to reinitiate such training. In April and May of 1983, 73 selected F-15 and F-16 pilots completed high-G centrifuge training at USAFSAM. The results of this training, reported elsewhere (1), indicated that the pilots tolerated the training very well, and that they strongly endorsed such training for all pilots of high-performance fighter aircraft.

In June of 1983 the USAFSAM centrifuge was removed from service to accommodate a major renovation, which included installation of an all-electric drive system permitting up to 6 $G \cdot s^{-1}$ G-onset rates and subject-in-the-loop control. By January 1985 the renovation was essentially complete, and high-G centrifuge training of TAC fighter aircrew began again and has continued to the present time. The results of the current training episode are the subject of this report.

MATERIALS AND METHODS

The high-G training course has one primary and three secondary training objectives for the trainees. Primary is the increase in G tolerance resulting from improved skill in performing an AGSM. Secondary are a better understanding of the physiologic mechanisms of G stress and G tolerance, a greater respect for the hazards associated with the high-G environment, and an increased confidence in the ability to tolerate high-G stress.

The course conducted at USAFSAM is completed in 1 day. It begins with 2 hours of lecture, follows with a series of centrifuge rides, and concludes with a short debriefing. The didactic portion of the course is introduced by relating certain historical aspects of the G-LOC-in-flight problem, including a recapitulation of aircraft accidents and incidents due to G-LOC and a review of statistics indicating that 12% to 30% of tactical aircrew have experienced G-LOC in flight. Emphasized is the fact that the potential for G-LOC-related mishaps is rising rapidly as current-generation high-performance aircraft replace the older weapon systems.

A substantial fraction of the lecture is devoted to a review of high-G physiology. We introduce the hydrostatic-column model of G stress, including the principle that one loses about 22 mm Hg of head-level blood pressure for each $+1\ G_z$ to which he is exposed. Both the immediate effect of G stress (loss of retinal and cerebral perfusion pressure due to hydrostatic pressure drop) and the delayed effect (loss of cardiac output due to blood pooling) are discussed. The visual symptoms of G stress—grayout, tunnel vision, and blackout—are explained; and the four important characteristics of G-LOC are described: 1) G-LOC can occur without premonitory visual symptoms; 2) recovery from a G-LOC episode usually takes 20–30 s; 3) amnesia of the G-LOC event is common; and 4) involuntary bodily movements can occur during a G-LOC episode. Discussed next are the two primary physiologic mechanisms that protect against symptoms of G stress: 1) the metabolic reserve that allows retinal and cerebral function to continue for several seconds after G force causes blood supply to the head to be inadequate; and 2) the cardiovascular (baroceptor) reflexes that are eventually mobilized to raise systemic arterial blood pressure in response to a G-induced fall in head-level blood pressure. Of extreme importance—in fact, a central instructional objective of the lecture—is that the aircrew understand the significance and characteristics of the G-time tolerance curve (Fig. 1). It demonstrates the temporal relation between the effects of the metabolic reserve and the cardiovascular reflexes on G tolerance, and indicates how G tolerance is minimal at the temporal intersection of those two effects (i.e., at the "trough" of the curve). It further demonstrates that, at any given time during G stress, visual symptoms appear at about 1 G lower than G-LOC. Moreover, it shows how the rate of application of G stress (G-onset rate) determines not only the G levels and durations that elicit symptoms but also the time interval between the appearance of visual symptoms and the development of G-LOC (Fig. 2). Specifically, it demonstrates in a readily understandable fashion how, because of the metabolic reserve, a sustained high-G stress very rapidly applied can result in G-LOC with essentially no warning from visual symptoms—a very hazardous characteristic.

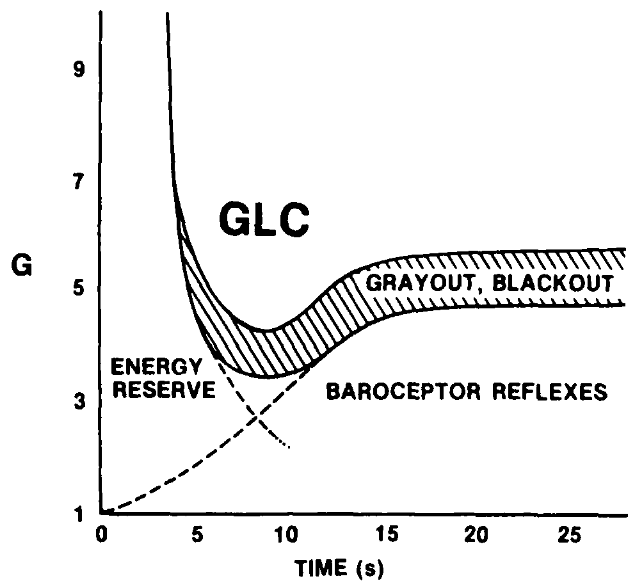

Fig. 1. The G-time tolerance curve. This graph depicts the temporal effects of the tissue oxygen reserve and baroceptor reflexes on relaxed $+G_z$ tolerance, and shows that visual symptoms generally appear at about 1 G lower than G-LOC (GLC in the figures). The trough in the curve, where G tolerance is lowest, occurs because of incomplete overlap of the oxygen reserve and baroceptor reflex effects at G levels above about 3 G.

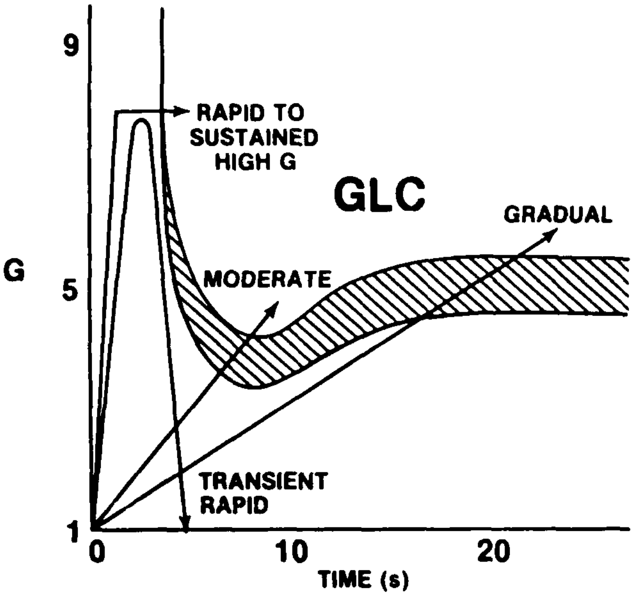

Fig. 2. Effect of G-onset rate on G tolerance. While slow and moderate rates of G force application result in visual symptoms occurring *before* G-LOC, rapidly applied and sustained high-G forces can result in G-LOC without premonitory visual symptoms.

The next segment of the didactic portion of the course covers the various means of protection from the effects of high-G stress. Whichever means of protection is employed, its ultimate action must be to drive the G-time tolerance curve upward, so that one can enter with impunity the G-time region where G-LOC would occur in an unprotected individual (Fig. 3). Mechanical methods of G protection discussed include use of the anti-G suit and valve, aircraft seats that recline the torso and elevate the legs relative to the direction of the G force vector, and assisted positive-pressure breathing. Physiologic methods presented include: frequent and regular exposure to high G forces (with a discussion of the especially deleterious effect of an illness necessitating prolonged recumbency); physical conditioning (with a discussion of the beneficial effect of resistance training and the counterproductive effect of extreme aerobic conditioning); and avoidance of dehydration, improper diet, and other tolerance-dissipating conditions. The most effective physiologic method of protection, however, is the AGSM; and instruction in performing an efficient and effective AGSM constitutes the nucleus of the whole high-G training course.

We teach an AGSM consisting of two components: 1) vigorous tensing of arm and leg muscles to minimize pooling of blood in the extremities; and 2) cyclically increasing intrathoracic pressure with chest and abdominal muscles to drive up blood pressure directly. We recommend a 3-s cycle for the latter component—about 2.5 s of expiratory effort and 0.5 s of inspiration. Two types of AGSM have been described, the M-1 and the L-1 (2). They differ only in that the expiratory phase of the M-1 is against a partially closed glottis, resulting in vocalization (groaning), whereas the expiratory phase of the L-1 is for the most part against a completely closed glottis, resulting in a silent strain (grunting). Although the M-1 and L-1 are equally effective, we teach the L-1 rather than the M-1 because the M-1 interferes with oral communication and tends to irritate the vocal cords. Some descriptions of the AGSM include an optimal positioning of the body—leaning forward and pulling the head down, for instance. We do not teach this as a component of the AGSM because a fighter pilot must be able to perform his AGSM in whatever body position his inflight situation demands, even while turning around in his seat to look behind him. The course instructor demonstrates for the class a few cycles of a properly executed AGSM, but does not persist in the demonstration because in a 1-G environment a good straining maneuver can elevate head-level blood pressure to well over 200 mm Hg, which is certainly not desirable from a medical standpoint. The reasons for doing the AGSM in the specific way taught are presented with the aid of graphs of head-level blood pressure during effective and ineffective straining (Fig. 4). Video tapes of centrifuge subjects performing poor straining maneuvers and consequently experiencing G-LOC episodes are shown and discussed. Examples of excellent, and therefore successful, straining techniques recorded during high-G centrifuge runs are also presented at this time.

The didactic portion of the course is completed with descriptions of the upcoming centrifuge runs and instructions pertaining to accomplishment of this phase of the training.

Each trainee is subjected to five standard training G profiles on the centrifuge and has the option to experience one other. All trainees wear an anti-G suit and sit in a centrifuge seat currently configured to resemble the seat in

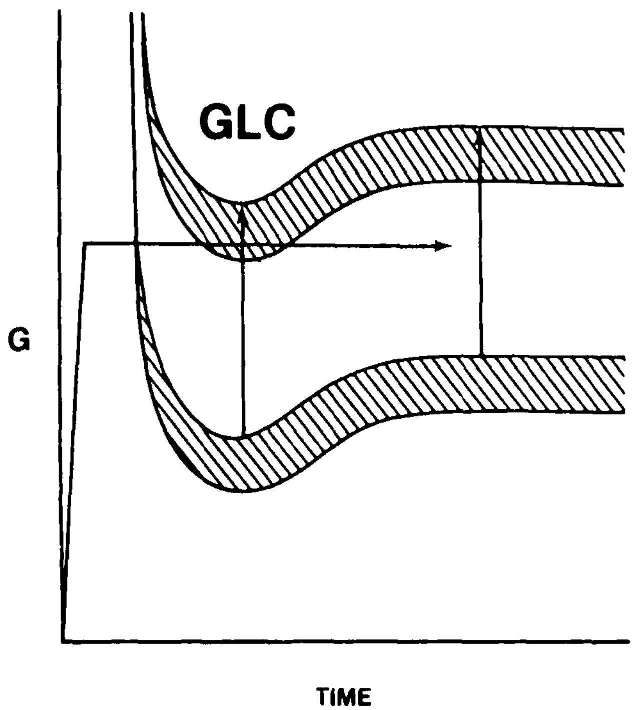

Fig. 3. Desired effect of anti-G straining maneuver (AGSM) and other countermeasures on G tolerance. For a rapidly applied, sustained high-G force to be tolerated, the G-time tolerance curve must be driven upward so that the region of G-LOC lies above the level of the applied G force by the time the oxygen reserve runs out, i.e., within a few seconds.

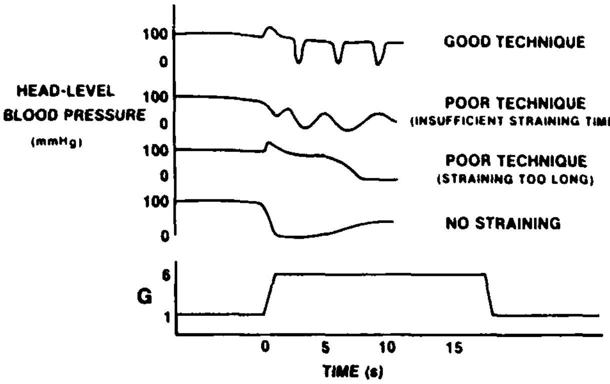

Fig. 4. Effect of AGSMs on head-level blood pressure during sustained high-G stress. Good technique allows sufficiently high mean blood pressure to prevent symptoms. Inefficient techniques result in low mean head-level blood pressure or inability to maintain blood pressure.

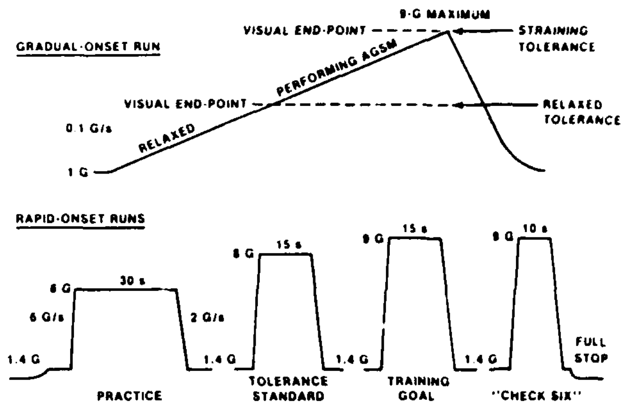

Fig. 5. G profiles used in high-G training. The gradual-onset run (GOR) shows the trainee his relaxed G tolerance and how much protection he can get from his AGSM. The rapid-onset runs (RORs) allow the trainee to perfect and practice his straining maneuver under progressively more stressful conditions. The final run, 9 G for 10 s while the trainee looks over his left shoulder, simulates an inflight situation that is particularly likely to result in G-LOC.

an F-16 aircraft (30° seatback angle and elevated rudder pedals), although other seat configurations can be used. When the F-16-configured seat is used, the training profiles are set 1 G higher than they are when the conventional fighter aircraft seat (13° seatback angle, normal rudder pedal position) is used. The higher-G profiles are used with the F-16 seat because pilots report a 1- to 2-G subjective improvement in G tolerance in the F-16 as compared to other fighter aircraft, and because data obtained during centrifuge training when both types of seat were used revealed at least 0.8 G greater tolerances in the F-16-configured seat than in the conventional seat (1).

In the centrifuge, trainees are monitored by means of closed-circuit television and continuous two-way voice communication. As a matter of convenience, flight helmets are not worn during the training. Use of the helmet would add to the realism of the training and might reduce the probability of impact injury to the head during a G-LOC episode, but the added weight of the helmet on the head would also increase the likelihood of injury to the neck as a consequence of G-LOC. Use of an oxygen mask during the training is definitely contraindicated because it prevents the trainer from observing the action of the trainee's facial muscles and mouth during the straining maneuver, thereby rendering the trainer less able to evaluate the trainee's technique and offer him constructive criticism.

During routine high-G training of line aircrew, electrocardiographic (ECG) monitoring is not done. It is standard practice, however, to monitor the heart rate and rhythm during all other conditions in which subjects are exposed to high G forces in the USAFSAM centrifuge (e.g., experimental studies, training of aeromedical professionals, and medical evaluations). Pilots' concerns about the possibility of medical disqualification from flying status, as a consequence of some ECG abnormality appearing during high-G stress on the centrifuge, are so great as to make the majority of pilots unwilling to undergo the training if ECG monitoring is required. As it is far more likely that a fighter pilot would suffer a fatal G-LOC in flight if he did not have high-G training than it is that he would be injured on the centrifuge because of lack of ECG monitoring, we elected to forego ECG monitoring for line aircrew during high-G training in the interest of salvaging a valuable preventive medicine program.

The first high-G training centrifuge ride is a gradual-onset run (GOR) with a G-onset rate of 0.1 $G \cdot s^{-1}$ to a peak, and a G-offset rate of approximately 1 $G \cdot s^{-1}$ back to a 1-G condition (Fig. 5). During the GOR the trainee's anti-G suit does not inflate and he rides passively, i.e., he does not apply the G force himself by pulling on his control stick. The trainee is instructed first to ride completely relaxed and fix his gaze on the red light straight ahead of him (Fig. 6). When his vision tunnels in to the point where he can no longer see the green lights located 25° to each side of the red light, the trainee says "Now" and begins to perform his AGSM. The GOR continues, with the trainee doing his

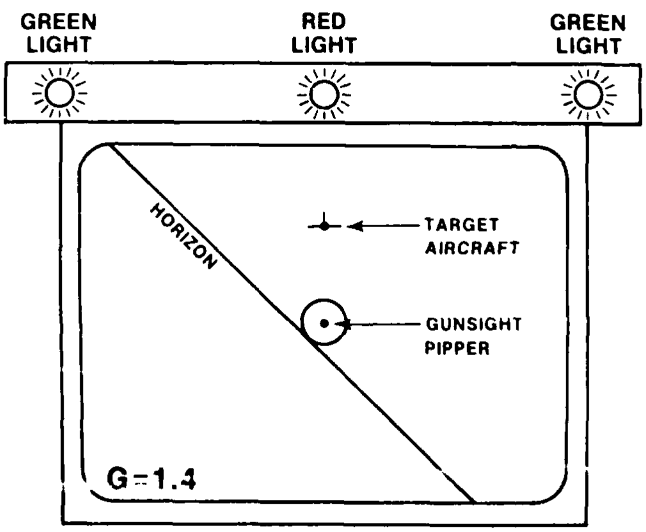

Fig. 6. Light bar and video display viewed by trainee during centrifuge runs. On the GOR he fixates the central red light of the light bar while monitoring the intensity of the peripheral green lights. During RORs (except the final one) he tracks the aircraft symbol to maintain the desired G level. Displayed horizon is veridical.

straining maneuver more and more vigorously as the G load increases, until he no longer can see the green lights even while straining as hard as he can. At that point the trainee releases a switch he had been holding closed with his left hand and the centrifuge stops. If the trainee can still see the green lights and has not released the switch by the time the GOR reaches the 9-G run limit, the centrifuge comes to a stop automatically. When the GOR is completed, the trainee reports the degree of subjective loss of intensity of both the peripheral green lights and the central red light that he experienced at the peak of the GOR (usually 100% loss of the green lights and less than 50% loss of the red light). The trainer then informs the trainee of his relaxed G tolerance (G level at which he said "Now"), his straining G tolerance (G level at which he released the switch) or that he reached the 9-G run limit, and the amount of G-tolerance improvement he got as a result of his AGSM. The trainer also offers constructive criticism of the trainee's straining maneuver at this time.

After a rest of 1–2 min, the trainee begins the high-G training series of rapid-onset runs (RORs). The centrifuge is brought up to a 1.4-G "base-G" condition, from which the RORs are initiated, to allow the generation of $6\text{-G}\cdot s^{-1}$ G-onset rates and to reduce the deleterious effects of prolonged high starting torques on the centrifuge drive mechanism. The trainee's anti-G suit is pressurized during the RORs in accordance with the standard USAF inflation schedule (1.5 psi/G above 2 G, 10 psi maximum). To initiate and sustain an ROR in the centrifuge, the trainee must pull back on an F-16-style side-mounted control stick with sufficient force to cause the centrifuge to deliver the maximum allowable G force for the particular ROR being executed. For all but the final ROR, he is prompted to begin the run by the upward displacement of a simulated target aircraft on the video monitor in front of him in the centrifuge gondola (Fig. 6). Within limits, the G force generated is proportional to the amount of backward control-stick pressure applied, and the displacement of the target aircraft from the gunsight pipper in the center of the video monitor is proportional to the instantaneous difference between the desired G level and that actually obtained. Stick forces above that sufficient to obtain the desired G level for the run have no additional effect on G level or G-onset rate; i.e., the trainee cannot overshoot the desired G level. The target aircraft lies under the gunsight pipper when the desired G level is reached. At the end of the run the target aircraft drops below the pipper, signaling the trainee to release his back pressure on the stick and thereby allow the centrifuge to return to the base-G condition. Our experience is that pilots who are allowed to control the G force actively with the simulated aircraft-tracking task are far less likely to complain about lack of realism in the high-G training than are those who must ride passively, i.e., without being able to control the G force. Furthermore, pilots having active control and using the simulated aircraft-tracking task with the veridical horizon display seem to be less likely to suffer symptoms of motion sickness during and after the centrifuge training.

All of the RORs consist of a $6\text{-G}\cdot s^{-1}$ rise to a sustained high-G plateau and terminate with an approximately $2\text{-G}\cdot s^{-1}$ return to base G (Fig. 5). The first ROR is a 6.0-G, 30-s, practice run, during which the trainee perfects his AGSM under the critical eye of the trainer. The 6-G level is sufficiently low that the trainee is not liable to lose consciousness as a result of an imperfect technique, and the 30-s duration is long enough to allow him to respond to criticism by changing his technique and to notice the effect of that change. At the end of this and all subsequent runs, the trainee is asked to estimate the degree of dimming of his peripheral and central vision and report the two respective percentages, even though he is not looking at the red and green lights during the RORs. Requiring the trainee to estimate and report his visual loss helps him focus his attention on his symptoms of G stress, and thereby enhances direct feedback relating to the effectiveness of his AGSM.

Next is the 8.0-G, 15-s, G-tolerance standard run, so called because we expect every trainee to make it through this run without complete loss of peripheral vision if he has learned how to do an effective AGSM. The 8-G level is high enough to cause G-LOC if the straining maneuver is incorrect, and the 15-s duration is sufficient to traverse the trough of the G-time tolerance curve. Any trainee who is unable to complete the 8-G ROR on the first attempt is reinstructed in the L-1 maneuver and given additional opportunities to complete the run.

The next ROR is the 9.0-G, 15-s, training goal. In this run the G stress is sufficient to challenge most trainees to give their best effort, as G-LOC can easily result from any lack of concentration, vigor, or efficiency in performing the straining maneuver. Because even current-generation fighter aircraft are unlikely to operate in a sustained 9-G environment (4), we feel that a trainee who successfully completes the 9-G, 15-s, training goal has demonstrated he can tolerate any sustained high-G load that he might have to pull in flight.

The final ROR is another 9.0-G run, but it is accomplished with the trainee looking over his left shoulder rather than straight ahead, and lasts for 10 rather than 15 s. This run was added to the training RORs for two reasons. First, it allows the trainee to practice the straining maneuver in a semblance of the non-optimal body positions he must frequently assume in flight. Second, it emphasizes to the trainee that many if not most inflight G-LOC incidents and mishaps occur when the pilot is looking behind him while in a high-G defensive turn, and that an effective AGSM is especially important under such conditions. The trainee initiates the 9-G, 10-s, "check-six" ROR by turning his head to the left (slowly, to avoid vestibular Coriolis effects in the rotating centrifuge), viewing a numeric display at about his 7 o'clock level position, calling out the displayed number, and immediately pulling on the control stick with his right hand to drive the centrifuge to the 9-G level. During the run the displayed number changes and the trainee calls out the new number. At the end of the 10 s at 9 G, the trainee is told to let go of the control stick to allow the centrifuge to return to base G. The centrifuge is then brought to a complete stop by the operator, and the trainee turns his head back to the normal position.

For most trainees, their centrifuge experience is over with the termination of the "check-six" ROR. At the end of the training session, if time permits, trainees may volunteer to ride the simulated air combat maneuvering (SACM) G profile (Fig. 7). This profile consists of an 86-s exposure to G levels of 3.0 G or greater—including two 9.0-G, 10-s

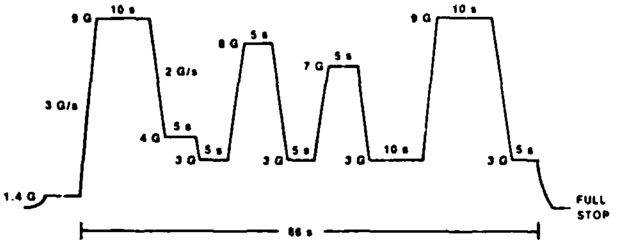

Fig. 7. Simulated air combat maneuvering (SACM) G profile. While this run is optional in the 1-day USAFSAM G-training curriculum, it would be a very worthwhile component of a longer training program.

peaks, one at the beginning of the run and the other at the end. The trainee flies this profile with the control stick by trying to keep the simulated target aircraft under the gunsight pipper on the video monitor; he also shoots at the target when it is under the pipper by squeezing the trigger on the control stick. When the run is over, the trainee's tracking and shooting scores are given to him, along with the average and record-setting previous scores. The optional SACM run gives the trainee an opportunity to practice his AGSM under somewhat more realistic conditions than exist during the GOR and RORs, including that of a "flying-skill" competition that tends to divert his attention from the AGSM.

When each trainee finishes his centrifuge runs, the trainer reviews with him his performance of the AGSM and gives him the strip chart record of his anti-G suit pressure during the runs. This record (Fig. 8) shows the temporal pattern of the trainee's inspiratory and expiratory efforts, and usually gives an indication of the vigor of his abdominal muscular contractions during the straining maneuver. Each trainee's centrifuge runs are recorded on a videocassette tape so he can review and critique his performance at his leisure. If some particularly instructive event such as a G-LOC episode occurs during the training, the trainer replays it on the video monitor for all the trainees and provides appropriate commentary.

While one trainee is in the centrifuge, the others who are not busy preparing for or recovering from their own rides

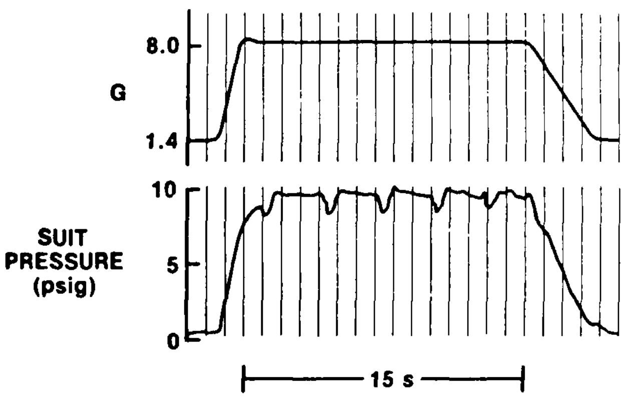

Fig. 8. Anti-G suit pressure during high-G training. Because the trainee's abdominal wall relaxes and the abdominal bladder of the suit expands during the inspiratory phase of the AGSM, the resulting pressure swings in the suit allow the trainer to monitor and record the rhythm, and to some extent the vigor, of the trainee's straining.

watch the training on closed-circuit television in the waiting room. By observing their fellows' performances, the trainees quickly learn how to critique an AGSM and come to recognize potential deficiencies in their own techniques, thereby saving the trainer considerable time and effort in correcting straining maneuvers as the training day progresses.

RESULTS AND DISCUSSION

Between 8 January 1985 and 12 February 1986, 741 TAC aircrew (58 classes) were given high-G training at USAFSAM. F-4 crewmembers comprised 22% of the trainees, 18% were F-16 pilots, 15% were AT-38 pilots, 14% were F-15 pilots, and the remainder flew A-10, F-5, F-111, A-7, and assorted other aircraft.

Measures of the trainees' performance as a group are presented in Table I. Their mean relaxed G tolerance (G level at which they lost peripheral vision, said "Now," and started straining) was 5.17 G with a standard deviation of 0.94 G. This mean value is significantly lower ($p < 0.01$, unpaired t-test) than the 5.51 ± 0.91-G relaxed tolerance recorded for the 62 TAC pilots trained at USAFSAM in the F-16-configured seat in the spring of 1983—possibly because the G-onset rate was only 0.067 $G \cdot s^{-1}$ in 1983 as opposed to 0.10 $G \cdot s^{-1}$ presently used. The 11 pilots in the 1983 training session who rode in the conventional centrifuge seat had a relaxed GOR G tolerance of 4.69 ± 0.34 G, a significant 0.8 G lower than that of their colleagues who rode in the F-16-configured seat ($p < 0.005$), but only 0.5 G lower than that of the current group of trainees ($p > 0.05$). An additional comparison can be made with the GOR G tolerances of 434 male subjects, largely non-aircrew, whose first exposure to G stress on the USAFSAM centrifuge was a 0.067-$G \cdot s^{-1}$ GOR in the conventional seat (3). Their mean relaxed tolerance was 4.65 ± 0.80 G, also 0.5 G lower than that of the 741 TAC trainees ($p < 0.0001$); but this highly significant difference may be due to G-tolerance differences between aircrew and non-aircrew, as well as to the effects of different G-onset rates, seat configurations, and whether an uninflated anti-G suit was worn. Nevertheless, the F-16-configured seat may be providing protection of 0.5 G or better for relaxed subjects.

Because 302 (40.8%) of the current group of trainees reached the 9-G run limit on the GOR after they started straining, the mean recorded straining G tolerance of 8.32 ± 0.85 G for this group is somewhat lower than it would have been had no limit been placed on the amount of G stress that could be provided, and the individual recorded

TABLE I. PERFORMANCE OF 741 TRAINEES ON HIGH-G TRAINING CENTRIFUGE RUNS.

Performance parameter	N	$\bar{X}$	S.D.	%
Relaxed G tolerance on GOR	741	5.17 G	0.94 G	
Straining G tolerance on GOR	741	8.32 G	0.82 G	
Reached 9-G peak on GOR	302			40.8
Completed 6-G, 30-s ROR	740			99.9
Completed 8-G, 15-s ROR	739			99.7*
Completed 9-G, 15-s ROR	697			94.1*
Completed 9-G, "check-six" ROR	692			93.4*
Completed 86-s SACM	39†			97.5

* Not all 741 trainees attempted all the RORs.
† 40 trainees attempted the SACM run.

tolerances are obviously not normally distributed. The mean straining GOR G tolerance of the 62 pilots trained in the F-16-configured seat in 1983 was 8.14 ± 0.94 G—not significantly lower than that of the current group ($p > 0.10$)—with 18 (29%) of them reaching the run limit on the GOR. The 11 pilots who trained in the conventional seat in 1983 had a mean straining GOR G tolerance of 7.22 ± 0.67 G, 0.9 G lower than that of the other 62 trained in 1983 ($p < 0.005$) and 1.1 G below that of the current group of trainees ($p < 0.0001$), with two of the 11 (18%) reaching the 8-G run limit. Thus, it appears that the protection afforded straining subjects by the F-16-configured seat is on the order of 1 G. We also note that the mean straining G tolerance of 354 male aircrew and non-aircrew subjects exposed to 0.067-G•s^{-1} GORs at USAFSAM was only 5.56 ± 0.94 G (3). Although their mean straining tolerance was a highly significant ($p < 0.0001$) 2.8 G less than that of the 741 TAC aircrew, the majority of that difference was most certainly due to the much more effective AGSM employed by the TAC aircrew, rather than to the effect of the different centrifuge seat configurations and other factors.

Of greatest significance in the context of this report, however, is the 3.2-G difference between the trainees' mean relaxed and mean straining GOR G tolerances, as this difference was entirely due to the effect of their AGSMs. This effect would have been even greater had there been no G limit placed on the GOR, as noted previously. The difference between the relaxed and straining GOR G tolerances of the 73 pilots trained in 1983 was 2.9 G—similar to that of the current group of trainees. In contrast, the difference between the mean relaxed GOR G tolerance of the 434 males mentioned earlier and the mean straining G tolerance of the 354 males who completed a subsequent, separate, GOR with straining maneuver was only 0.9 G. This difference represents the efficacy of the average straining maneuver in a population not provided with specific, detailed, intensive instruction in anti-G straining technique. In appears, therefore, that such instruction can add about 2 G to straining GOR G tolerance.

All but 1 of the 741 aircrew (99.9%) completed the 6-G, 30-s ROR and all but 2 (99.7%) completed the 8-G, 15-s, G-tolerance standard run on the day of the training. The one who failed the 6-G run was an F-15 pilot who, after losing consciousness three times at low G levels on three GORs and again on the 6-G ROR, was examined by the physician monitor and determined to be temporarily medically unfit for further high-G training. He was offered the opportunity to return on the following day to complete his centrifuge training. He returned the next day and completed the 8-G run successfully, and survived 11 s of the 9-G, 15-s run. The other TAC crewman who was unable to complete the 8-G ROR during the training session was an F-111 weapon systems officer. Because the need for him to be able to tolerate high G loads was less critical than that for an F-15 or F-16 pilot, he was not offered additional training. Of the trainees, 44 did not complete the 9-G, 15-s training goal, and 49 did not complete the 9-G, 10-s, "check-six" run, giving success rates of 94.1% and 93.4%, respectively. The usual reason for not completing these runs was either total peripheral visual loss or G-LOC, but some trainees terminated the runs early because of discomfort. A few of the trainees had so much difficulty maintaining vision on the 8-G run that they reckoned their attempts to complete a 9-G run would be futile and elected not to continue the training.

Although many more would have volunteered to try the SACM run if time had been available, 40 (5.4%) did attempt it; and all but one completed it, for a 97.5% success rate. The one who did not complete the SACM run suffered a G-LOC during the first 9-G peak.

Of the 741 trainees, 69 (9.3%) had one or more G-LOC episodes during the training. As shown in Table II, 44 of the 69 lost consciousness during the GOR. The main reason the GOR is associated with so many G-LOC episodes is that there is a natural tendency to relax immediately after reaching one's straining tolerance limit and releasing the hand-held switch to bring the centrifuge to a stop. As might be expected, if one relaxes at a G level so far above his relaxed G-tolerance level, he will lose consciousness precipitously. Although the trainees are told repeatedly and emphatically to continue straining even after they have released the switch, many neglect to do this and lose consciousness while the centrifuge is coming to a stop. Some trainees simply try to push themselves beyond their straining tolerance, perhaps trying to reach the 9-G run limit, and as a result lose consciousness while the G force is still increasing. Only two trainees lost consciousness on the 6-G ROR and only three lost consciousness on the 8-G run. Substantially more experienced G-LOC on the 9-G RORs: 18 on the 15-s run and 19 on the 10-s "check-six" run. As already mentioned, one lost consciousness on the SACM run. No unusual reason can be cited for the G-LOC episodes that occurred during the RORs and SACM as opposed to the GOR—only that the individuals experiencing the G-LOCs were not proficient with their AGSM, or that their G tolerance was insufficient for some other reason, such as illness, poor physical condition, or low inherent tolerance.

Although on the order of 10–20% of the trainees experienced mild symptoms of motion sickness (stomach awareness, cold perspiration) after their centrifuge runs, only three of the 741 had symptoms severe enough to cause the trainer to document their motion sickness, and only one actually vomited. The incidence of significant motion sickness associated with the training was thus considerably less than 1%.

Three of the trainees experienced sufficient physical discomfort after their centrifuge rides to cause them to seek the attention of the physician monitor, who examined them immediately and obtained x-ray films and radiologic consultation. One trainee had a paraspinous muscle strain in the lower thoracic/upper lumbar area and was treated with

TABLE II. G-LOC EXPERIENCED DURING HIGH-G TRAINING.

	N	%
Total trainees	741	100.0
Trainees having G-LOC	69	9.3
During GOR	44	5.9
During 6-G, 30-s ROR	2	0.3
During 8-G, 15-s ROR	3	0.4*
During 9-G, 15-s ROR	18	2.4*
During 9-G, "check-six" ROR	19	2.6*
During 86-s SACM	1	2.5†

* Not all 741 trainees attempted all the RORs.
† 40 trainees attempted the SACM run.

ibuprofen and local heat. The second was thought to have a cervical muscle strain due to the unusual head position during the high-G "check-six" run, but symptoms resulting from degenerative changes in the cervical spine (noted on X-rays) could not be ruled out. This patient was given ibuprofen for the acute problem and advised to begin neck-strengthening exercises after the pain subsided. The third trainee had suffered a transient costochondral junction separation during the "check-six" run; he was referred to his base flight surgeon for treatment. The only other trainee to require medical attention was the F-15 pilot who experienced repeated G-LOC episodes at low G levels: he was exhausted from a taxing travel schedule, and was advised to return for training after getting a good night's sleep. Most of the trainees had petechial hemorrhages over the arms (particularly the right arm), mid-torso, and unsupported areas of the legs after completing the centrifuge runs. Such cutaneous petechiasis is commonly observed in volunteer subjects exposed to high-G stress on the centrifuge during experimental studies. This condition is painless, essentially harmless, and disappears in a few days. Another common set of symptoms associated with the training was moderate pain in the right elbow joint occurring during and immediately after the high-G exposure, and stiffness and limitation of motion of the joint lasting several hours thereafter. These symptoms seem to be related to the fact that the elbow is in a relatively dependent position in the centrifuge and to the fact that the right arm is used to pull back on the control stick to drive the centrifuge. Experience with experimental subjects indicates that wrapping the arms with elastic bandages prior to G exposure helps prevent the development of the elbow pain and practically eliminates the cutaneous petechiasis in the arms.

The trainees in the 22nd and all subsequent classes (totaling 452 aircrew) were asked to write a short critique of the high-G training course after they completed their training, and 382 did so. Subjectively categorizing their responses as enthusiastic, positive, neutral, negative, and hostile, we found the distribution shown in Table III. From our perspective the critiques were highly favorable, with nearly three-fourths of the respondents providing comments in praise of the training. One of the critiques covered most of the favorable points made in the others and is quoted here:

> . . . This training is outstanding. I have learned a great deal about my personal G tolerance and straining abilities in the safety of the training environment. I feel this training was priceless and cannot be duplicated in the aircraft without great risk. I believe a refresher course periodically would be beneficial, and if the cost were not prohibitive . . . this program and equipment should be located at every fighter base. If it saves one pilot's life, especially mine, it was and is priceless. I'm sure the training also helps us [fight effectively against an enemy], if it should become necessary."

The comments categorized as neutral were generally constructive criticism, e.g., "Use the SACM in a follow-on, advanced course," and "Data should be collected during the training to determine the effect of physical conditioning on G tolerance." The few unfavorable comments questioned the need for centrifuge exposure, reflecting an opinion stated most directly in the one hostile critique: "I learned my lesson from 3 years of briefings, video tape, and experience. I didn't enjoy practice bleeding."

Each trainee who was not an F-16 pilot was asked to state in his critique whether he thought the training would be

TABLE III. TRAINEES' COURSE CRITIQUE RESPONSES.

	N	%	(%)
Total asked for critiques	452	100.0	
Total respondents	382	84.5	(100.0)
Enthusiastic	110	24.3	(28.8)
Positive	169	37.4	(44.2)
Neutral	95	21.0	(24.9)
Negative	7	1.5	(1.8)
Hostile	1	0.2	(0.3)

significantly better if the centrifuge seat were configured like the seat in his own aircraft rather than like the F-16 seat. Of the 304 who responded, 220 (72.4%) said no, 73 (24.0%) said yes, and 11 (3.6%) weren't sure. Even though it would be relatively easy to change the seat angle, rudder pedal position, and control stick location for each trainee or group of trainees, we don't believe it is necessary; and the majority of the trainees who conceivably would have benefited from changing the seat configuration apparently agree.

CONCLUSION

The G environment imposed by air combat in modern fighter aircraft is becoming increasingly rigorous. It is now sufficiently hazardous that fighter aircrew who are not thoroughly familiar with the physiologic effects of sustained high-G forces, and who have not mastered the means of preventing incapacitation due to those effects, are at high risk of becoming involved in a fatal aircraft mishap. Aircrew training—specifically, centrifuge-based physiological training in the effects of high G stress and in the performance of an adequate AGSM—is the safest and most cost-effective means of preventing losses of aircraft and aircrew due to G-LOC. Such training is well tolerated by aircrew; and it is acclaimed as highly appropriate and useful, even essential, by the great majority of aircrew who undergo the training and offer an opinion about it. It is an idea whose time has come.

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