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G INCAPACITATION IN AEROBATIC PILOTS: A FLIGHT HAZARD

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16. Abstract

This report presents some historical perspectives of aerobatics and the physiological effects of G acceleration, especially as pertain to in-flight loss of consciousness (LOC) by the pilot. Several accidents and incidents are reviewed to illustrate that LOC occurs in some pilots during aerobatic maneuvers. Accelerometer recordings made during aerobatic performances are analyzed in regard to the G's acting on the pilot during the entire performance and during some specific maneuvers. Human tolerance to G's and specifically to changes from positive to negative G's and vice versa is discussed in regard to some published animal and human studies. This report suggests that oscillating G's as encountered in aerobatics tax the body's mechanisms to maintain blood perfusion of the brain—and consciousness. Suggestions are given to help pilots reduce the physiological hazards of G's encountered in aerobatics.

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INTRODUCTION.

Aerobatic flying got its greatest impetus in 1913 when Pegoud, a Frenchman, jumped from his aircraft during a parachute test. During descent he saw the abandoned Bleriot monoplane go through a number of bizarre maneuvers that he thought might be repeated with a pilot at the controls. Later, Pegoud astonished onlookers by performing such stunts as vertical S's, inside loops, and inverted half-loops with rolls. Contrary to a comment in a leading flying publication of the day that "Pegoud-ing is not to become fashionable in the French Army," aerobatic flying became essential to combat tactics during World War I (1) and continues to be a spectacular aspect of both military and civilian flying.

The aircraft designer, Louis Bleriot, expressed concern for the limitations of the pilot when in 1922 he wrote that "It is not the resistance of material which limits the aerobatic performance of the artificial bird, but the physiologic resistance of man, who is the brain of the artificial bird." (2) Today, aerobatic aircraft are highly maneuverable and resistant to the stresses of aerobatic maneuvers but the pilot is still the critical component of the man-machine complex. For optimum performance and safety the aerobatic pilot must master unusual flying skills but, as noted by Bleriot, he must possess a physiological "resistance" so that during maneuvers he can maintain orientation, coordinate neuromuscular activity, and oxygenate the brain to assure consciousness and integrated bodily functions.

It is now well-established that acceleration (G's) can alter a pilot's physiology, degrading his/her ability to safely perform some of the desired aerobatic maneuvers. The most severe degradation of function is loss of consciousness (LOC), which often leads to loss of control of the aircraft and to a crash. Thus, G incapacitation is unique to aerobatic flying.

One of the first reports of the physiological hazards of acceleration was from a pilot of a Sopwith Triplane who experienced partial loss of vision (grayout) just before he fainted during a tight turn at 4.5 G's (3). Doolittle (4), in 1924, first logged the G's acting on the pilot when he equipped a Fokker PW airplane with a recording accelerometer. In a power spiral at a sustained 4.7 G's he gradually lost his sight, and for a short time everything went black. He retained all faculties except sight and had no difficulty in righting the aircraft. In the early thirties, U.S. Navy pilots in pullups from dive-bombing runs encountered accelerations up to 9 G's, experienced impaired vision, and sometimes LOC (5).

1.

In the early thirties, the German physician, Heinz von Dieringshofen (2) made a significant contribution to the understanding of acceleration with his in-flight measurements of physiological parameters and his studies using the first human centrifuge. He established and proved experimentally that the major effect of G's was on the columns of blood in the body (hemostatic theory) and noted that crouching, with the chest pressed against the thighs and the head held vertically, improved tolerance to positive G's. The necessity of compensating for the physiological embarrassments due to G loading in military aircraft led to many studies using human centrifuges. These studies have shown that establishing tolerance limits to G's is a complex subject.

An important consideration in military aviation operation is the pilot's resistance to G-induced LOC. This is evidenced by the continuing research on human subjects and the implementation of counteracting strategies such as tensing-grunting maneuvers (M1,L1), anti-G suits, and changes in the design of seats. Nevertheless, each year there continue to be documented incidents of LOC in military pilots during maneuvers at 3 to 5 G's. A recent study (7) revealed a number of incidents of LOC in a two-man-crew aircraft; these incidents did not result in accidents, possibly because one crewmember remained conscious. A disparity between incidents and accidents indicates the difficulty of establishing the cause of accidents when there is no survivor to reveal events that occurred in flight.

In civil aviation, incapacitating G loads probably are encountered only in aerobatics but this aspect of flying has received little attention. In 1976 the National Transportation Safety Board (NTSB) published a special study, "General Aviation Accidents Involving Aerobatics 1972-1974," citing 105 accidents (8). The study addressed the issues of airworthiness standards for aerobatic aircraft, aerobatic training, and regulating control of air shows. The report included a recommendation to "Issue an Advisory Circular explaining the operational considerations, airworthiness requirements and safety aspects associated with the performance of aerobatics." In 1977 the Federal Aviation Administration (FAA) did issue an Advisory Circular that addressed itself to training, aircraft, operations, etc., but did not speak of the physiological problems inherent in aerobatic maneuvers (9).

As medical investigators of civil aviation aircraft accidents, our attention was called to the problem by the occurrence of some particular accidents and by conversations with Eugene Roth, an Air Safety Investigator for the NTSB. Roth cited an accident (Case #2 below) and some correspondence from a pilot who, during aerobatic flying, had presumably suffered LOC. Using the findings from several accidents, and human centrifuge data, we called attention to the problems of LOC during aerobatic maneuvers (10). A physician, who recently had taken up aerobatics, reported that aerobatic competitors are experiencing life-threatening LOC "that does not have a medical explanation" (11). Whinnery and Mohler have commented on this observation (11).

2.

There is a need to disseminate to aerobatic pilots some of the accumulated knowledge of G-induced LOC so that they may become aware of this threat to safety, and we have drafted an Advisory Circular on the subject (12). In the present report we consider in greater detail a number of observations that bear on G incapacitation as a hazard.

ACCIDENT EXPERIENCE:

The following cases illustrate that accidents can be caused by G loading during aerobatic maneuvers:

Case #1. A 32-year-old male pilot was practicing for an air show. His aerobatic observer on the ground watched him perform a Cuban 8 maneuver and then saw the aircraft make an uncontrolled descent and strike the ground. The pilot was killed. Because of the aircraft's flight pattern, and the absence of mechanical problems, accident investigators suspected that the pilot had become incapacitated. An autopsy and toxicological tests failed to reveal any predisposing condition. A review of events disclosed that within a few hours of the practice session the pilot had told acquaintances that he did not feel well. Further history revealed that he occasionally had to pause climbing stairs, that he was unable to sustain a jogging program, and that his employer had heard him mention having tachycardia. The medical history showed frequent episodes of tachycardia (paroxysmal atrial tachycardia) occurring as often as several times a week and frequently associated with LOC. He did not reveal this condition and episodes of unconsciousness to his FAA Aviation Medical Examiner and thus had not lost aeromedical certification. The evidence pointed to this as an accident resulting from pilot incapacitation.

Possibly this pilot had attempted aerobatics while he had tachycardia, and the G loading during the Cuban 8 maneuver had reduced further an already-compromised brain perfusion. Possibly, also, the G stress imposed by the maneuver may have triggered an episode of tachycardia and a concomitant LOC. In either event, LOC was probably brought on by the aerobatic maneuver.

Case #2. During a practice session, the pilot of an Aerotek Pitts Special S2S had completed his "known" sequence of 18 maneuvers and, after a short rest at the suggestion of his ground observer (a judge of aerobatics), began to fly his "free" sequence of 25 maneuvers. After the 19th maneuver (a three-fourth outside loop followed by two and one-half rolls from inverted to upright) the aircraft flew straight and level for a short time, then left the practice box in a 45° nose-down attitude, crashed, and burned. The pilot was killed. He had not responded to a radio call as he departed the practice box. Postmortem examination did not reveal significant preexisting disease. The events suggest that the pilot, who had previously placed first in national aerobatic competition, was incapacitated in flight.

3.

Case #3. A pilot who survived LOC during aerobatic flight reported that, as he practiced normal inverted turns, the nose of the aircraft began to drop and outside reference was lost. He applied forward stick pressure, which resulted in 2.1 to 2.3 negative G's. In his last conscious act he reduced power to idle. He thought he had been unconscious for 3-4 seconds. On regaining consciousness he found the aircraft in a nose-high attitude, the G meter needles were at 9 positive and 2.4 negative. He landed at the nearest airport for structural damage check. The leading edges of both wings were substantially damaged. Most of the metal ribs near the front spar of the right wing were deformed. One wing spar brace was bent. Ribs on the left wing near the front spar were also bent. There was no underlying medical history consistent with LOC.

Case #4. In discussions of G-induced LOC, an accomplished pilot, Art Scholl, told of a relevant episode (13). The day of the incident he was not feeling well, but attempted the vertical 8 "the hard way," an outside loop on the top and inside on the bottom. He did the top loop and was pulling out of the bottom loop when he thought he heard the sound of a clock alarm and he had the vague impression of some urgency in "getting up"--there was something important he had to do. When he became fully conscious, he was flying inverted and a mile or so away from the practice box. This is his only experience of LOC during an aerobatic maneuver.

Incidents similar to these four cases are on record but, because of inadequate investigating and reporting systems, we do not know how frequently G-induced LOC causes civil aerobatic accidents.

G's IN AEROBATICS--GENERAL OBSERVATIONS:

The most significant G accelerations in aerobatic pilots are in the head-to-foot (or Z) axis. Positive ($+G_z$) accelerations are encountered in maneuvers such as upright banks, turns, and dive pullouts. Negative ($-G_z$) accelerations are encountered in maneuvers such as pushovers, outside loops, and many maneuvers during inverted flight. Human tolerance to $+G_z$'s has been well-studied. Tolerance to $-G_z$'s has been less well-studied because such accelerations cause severe congestion of blood in the head and uncomfortable symptoms. A deterrent to exposing human subjects to $-G_z$'s has been the fear of permanent brain damage from intracerebral hemorrhages; animal experiments, however, indicate that the cerebral vessels are quite resistant to $-G_z$'s (14).

4.

Frazer (6) summarized positive and negative G_z effects as follows:

+1G$_z$:   Equivalent to the erect or seated terrestrial posture.

+2G$_z$:   Increase in weight, increased pressure on buttocks, drooping of face and soft body tissues.

+2 1/2G$_z$:   Difficult to raise oneself.

+3-4G$_z$:   Impossible to raise oneself, difficult to raise arms and legs, movement at right angles impossible; progressive dimming of vision after 3 to 4 seconds, progressing to tunneling of vision.

+4 1/2-6G$_z$:   Diminution of vision, progressive to blackout after about 5 seconds; hearing and then consciousness lost if exposure continued; mild to severe convulsions in about 50 percent of subjects during or following unconsciousness, frequently with bizarre dreams; occasionally paresthesias, confused states and, rarely, gustatory sensations; no incontinence; pain not common, but tension and congestion of lower limbs with cramps and tingling; inspiration difficult; loss of orientation for time and space up to 15 seconds postacceleration.

-1G$_z$:   Unpleasant but tolerable facial suffusion and congestion.

-2 to -3G$_z$:   Severe facial congestion, throbbing headache; progressive blurring, graying, or occasionally reddening of vision after 5 seconds; congestion disappears slowly, may leave petechial hemorrhages, edematous eyelids.

-5G$_z$:   Five seconds, limit of tolerance, rarely reached by most subjects.

Do maneuvers performed by civil aerobatic pilots approach recorded threshold values? Krier (15), a noted aerobatic pilot, wrote, "Each time I perform, I experience a succession of such forces, up to about 5 G's negative and 7 to 7 1/2 G's positive. . ." He noted that negative G's send blood into your head and sometimes cause a slight tight feeling in the top of your head. "This is a signal that I never ignore. When this happens I immediately loosen up on the maneuver even if it means sacrificing a perfect arc." He cautioned pilots that a below-par physical condition will reduce tolerance to repeated G loadings. Mohler (16) noted that an outside loop exposed the pilot to -3.5 G$_z$ for 1 second; an inside aileron roll requires 6 seconds and imposes a maximum of +2.5 G$_z$. An inside snap requires 3 seconds and imposes +2.5 G$_z$; pullout from a three-turn spin

results in +3.5 G_z for 3 seconds; and a square loop imposes +4.2 G_z which will surely cause blackout in an unprepared pilot. Further, Mohler has commented, "In communication with various pilots who have practiced the maneuver (vertical 8), periods of unconsciousness occur at the 7-9 o'clock position on the inside loop which follows the outside loop. If the inside loop is performed firs:, followed by an outside, lower loop, the unconsciousness does not happen; but, as previously stated, the maneuver is worth fewer points." Questions about the hazards of the sequences of -G_z followed by +G_z forces as may occur in some aerobatic maneuvers are obviously raised by these observations. There is also a question of the duration of LOC that may be imposed by such maneuvers.

Our offer to poll aerobatic pilots and compile information on physiological effects related to G tolerance was poorly received by officials of a major aerobatic association. To a great extent, then, the opinions and experiences of the most experienced aerobatic pilots remain anecdotal.

MEASURED ACCELERATION IN AEROBATICS:

Materials and Method.

How much G loading is encountered in aerobatic flying? Hall (17) and Jewell and Morris (18) made in-flight measurements with V-G (vertical gust) accelerometers in aerobatic aircraft flown in competition. The limits of these accelerometers were +8 G_z to -6 G_z. They did not record the duration of the accelerative forces but the VGH (velocity gravity height) device used by Jewell, of the National Aeronautics and Space Administration (NASA), did record duration. The VGH accelerometer was mounted in a DeHavilland Chipmunk aerobatic aircraft piloted by Art Scholl in competitions and in air shows. We obtained from Jewell a VGH tracing made in four performances and Scholl provided notations of the sequences of maneuvers he had flown. We enlarged the tracings photographically to better apply scalar values and measurements were made of the levels, durations, and transitions of G_z's encountered.

The original VGH recordings for the four performances are produced in Figure 1. The tracings show altitude, airspeed in knots, accelerations in G's, and time. Jewell provided a transparent overlay for the first three quantities; time is recorded as vertical dots on the lower portion of each tracing. The two horizontal reference lines on the tracings correspond to reference lines on the scalar overlay, allowing for quantitation of each component. There are sections in which the recording is defective or uninterpretable. The time scale is in minutes; the timing marks were found to vary from extremes of 51 to 72 millimeters of paper traverse per minute and these variations were taken into account in the analyses.

At the beginning of each record--prior to takeoff--the VGH recorded 0 G acceleration, so that the instrument was nulled at 0 for +1 G absolute. Thus, absolute values of accelerations are the algebraic sum of measured accelerations plus 1 G. For example, a recorded or measured +4 acceleration equals 4 G acceleration plus the +1 G acceleration of gravity, or an absolute +5 G's. A measured -3 G's would equal -2 G's absolute (-3+1=-2). All subsequent G values are as measured by the VGH accelerometer.

6.
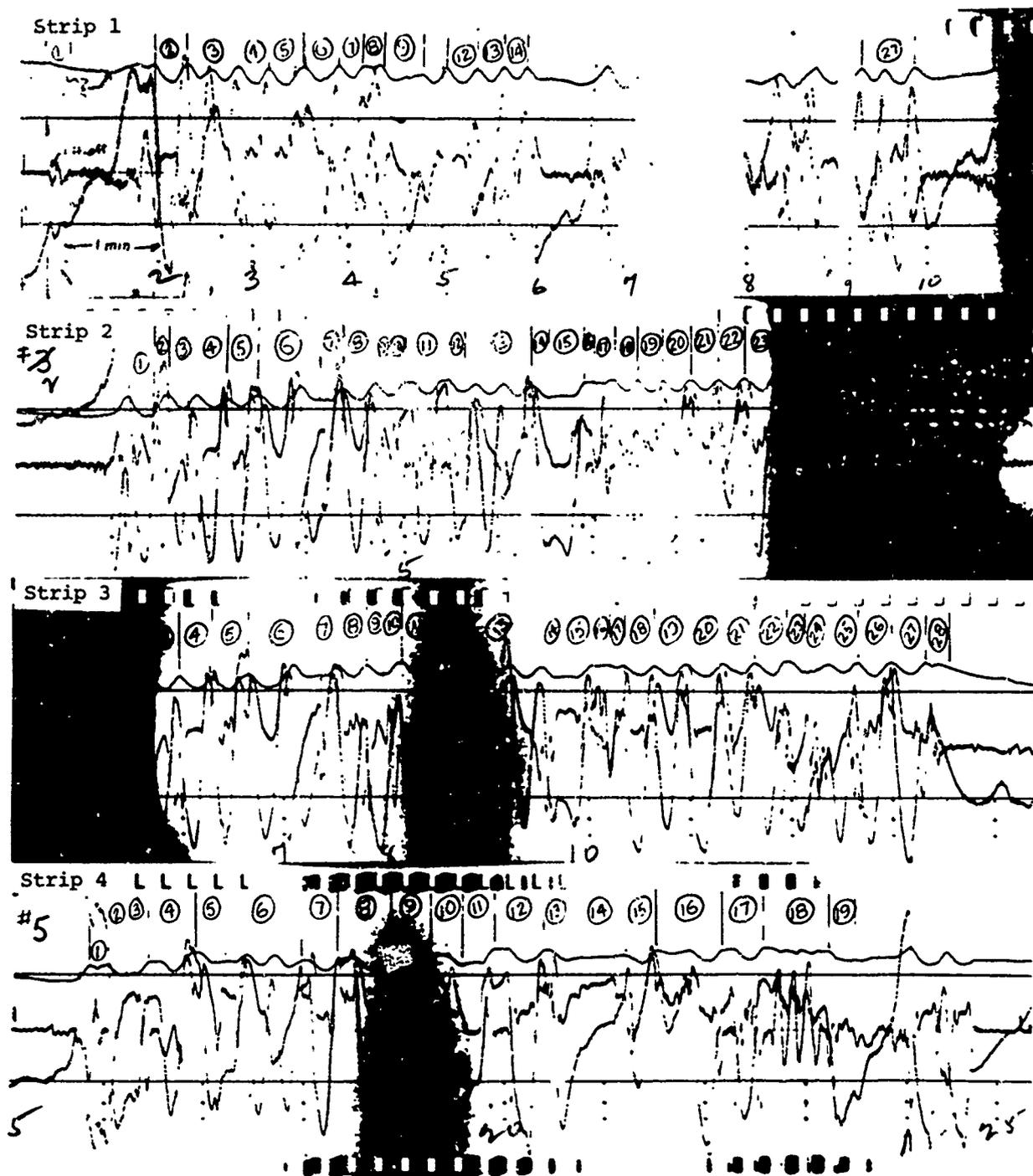
Figure 1. VGH recordings of four aerobatic performances. Circled numbers indicate the maneuver. The altitude tracing is directly under the circled numbers. G's and airspeed occupy the midportion of the recording; the smoother transitions usually represent airspeed. Time in minutes is given by three vertical dots toward the bottom of each strip.

7.

The vertical lines and circled numbers at the top of each tracing represent an estimate (by Jewell) of the beginning and end of the individually numbered maneuvers. Figures 2b, 3, 4, and 5 were derived from photographic enlargements of the VGH recordings and present only the G component of the original recordings. The considerable variations in acceleration experienced by the pilot are clearly illustrated in these figures. A typical aerobatic performance protocol, using Aresti* symbols and demonstrating the sequencing of maneuvers, is presented in Figure 2a.
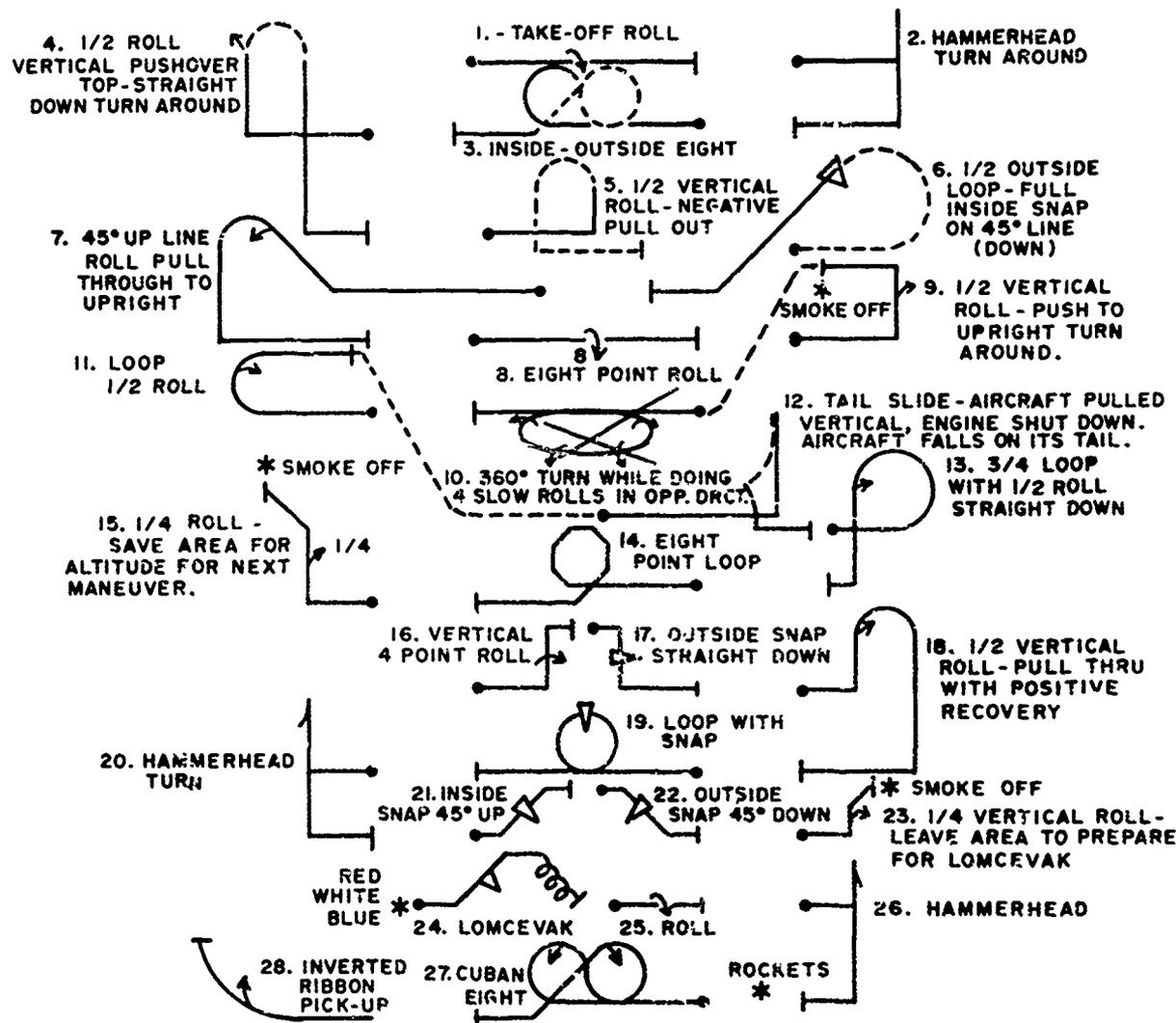
Figure 2a.   Aresti depiction of maneuvers recorded in aerobatic performance corresponding to Strip 1 of Figure 1. (Copied from aerobatic protocol.)

*A widely accepted system for graphic representation of aerobatic maneuvers.

8.

Figure 2b depicts the G accelerations recorded during these maneuvers. Segments of the continuous recording are marked and numbered to correspond to the prescribed maneuver indicated in Figure 2a. The original tracing is represented by strip 1 in Figure 1. A listing of the maneuvers, corresponding to the numbers on the figures, accompanies each figure.
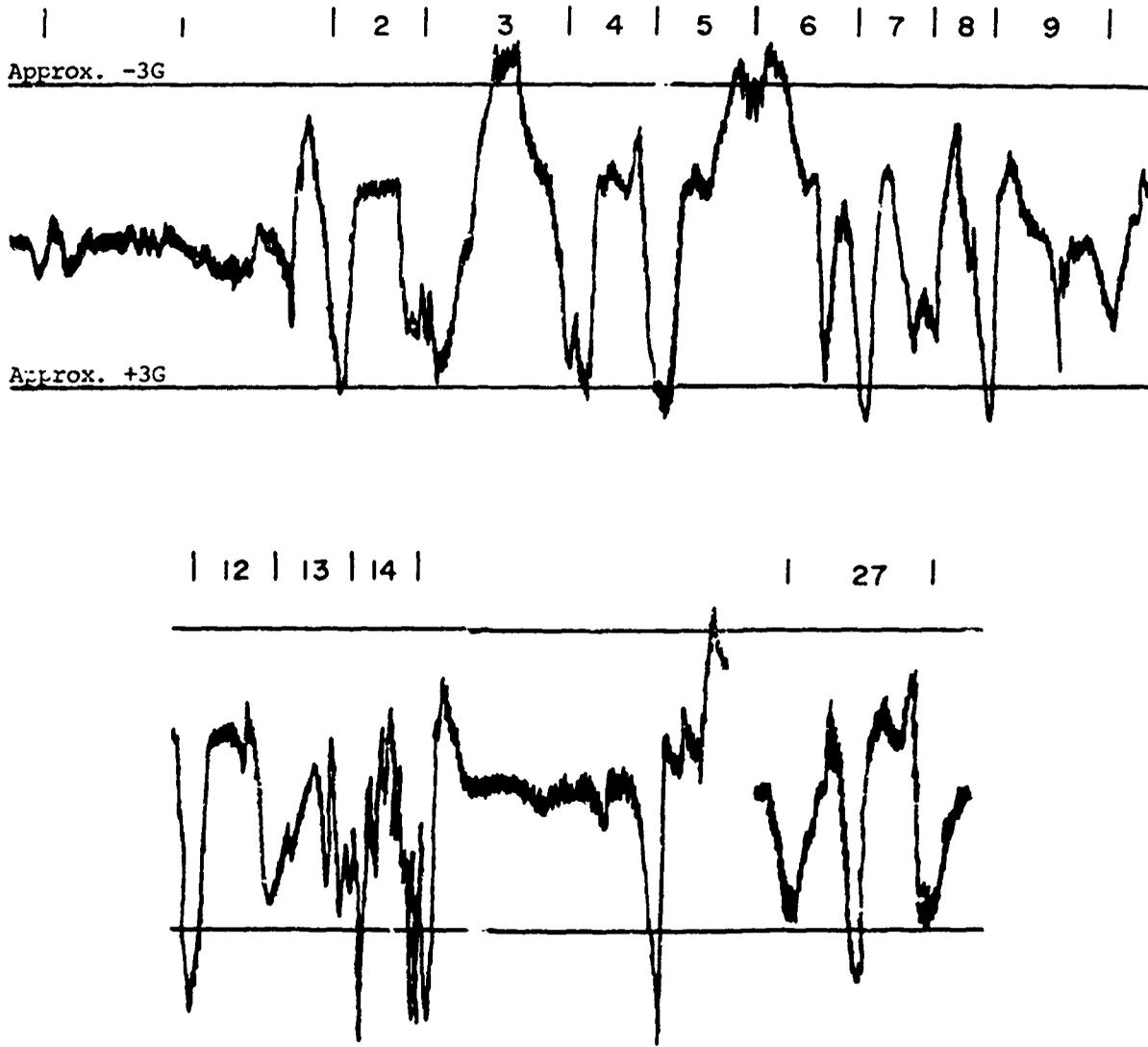

Figure 2b. G's recorded during aerobatic performance.
Enlargement of G's recorded in Strip 1 of Figure 1.
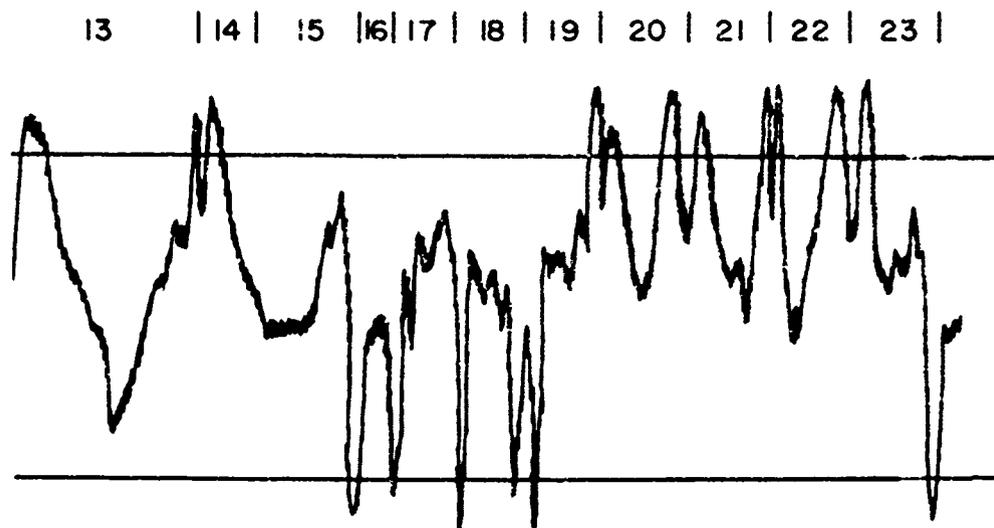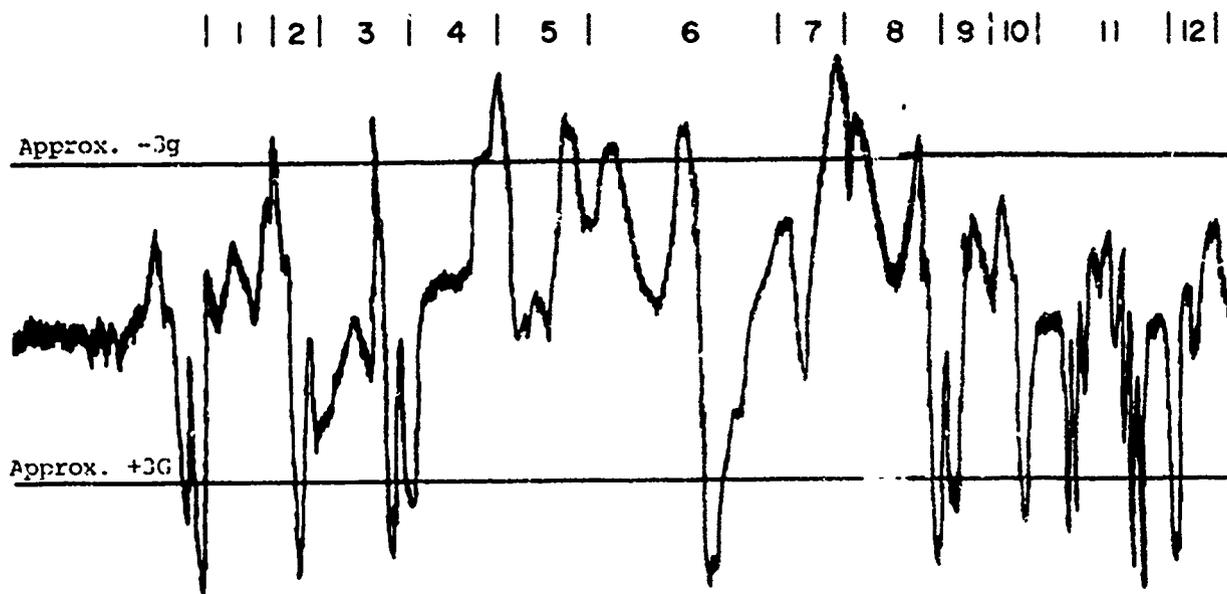
1. Vertical roll	12. 1/2 square loop
2. Straight down outside snap	13. Outside-inside eight
3. 3/4 loop-1/2 inside snap	14. Outside pushover
4. Hammerhead turnaround	15. 1 turn inverted spin
5. Outside straight up 1/2 roll	16. 90° level turn
6. Outside-inside vertical eight	17. 90° turn roll outside
7. 1/2 roll outside, push under to inverted flight	18. 1/2 roll pull through
	19. 1/2 roll push
8. 3/4 outside loop, 1/2 outside snap	20. Outside loop
9. 1/4 roll up	21. 3/4 outside loop, 1/2 roll
10. 1/4 roll down	22. 45° up 4/8 of 8 point roll
11. 8 point loop	23. 1/2 roll push

Figure 3. Enlargement of G's recorded during an aerobatic performance corresponding to Strip 2 of Figure 1. Numbers refer to maneuvers listed.

| 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 13 | 14 |

Approx. 3C

Approx. +3G

| 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
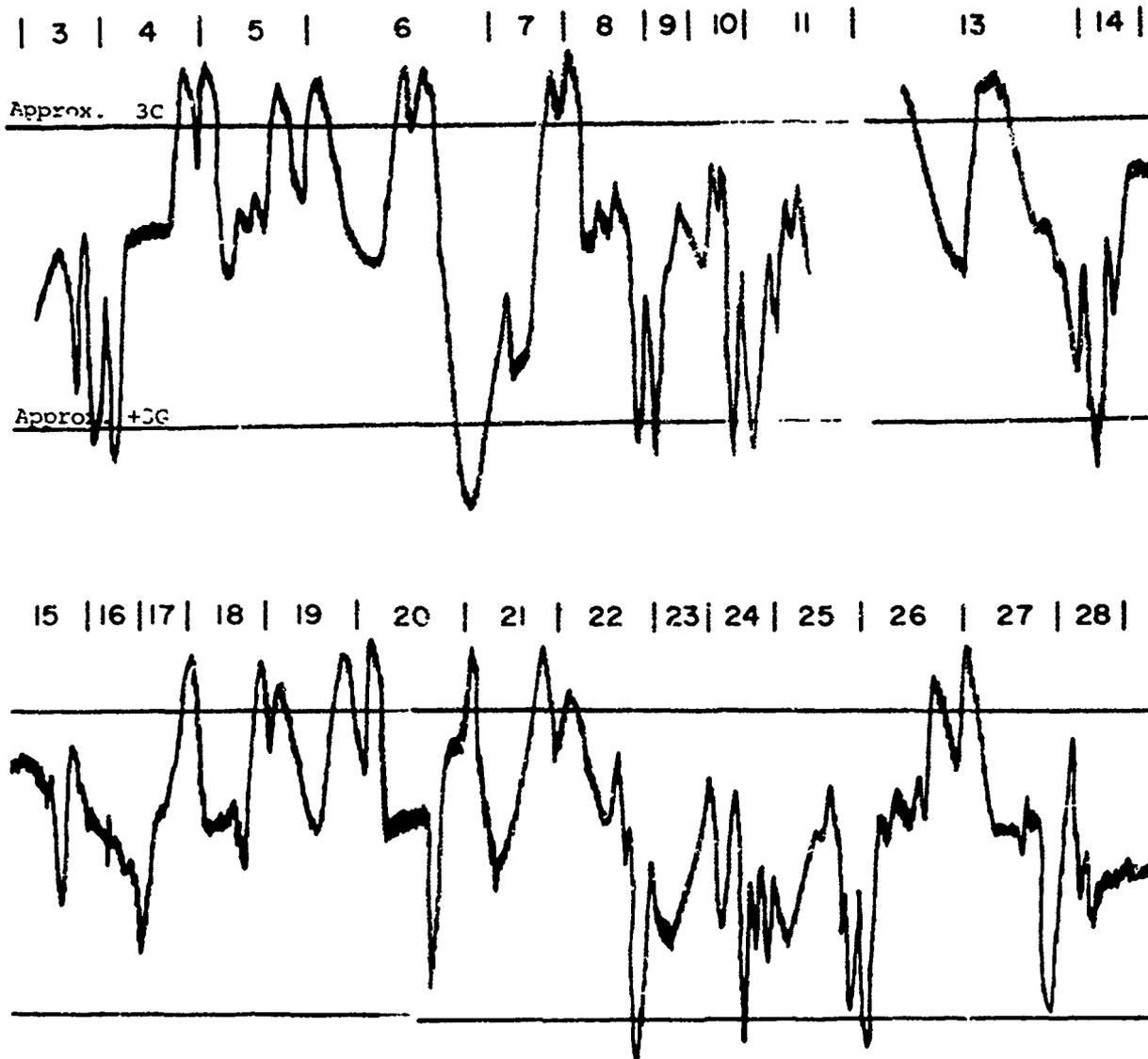
3. 3/4 loop, 1/2 snap inside
4. Hammerhead inverted
5. 1/2 roll up, push to inverted
6. Outside-inside vertical eight
7. 1/2 outside snap, push under
8. 1/2 roll
9. 1/4 roll up
10. 1/4 roll down
11. 8 point loop
12. 1/2 inside loop
13. Outside 1/2 roll, outside eight
14. 1/2 square loop
15. One turn spin

16. 90° inverted turn
17. 90° inverted turn, roll inside
18. 1/2 roll
19. Outside loop
20. Outside hammerhead, 1/2 roll up, 1/2 snap down
21. 4/8 of 8 point roll on 45°
22. 3/4 outside, 1/2 roll down
23. 1/2 loop, 1/2 roll
24. Snap 45° down
25. 3/4 loop 2/4 of 4 point roll
26. 1/2 roll
27. Tail slide, stick back
28. 8 point roll

Figure 4. Enlargement of G's recorded during an aerobatic performance corresponding to Strip 3 of Figure 1. Numbers refer to maneuvers listed.
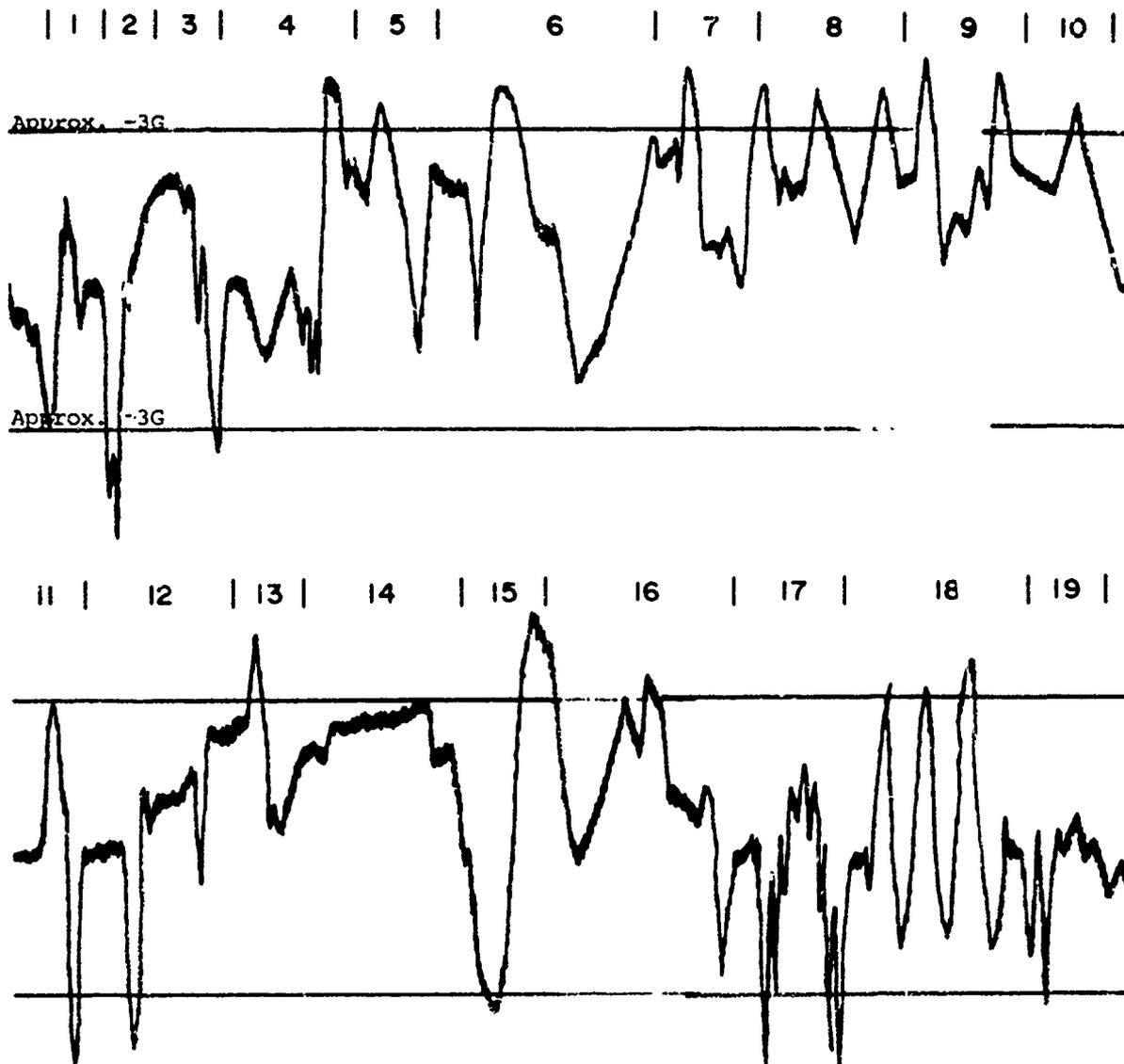
1. 3 point roll
2. 3/4 vertical snap to inverted
3. 1 turn outside spin
4. 3/4 loop, 3/4 inside snap
5. Outside push over, 1/2 inside snap
6. Outside-inside horizontal eight
7. Straight up 1/2 roll, 1/2 loop
8. Outside loop
9. Negative straight up 1/2 roll
10. Outside pushover

11. 1/4 roll straight down
12. Hammerhead 1/2 roll up
13. 1/4 roll, pull to inverted
14. Outside 360° turn
15. 45° 1/2 roll push
16. Tail slide
17. 8 point loop
18. 360° horizontal roll
19. Full snap on 45° up line

Figure 5. Enlargement of G's recorded during an aerobatic performance corresponding to Strip 4 of Figure 1. Numbers refer to maneuvers listed.

12.

We expanded the time scales of these recordings and examined a few
aerobatic maneuvers for greater details of the G accelerations acting on
the pilot. The G scale is identical to that of the photographic enlarge-
ment, but the time scale has been expanded; the time scale is the same
for each maneuver.

HAMMERHEAD TURNAROUND: (See Figure 6; also maneuver 2, strip 1, Figure 1;
and maneuver 2 in Figure 2a. and 2b.)

The duration of the maneuver was an estimated 21 seconds. It was begun
at an airspeed of 160 knots; the VGH measured +3.3 G's at the beginning of
the pullup. Airspeed slowed to 40 knots or less at the top of the hammer-
head turnaround. The VGH recorded -1 to -1.3 G's for approximately 10
seconds. During the fall-off the airspeed increased to 170 knots and the
G's changed from -1.3 to approximately +2 G's and remained at approximately
+2.0 G's for 3 seconds. Despite the fact that the hammerhead turnaround is
an impressive maneuver, the fall-off from the stall is accomplished at
relatively low airspeeds and the pullout from the dive subjected the pilot
to less +G load than occurred in some other maneuvers. The -1 to -1.3 G's
(near zero in absolute terms) represent a short period of virtual weightlessness.


TIME IN SECONDS
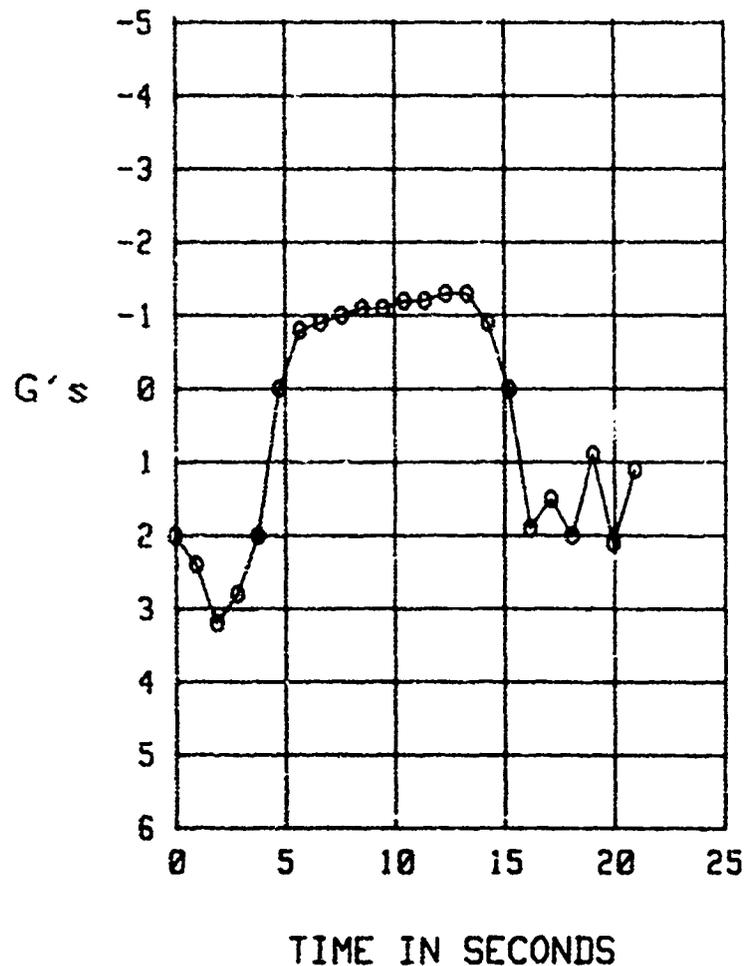
Figure 6. G's in a hammerhead turnaround.

13.

HALF VERTICAL ROLL WITH NEGATIVE PULLOUT: (See Figure 7; also maneuver 5,
strip 1, Figure 1; and maneuver 5 in Figures 2a. and 2b.)

The duration was estimated to be about 25 seconds. The maneuver as
entered from a straight down turnaround at 158 knots and at the pullup
the VGH recorded +3.6 G's. After about 6 seconds, at a maximum altitude
and a minimum airspeed of about 44 knots, the aircraft was inverted and the
VGH recorded from -1 to -1.6 G's. As the aircraft descended, airspeed
rose to a maximum 178 knots; the pullout from this dive while inverted
raised the -G recording to a maximum of -3.6 G's. As the aircraft, while
still inverted, pulled up into the next maneuver the G value increased to a
-4, one of the highest negative G's recorded during this aerobatic perform-
ance. The G's ranged from +3.6 to -3.6, a change of 7.2 G's from positive
to negative with a rate of onset as high as 1.9 G/s. In this particular
performance, maneuver 5 was followed by a one-half outside loop, a negative
G maneuver (see maneuver 6). This prolonged the high negative G load on
the pilot. As indicated by the relatively broad peak on the VGH tracing,
the pilot was subjected to approximately -3.0 (or more) G's for about
14 seconds.
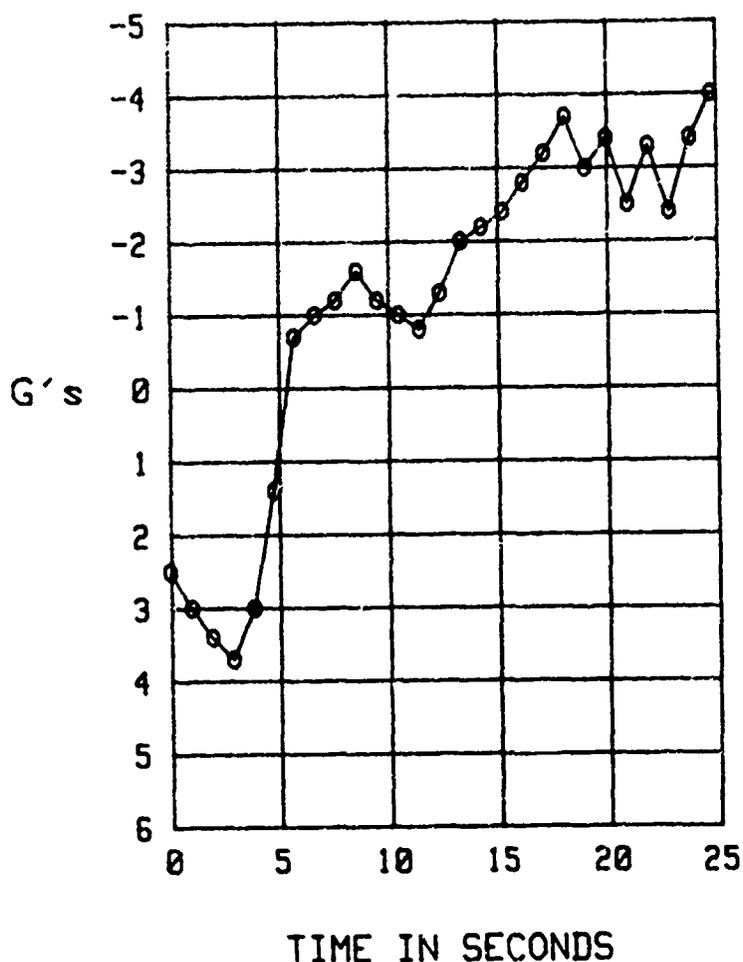
Figure 7. G's in a half-vertical roll with negative pullout.

14.

OUTSIDE-INSIDE VERTICAL EIGHT: (See Figure 8; also maneuver 6, strip 2
of Figure 1 and maneuver 6 of Figure 3.)

Another vertical eight is recorded as maneuver 6, strip 3 of Figure 1
and maneuver 6 of Figure 4. The following description relates to the first
named maneuver (Figure 8). The vertical eight is made up of two loops, one
above the other, to form the Figure 8. The maneuver has been analyzed in
considerable detail and is represented schematically in Figure 9. Altitude,
airspeed, and G's were measured from enlarged recordings and plotted on two
almost-symmetrical circles to represent the maneuver. The maneuver pre-
sented this way illustrates relative times and G's; in actual performance it
may vary considerably. The horizontal axis on the figure has only relative
significance. Even so, the maneuver illustrates accelerations experienced
in relation to altitude, airspeed, and time, during the maneuver.

The maneuver was preceded by the negative G activity of an outside push-
over and a half inside snap with an inverted pullout imposing a considerable
negative G load on the pilot. On entry into the vertical eight (at second #1)
the aircraft was inverted, the airspeed was 148 knots and the acceleration
was recorded as -3.2 G. The airspeed decreased during the outside climb
but for 7 consecutive seconds the G's were measured as -3.3, -3.3, -3.4,
-3.5, -3.5, -3.5, and -3.2. Then, as the airspeed decreased further, accel-
eration diminished until, at the top of the eight, G's fell to -0.4. As the
airspeed increased on the downward side of the outside loop and the pilot
pushed the aircraft under while inverted, the acceleration rose to a maximum
of -5.2 G's at 22 seconds. As the aircraft entered the down leg of the inside
lower loop, the airspeed increased (as did the positive G loading), so that
maxima of 157 knots and +5 G's occurred at second #27. The positive G load-
ing and airspeed diminished at the bottom of the lower loop. Two distinct
surges of negative G loading occurred in the upper loop, first to -3.5 on the
climb then -0.4 and back to a maximum of -5.2 G's. Then there was a transi-
tion from -5.2 G's at second #22 to +5 G's at second #27, a difference of
10.2 G's in 5 seconds. This amounts to an average rate of change of slightly
more than 2 G's/second, sustained for 5 seconds.

Figure 8 shows the two surges of negative G's in the upper loop and the
rapid and marked change from negative to positive G's over a short period,
representing transition from the upper outside loop to the accelerations
experienced in the lower inside loop.

15.
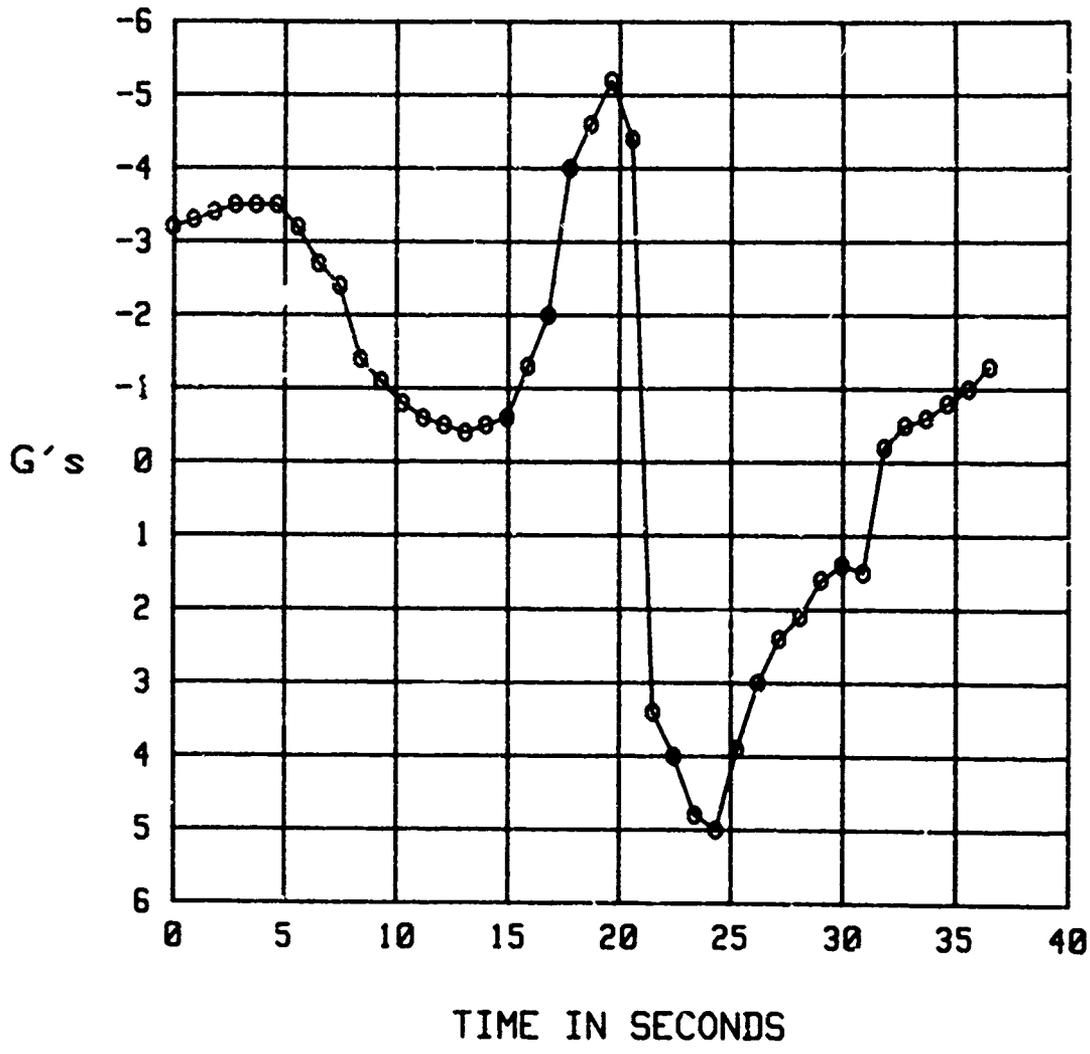
Figure 8.   G's in an outside-inside vertical eight.

16.
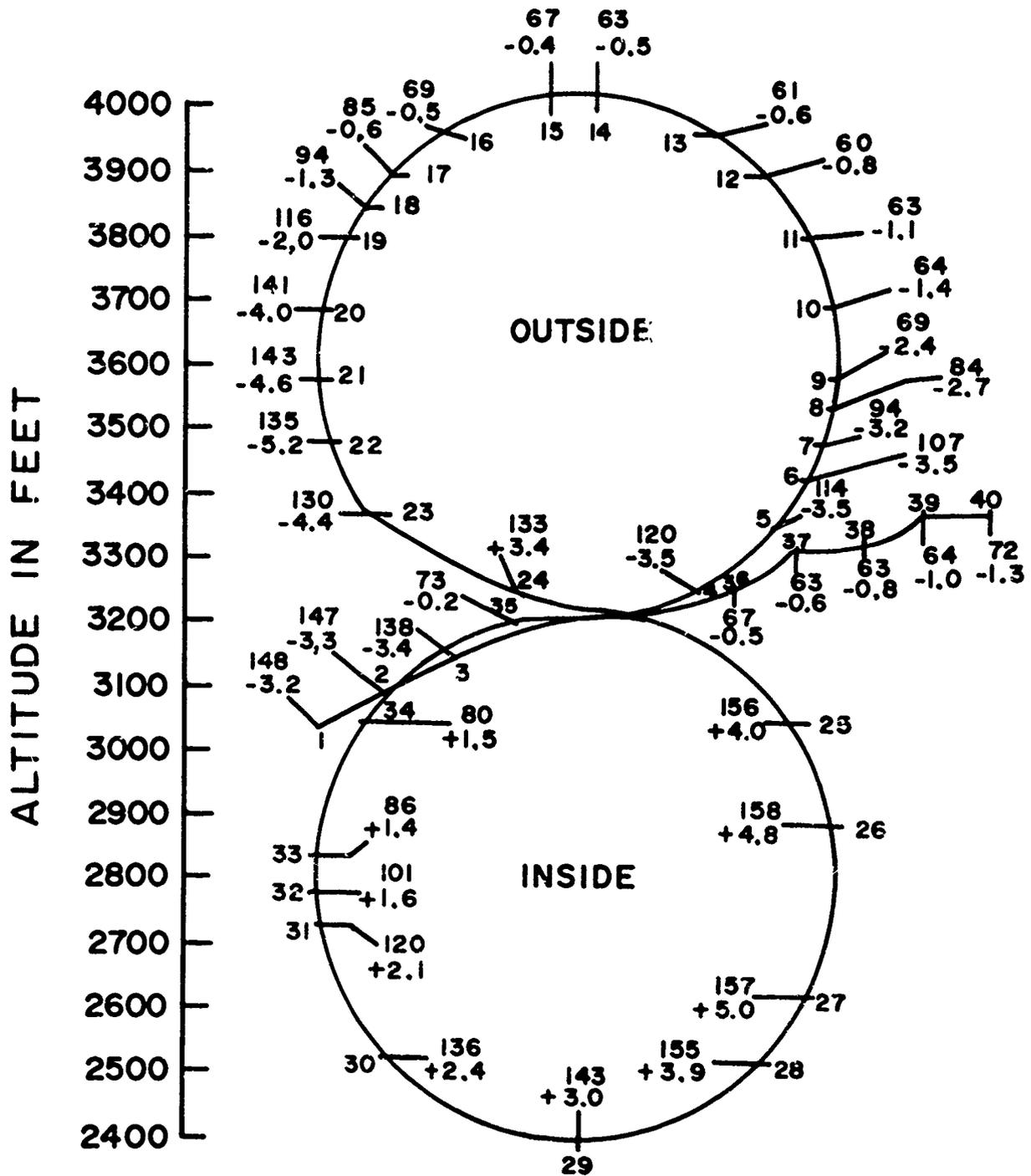
Figure 9. Schematic representation of the outside-inside vertical eight as derived from VGH recording. G's, airspeed, seconds during the maneuver, and altitude are given. The maneuver was entered from an inverted position at about 3,050 ft. (left midportion of drawing). Seconds into the maneuver are noted sequentially. G's are noted as negative or positive numbers. Airspeed is recorded adjacent to the number for G's. The transition from the outside to the inside (- to + G's) is one of the most physiologically hazardous segments in aerobatics.

17.

SNAP 45° DOWN ROLL: (See Figure 10; also maneuver 24, strip 3, Figure 1;
and maneuver 24, Figure 4.)

    The snap 45° down roll was entered from a half loop, half roll at
-1.8 G's and an airspeed of about 54 knots. Airspeed rose to 105 knots
during the 45° dive. Acceleration changed from -1.8 G's to +1.2 G's then
back to -1.5 G's, then to +3.6 G's at 90 knots; and finally, back to near
0. The transition from -1.5 to +3.5 G's was made in 1.5 seconds (or at
a rate of 3.3 G's/second).
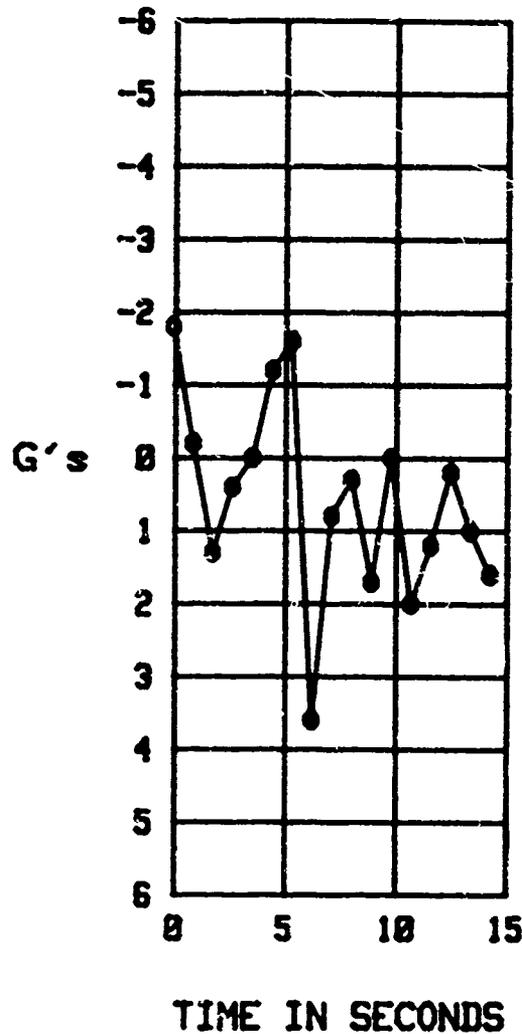
Figure 10. G's in snap 45° down roll.

18.

1/4 ROLL DOWN: (See Figure 11; also maneuver 10, strip 3, Figure 1 and maneuver 10, Figure 4.)

This is another maneuver that illustrated the rapid transition from negative to positive G's. During this maneuver the pilot experienced -G's of nearly -2 for about 4 seconds; this was followed by a rapid transition of -2.2 to +3.7 G's in 2 seconds.
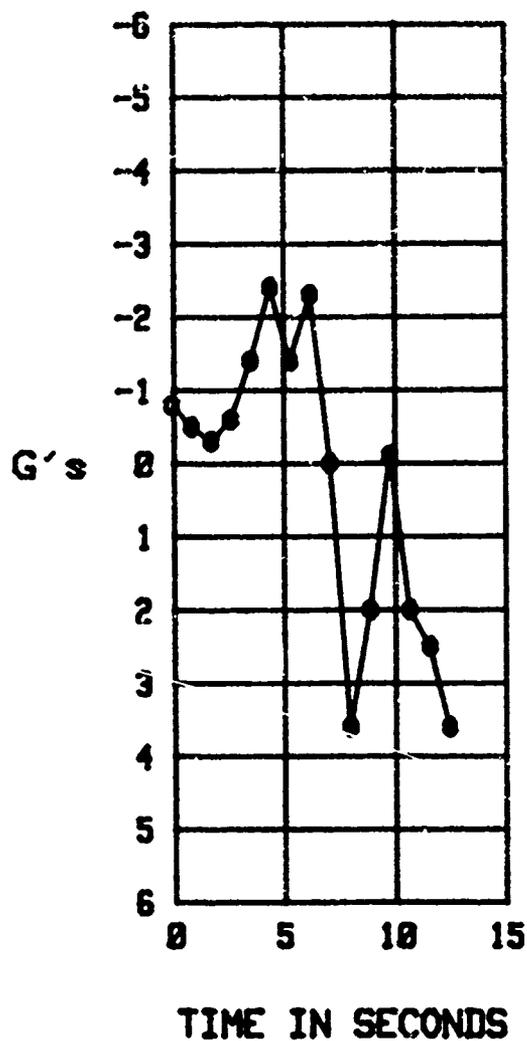
Figure 11. G's in 1/4 roll down.

OUTSIDE 360° TURN: (See Figure 12; also maneuver 14, strip 4, Figure 1; maneuver 14, Figure 5.)

This maneuver demonstrates a prolonged exposure of the pilot to negative G's. The maneuver was 34 seconds long and entered at -2.0 G's, and progressed to a maximum of -3.2 G's. The pilot experienced G's at -2 (or more) for 32 seconds.
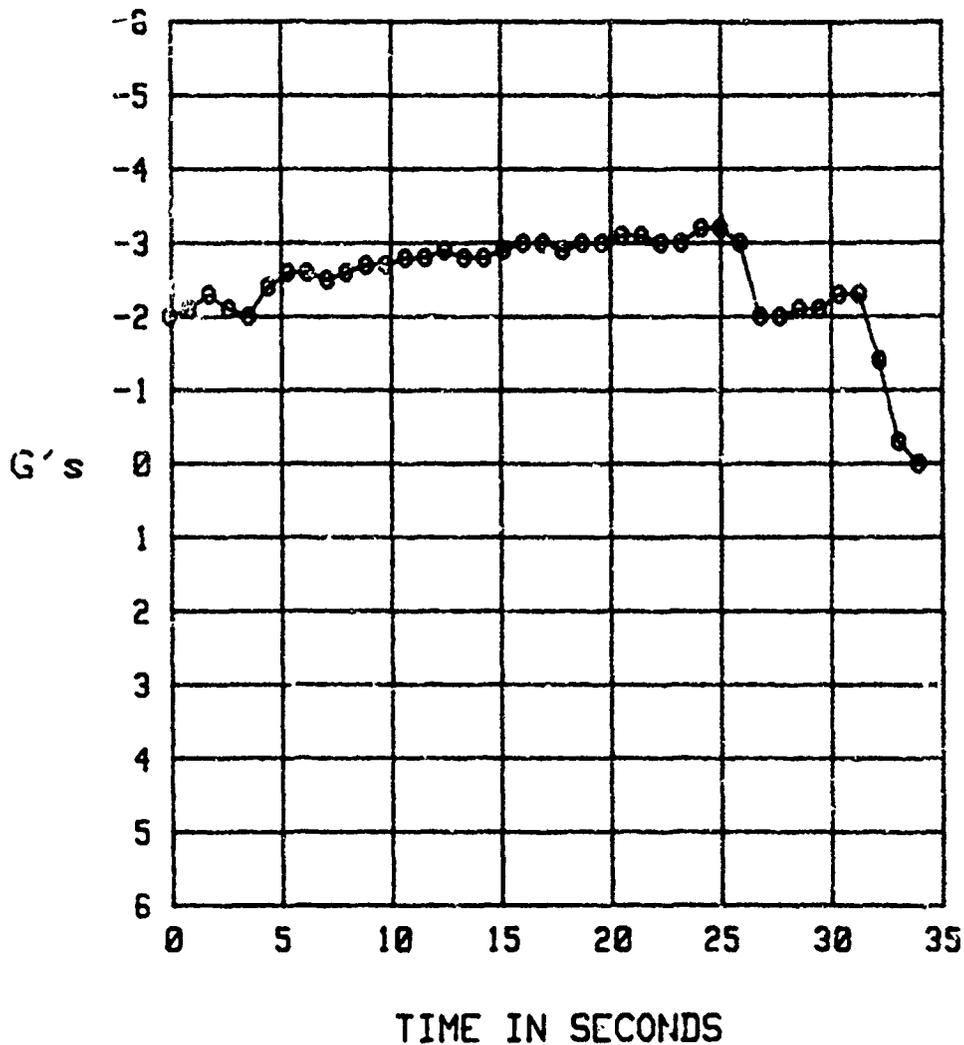
Figure 12. G's in outside 360° turn.

HORIZONTAL ROLLING 360° TURN: (See Figure 13; also maneuver 18, strip 4, Figure 1; and maneuver 18, Figure 5.)

This maneuver subjects the pilot to rapid and repeated G oscillations. For 28 seconds, rolling of the aircraft produced six major G excursions, first to -3.4 G's then to +2.3 G's; back to -3.5 G's, then to +2.0 G's; back to -4.0 G's, and on to +2.3 G's. The first transition from negative to positive G's was 5.7 G's in 2 seconds for a rate of 2.9 G's/second.
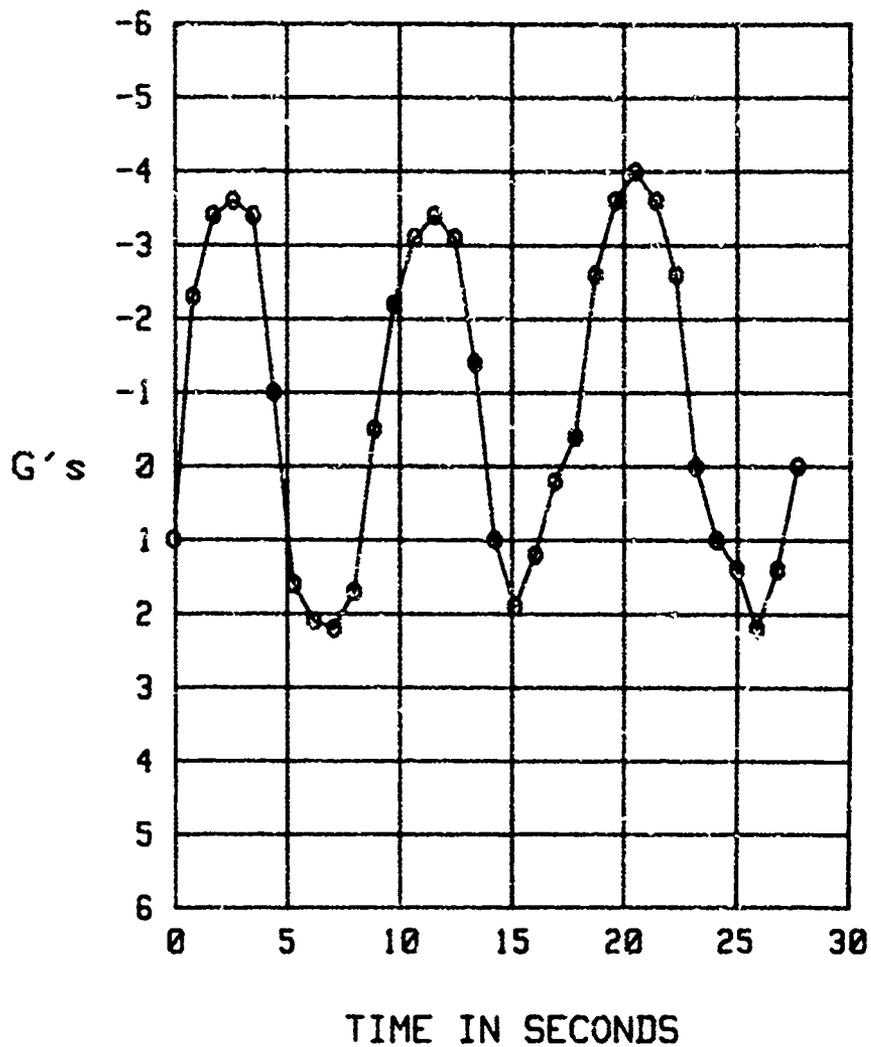
Figure 13. G's in a horizontal rolling 360° turn.

21.

DISCUSSION.

Aerobatics is an art form. Pilots strive for perfection and attempt graceful, precise, and sometimes even bizarre maneuvers, outlined by others or invented by themselves for free-style flying. To carry out the maneuvers the pilot forces the aircraft through various sustained accelerations. His/her body must withstand these accelerations, one after another, if he/she is to complete the program. Other pilots, including military combat pilots, can, if need be, ease off on their diving runs and combat maneuvers to spare themselves the full adverse effects of G acceleration. However, the aerobatic pilot, to please the crowd or score high with aerobatic judges, must carry through with the maneuvers. In this respect, G effects on the pilot are unique to the sport of aerobatics.

We cited some accidents and incidents to illustrate that G accelerations during aerobatics have caused LOC, even in expert pilots. The number of accidents attributable to G incapacitation is unknown but, in view of what is known of human tolerance to G's, we must conclude that G incapacitation represents a significant safety hazard to this select group of pilots.

How close has an aerobatic pilot come to incapacitation from G acceleration during various maneuvers? There is no ready answer; the effects of G's vary from pilot to pilot, probably because of constitutional or genetic factors. Some insight into the problem of individual variation can be gained by comparing the G's experienced in flight with tolerance levels established by human centrifuge studies. The experiences of military researchers help in this comparison. As a result of the U.S. Naval Air Training Program's finding that "a relatively high percentage of instructors and students frequently experience episodes of blackout and unconsciousness," the Naval School of Aviation Medicine measured G tolerance in 1,000 subjects (19). Those studied were 575 naval aviators, 79 students who had been referred because of blackout and LOC during aerobatic maneuvers, 53 naval aviation cadets who volunteered for the study during preflight training, and a group of 293 student flight surgeons, student aviation medical technicians, staff personnel, and others. The researchers found no statistical variations between the subgroups. The data are summarized as follows:

Symptom	Mean Threshold	Standard Deviation	Range
Loss of peripheral vision (grayout)	4.1G	±0.7G	2.2 to 7.1G
Blackout	4.7G	±0.8G	2.7 to 7.8G
Unconsciousness	5.4G	±0.9G	3.0 to 8.4G

Thus, more than 80 percent of these subjects (predominantly pilots) became unconscious at +6.0 G's or less, about 16 percent had LOC at G loads between 3.0 and 4.5, and only about 16 percent could tolerate more than

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+6.0 G's. The data show considerable variation in individual tolerance.
The G's recorded in aerobatic maneuvers are within the range of these
centrifuge findings, and thus it appears that some pilots would be more
tolerant to aerobatic acceleration than others. Important questions
are: Are the top aerobatic pilots a group highly tolerant to G? Have
they been selected, by one mechanism or another, in the course of reach-
ing high levels of proficiency in this sport?

Researchers at the U.S. Air Force School of Aerospace Medicine have
evaluated human performance under G loading in the human centrifuge. In
a study of the duration of LOC they found that +G's applied at the rate
of 1 G/s produced LOC at a mean of 5.4 ±0.3(s.e.)* G's. The tolerance
range was 2.4 to 7.0 G's (20). It is difficult to extrapolate from these
centrifuge data to G's that may be experienced in civil aerobatics; but the
vertical eight maneuver, with a transition of from -5.2 to +5.0 G's at a
rate of greater than 2 G's per second for 5 seconds, is certainly at a level
to cause LOC in many subjects if the G loading were done under laboratory
conditions.

An important factor in G-induced LOC is the duration of the uncon-
sciousness. If LOC occurs, will the pilot recover consciousness in time
to regain control of the aircraft, or is a crash inevitable? The U.S. Navy
centrifuge data (19) indicated that once LOC was induced, an average of
16 seconds was required for recovery. This finding is consonant with the
USAF centrifuge data (20) which indicate a mean LOC duration of 15 ±0.6(s.e.)*
seconds. The duration of incapacitation was within a range of 9.0 to 20.5
seconds and independent of the characteristics of the subject. his/her
previous G experience, the onset rate, or the +G's used to induce LOC. The
15 seconds of unconsciousness is followed by an additional 5 to 15 seconds
of disorientation (21); thus, one who has LOC in flight could expect a period
of 20 to 30 seconds during which the aircraft is uncontrolled. The duration
of unconsciousness would further depend on the rate of decrease of G's
acting on the pilot; i.e., LOC could be prolonged in some maneuvers. Another
threat to recovery of control after LOC is the failure of some pilots to rec-
ognize that they have experienced it. A realistic estimate is that the
period of incapacitation is 20 to 30 seconds, or longer in unusual cases.

Another important physiological factor is the ability of the body to
compensate for swings from positive to negative G's and vice versa. The
G tracings for the four performances in Figures 2b, 3, 4, and 5 exemplify
those swings. The horizontal rolling 360° turn in Figure 13 illustrates
a rather smooth G transition back and forth from positive to negative and
vice versa. Rapid and extreme transitions from negative to positive G's
are found in the outside-inside vertical eight. Since the primary effect
of G_z accelerations is on the columns of blood, the cardiovascular responses
that maintain blood flow to the brain are of prime physiological interest.

Positive G_z accelerations increase the apparent weight or hydrostatic
pressure of the blood in vertically oriented blood vessels. Under condi-
tions of +1 G_z the approximately 30-cm column of blood connecting the heart
to the brain exerts a hydrostatic pressure of 22 mm Hg; so the average

* Standard error of mean

23.

person with a 120 mm Hg systolic blood pressure at the heart will have
at the base of the brain an arterial pressure of 120-22 = 98 mm Hg, and
about 175 mm Hg in the feet. Without cardiovascular compensating mechan-
isms the pressure at the base of the brain at +5 G_z would be 120-110 (5x22)
or about 10 mm Hg--not enough for normal perfusion (and oxygenation) of the
brain. The +5 G_z acceleration also pools blood in the vessels below the
heart. In a reflex response to decreased blood pressure in the major
vessels of the upper torso and head, blood vessels become constricted and
the rate and force of cardiac contraction are increased The decreased
filling of the right chambers of the heart acts to increase the heart rate
and force of contraction. There are other slower compensating mechanisms
(22) that tend to maintain adequate blood flow through the brain.

Whereas the effects of +G_z acceleration are fairly well understood,
the effects of -G_z accelerations are much less understood. The immediate
effect of -G_z acceleration is to increase the apparent weight of the blood
columns, or hydrostatic pressure, in blood vessels and tissues above the
heart and to decrease the blood pressure below this level. The arterial
pressure at eye level increases immediately by 20-25 mm Hg per G, so that at
-3.0 G_z it would be 120+60 (3x20) (or about 180 mm Hg in the arterial system)
and shortly thereafter about 100 mm Hg at eye level in the venous system.

The increased arterial pressure on the stretch receptors in the carotid
arteries produces a reflex slowing of the heart (bradycardia) and a variety
of irregular rhythms (dysrhythmias) ranging from a slow propagation of the
conduction impulse down the heart (prolonged P-R interval); to a complete
uncoupling of the coordinated beating of the atria and ventricles (AV dis-
sociation); to a more irregular beating due to an impetus originating
from sites within the heart muscle (ectopic beats); or to the cessation of
beating for periods of 5 to 7 seconds (asystole).

> Sharp and Ernsting summarized -G_z effects by stating:
> 'Cardiac arrhythmias almost invariably occur on ex-
> posures to negative accelerations greater than 1 G.
> Periods of asystole of 5-7 seconds are not uncommon at
> -2.5 G_z. The arrhythmias, especially asystole, greatly
> reduce the cardiac output, so that the mean arterial
> pressure in the head declines after the initial increase
> caused by the acceleration per se. The generalized arterio-
> lar dilation also contributes to the reduction of arterial
> pressure. The decreased output of blood by slowing of the
> heart rate, and the simultaneous progressive back pressure
> from congestion of blood in the veins, reduce blood flow
> through the brain so that mental confusion and unconscious-
> ness result. The immediate cause of loss of consciousness
> on exposure to negative acceleration is generally a prolonged
> temporary cessation of beating of the heart (asystole) or
> an abnormally slow heartbeat (slow ectopic rhythm) (23).

Whinnery (11) in commenting on accelerations in military flying noted
that aerial combat maneuvering does not routinely involve high levels of
-G but may produce brief 0 G and -0.5 to -1 G exposures. He further
noted that instead of using -G outside maneuvers in aerial combat it is

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usually more efficient and more pleasant for the pilot to rapidly snap
over and use +G maneuvers. Because in competitions the maneuvers are
prescribed, the civil aerobatic pilot must endure both + and - G loads
that result from these designated maneuvers.

As noted before, there is little understanding of the physiological
effects of transitions from positive to negative G's, from negative to
positive G's, or oscillating positive to negative transitions, typical of
some aerobatic maneuvers (see for example, Figure 13). To better advise
pilots of the seriousness of the threat of G-induced LOC in aerobatics
there is a need to define (in centrifuges and in flight) physiological
responses and tolerance to transitions and oscillations of G's at the
frequencies encountered in aerobatic maneuvers. Some studies on the physio-
logical responses to oscillating G's give insight into the body's responses.
For example, Knapp and coworkers (24) subjected dogs to sinusoidal oscilla-
tion of ±G's along their spinal axes and found that responses to counteract
the G-induced changes were most effective when the frequency of disturbance
was below 0.012 Hz (83 or more seconds per cycle). The responses ecame
progressively out of phase (a detriment to maintaining arterial u .od
pressure) for frequencies between 0.012 and 0.052 Hz (83 to 19 s/cycle) and
failed to significantly participate in responses to counteract G-induced
changes at frequencies between 0.052 and 0.25 Hz (19 to 4 s/cycle); although
at the latter frequencies some "protection" was provided by hydraulic and
biomechanical mechanisms. The frequency in the horizontal rolling 360° turn
is 9 to 10 seconds per cycle (Figure 13) and falls into the range for which
Knapp and coworkers found no significant protective response in dogs.

Lim and Fletcher (25) tumbled human volunteers, subjecting them to
sinusoidal ±G's. They called attention to phase shifts in cardiovascular
responses, especially as changes in heart rate. If there were no phase
shifts during tumbling, the heart rate would be minimum in the head down
position (comparable to -G_z) and maximum in the head up position (+G_z) or
in phase with the head down/head up cycle. The differences in heart rates
were greater at slower tumbling rates of 2 to 8 rpm (30 to 7.5 s/cycle) than
at faster rates of 16 to 20 rpm (3.7 to 3 s/cycle). They observed greater
phase shifts for maximum heart rates than minimum heart rates. For example,
at tumbling rates of 6 to 8 rpm (7.5 to 10 s/cycle) the time of maximum
heart rate was out of phase, lagging about 80° to the heads up position. Mini-
mum heart rate occurred in phase with head down position. The greatest phase
shift in heart rate occurred on the first rotational cycle. Gillingham et al.
(27) studied human subjects with intra-arterial catheters in place. Through
a series of accelerations in the centrifuge and mathematical analyses of
responses they noted that arterial pressure variations were least at lower
acceleration frequencies and increased with increasing frequencies, between
0.035-0.07 Hz (corresponding to 28.5 to 14 s/cycle) and reached an apparent
peak resonance at 0.06 Hz (16 s/cycle). These studies all suggest a poor
or possibly detrimental cardiovascular response at G oscillations in the
frequency range of those encountered in aerobatic flight.

The smoothest G-oscillatory pattern recorded on the VGH tracings were
in the horizontal rolling 360° turn (Figure 13). The frequency was about
0.1 Hz (10 s/cycle), or 6 rpm. For this rate, the data from tumbling studies

25.

(25) suggest that the maximum heart rate would be in phase at $-G_z$ peaks
and about 85° out of phase (lagging about 2.5 seconds) at $+G_z$ peaks.
These minimum and maximum heart rates and phase shifts are depicted in
Figure 14. If such phase shifts actually occur during this maneuver the
system compensates to reduce blood pressure to a minimum during $-G_z$ peaks,
but lags or is too slow in compensating to increase blood flow to the brain
during $+G_z$ peaks.

Recently, Bloodwell and Whinnery (28) reported on accelerometer and
heart rate (EKG) findings obtained during aerobatic flights. They noted
heart rate changes from 175 bpm to 40 bpm within a 5-second period (as
determined from the EKG) during cyclic G_z changes. Records showed occasional
premature atrial and ventricular contractions but no significant stress
induced rhythm changes other than $-G_z$ induced slowing. Bloodwell and
Whinnery did not discuss phase lags but we believe that the changes in
heart rate (during the horizontal rolling 360°) within a 5-second period at
an oscillation rate of 0.11 Hz (as determined from the accelerometer tracings
presented) would be expected to show a phase lag in maximum heart rate of
about 90° in relation to $+G_z$ peaks. Although Bloodwell and Whinnery observed
only occasional premature atrial and ventricular contractions, the occurrence
of marked variations in heart rate suggest that even in the relatively sim-
ple horizontal rolling 360° turn, there is considerable excitation of cardio-
vascular reflexes, which in some pilots might trigger serious cardiac
irregularities.

The observation by Lim and Fletcher (25) that the heart rate variation
in tumbled subjects was more pronounced during the first few rotational cycles
may relate to aerobatic maneuvers that are not as cyclic as the horizontal
rolling 360° turn but could be considered an imperfect single cycle or half-
cycle. This is not to say that a given maneuver is unique and physiologi-
cally unrelated to other maneuvers of a sequence. Indeed, Figures 2b, 3, 4,
and 5 indicate that a competitive aerobatic routine imposed random oscilla-
tions; these may condition the pilot to better compensate for the physio-
logical stress of any single maneuver. In any event, in a maneuver such as
the outside-inside vertical eight, the pilot experiences a full cycle of $-G$
loading with the first peak of -3.5 G's, a minimum of -0.4 G and another peak
of -5.2 G's occurring in 17 seconds, about .06 Hz (poor for cardiovascular
response). This second $-G$ peak would be expected to induce a minimum heart
rate (reflex bradycardia) without an appreciable phase lag. Continuing the
maneuver, there is a transition from -5.2 G's to $+5$ G's in 7 seconds (half
cycle) at about .07 Hz. This is in the frequency range of minimum cardio-
vascular compensation in accordance with the studies of Gillingham et al.
(27) and there probably would be 100° or more phase lag in accordance with
data by Lim and Fletcher and probably even greater bradycardia and phase
lag, possibly as much as 180°, because of this being the first half-cycle
of this frequency. Such an analysis suggests that in pulling out of the lower
inside loop there is the demand for rapidly increasing heart rate and
increased blood pressure at the base of the brain to insure perfusion and
maintenance of consciousness; but that the heart would be relatively unrespon-
sive because of previous marked slowing due to the $-G$'s. For these reasons
some pilots performing the outside-inside vertical eight may come close to
or actually lose consciousness. Of course, depending on the tolerance of a
given pilot, other physiologically less demanding maneuvers may have similar
effects.

26.
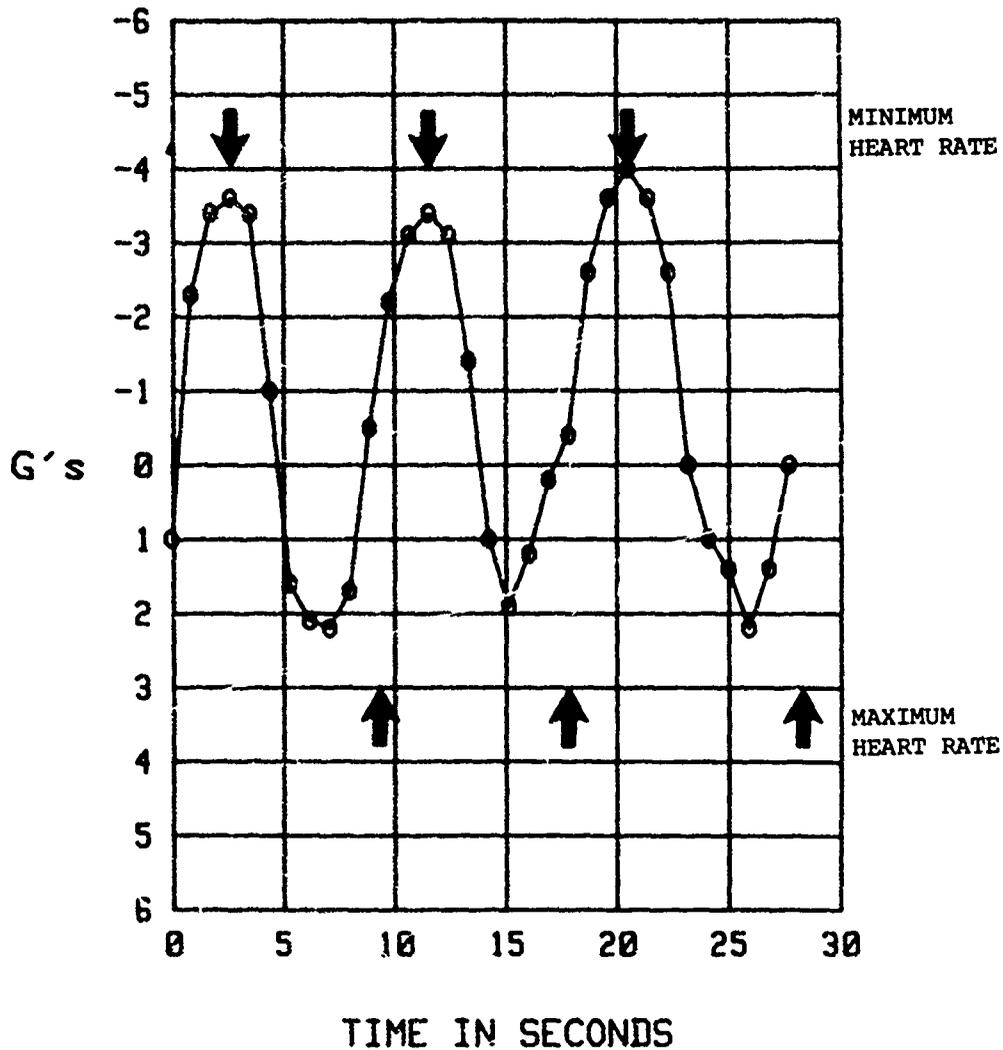
Figure 14. G's in the horizontal rolling 360° turn in relation to hypothetical minimum and maximum heart rates based on experience in tumbling human subjects. Negative G's induce minimum heart rates which are in phase with peaks at negative G loads. At peak positive G loads, maxima for heart rates lag in time and are about 90° out of phase at a time of greatest requirement for cardiac output to maintain adequate perfusion of the brain. There is a need to better define human cardiovascular responses to G transitions and oscillations as experienced in aerobatics.

27.

Physiological considerations must be tempered with other factors--for example, "pilot effect." The term implies that the pilot, knowing what maneuvers he/she is to do (or is doing) and remembering or anticipating what accelerations he/she will experience, will unconsciously achieve a higher state of physiological tension, so that physiological adaptations are made more quickly. One aerobatic pilot noted that he could perform maneuvers that cause LOC in another pilot, flying as a passenger, without experiencing LOC himself. Or, that he could be caused to have LOC when he accompanied (not controlling the aircraft) an aerobatic pilot and yet that pilot would not have LOC. This effect is probably similar to the often observed sparing of vehicle operators the full effects of motion that readily bring on motion sickness in passengers. Lambert (3) found that the act of piloting raised tolerances 0.7 G's as compared to passengers in the plane and 1.4 G's over subjects in centrifuge studies. Gillingham et al. (27) found some of this anticipatory effect in centrifuge studies during a simulated aerial combat protocol. Thus, a certain level of anticipatory physiological tension is protective against G incapacitation. The voluntary muscle straining-grunting M-1, L-1 maneuvers taught military pilots are deliberate attempts to raise physiological tone to the highest level. Similarly, in civil aerobatic flying a certain level of anticipation probably protects from G incapacitation. It follows that a pilot who "relaxes" during certain portions of a given maneuver may significantly lower his tolerance to the G's encountered.

CONSIDERATIONS IN AVOIDING G INCAPACITATION:

Any type of flying involves some degree of risk. The prudent pilot, the skilled pilot, is familiar with the risks involved in all aspects of his/her particular flying interest(s) and acquires the knowledge and skills necessary for reducing these risks to a minimum. In addition, he/she is aware of his/her own limitations and can make accurate judgments of his/her ability to withstand the stresses of flight. As noted, susceptibility to G's is an especially important limitation of the aerobatic pilot, and to recognize and understand this limitation is important to safe aerobatic flying. Briefly, the response of the heart, the amount of mobilizable blood, and the tone of the vessels determine the tolerance to G's. Because of this, the following factors do, or may, play a role in a pilot's tolerance.

1. Body size: Tall persons appear to be more susceptible than shorter persons (16). This is probably related to the length of the column of blood between the heart and the head, it being longer in taller persons and thus more difficult to maintain a head of pressure at the base of the brain to permit adequate perfusion.

2. Physical fitness: Common sense suggests that a certain degree of physical fitness would keep the anti-G compensating mechanisms in a desirable state of tone. Studies have indicated that weight lifting can increase tolerance to G's (29) but intense aerobic training (marathon running) probably decreases tolerance (30). Endurance trained individuals have enhanced cardiovascular vagal

28.

tone evidenced by slower heart rates both during exercise and at rest. It is probably because of poor cardiac response to the $+G_z$ accelerations that such individuals have lowered tolerance.

3. Preexisting cardiac arrhythmias--An arrhythmia reflects cardiac dysfunction of one degree or another. Since the major anti-G physiological response is a speeding or slowing of the heart, before aerobatic flying, a pilot with an arrhythmia would be advised to have a careful cardiac evaluation by a flight surgeon familiar with the effects of G's

4. G-induced dysrhythmias or LOC--Any pilot who has had a symptomatic G-induced dysrhythmia or LOC should avoid aerobatic flying until he/she has had a thorough evaluation by a flight surgeon familiar with the hazards of G's in aerobatic flying. In civil aviation this is a decision to be made by the pilot. In military aviation such an incident may call for a thorough cardiovascular evaluation with additional studies conducted on the human centrifuge.

5. Other factors that may reduce tolerance to G's are:

   a. Hypoglycemia state--Tolerance is lowered with lower blood sugar levels.

   b. Dehydration/excessive sweating--Loss of salt and water cause decrease in blood volume and makes it more difficult for the body to maintain the blood pressure needed to perfuse the brain under G loading. Dietary restriction of salt, sunburn, and weight reduction dieting have been found to decrease G tolerance (32).

   c. Prolonged inactivity--Inactivity causes increased pooling of fluids in the lower parts of the body and probably reduces G tolerance because of apparent decrease in readily mobilizable blood volume. Prolonged bed rest reduces G tolerance (32).

   d. Postprandial state--Following a large meal there is pooling of blood in the abdominal organs and this would tend to counter-act the mobilization of blood to maintain brain perfusion pressure.

   e. Fatigue--The physiological tone necessary to mount a counter G response is probably progressively lowered with increasing degrees of fatigue so that aerobatic pilots would be advised to avoid flying strenuous maneuvers during states of appreciable fatigue.

   f. Illness and disease--Just as fatigue probably lowers physiological tone and impairs the desired anti-G response, so probably do acute and chronic illnesses. Pilots who are ill or do not feel "well" should avoid exposure to significant levels of G's.

g. Medication and drugs--Many prescription and over the counter
    medications have an effect on the cardiovascular system and
    could impair the desired response to G loading. Pilots taking
    medications for colds, sleeplessness, diarrhea, ulcers, high
    blood pressure, pain, etc., should not perform aerobatics
    unless the issue is thoroughly checked out with a flight
    surgeon familiar with the rigors of aerobatic flying.

h. Alcohol and recreational drugs--Alcohol has been shown to im-
    pair a pilot's ability to perform tasks during G loading (31).
    Hangover does not decrease performance although the subjects
    often feel fatigued. Recreational drugs have effects on brain
    function. Their effects on G tolerance are not described;
    however, alcohol and drugs should be avoided by the serious
    aerobatic pilot. In addition to changes in G tolerance as
    noted above, Voge (32) has reviewed indicators of other physio-
    logical changes that may occur in individuals subjected to high
    levels of G acceleration. All of these have been shown in
    animals and humans accelerated under laboratory conditions.

CONCLUSIONS.

    Historical evidence suggests that humans have a variable but limited
tolerance to G's and that if tolerance is exceeded the individual may lose
consciousness. Much research has been conducted to define G tolerance and
to find ways to counteract the effects of G's. Aerobatics is unique in that
the pilot strives to put the aircraft through a series of maneuvers that
subject him/her, as an occupant, to the full physiological effects of the
accelerations encountered. Most aerobatic pilots repeatedly perform these
maneuvers without adverse effects but an occasional aerobatic pilot loses
consciousness due to the physiological effects of G's. If a pilot has
G-induced LOC in flight it will last an average of 15 seconds and be followed
by an additional 5 to 15 seconds of confusion and disorientation. Such LOC
places the pilot in grave danger because he/she may not regain consciousness
and control of the aircraft before it crashes. Some incidents and accidents
attest to G-induced LOC as a cause of accidents. G tolerance varies con-
siderably from individual to individual. The G's experienced in aerobatics
are in the general range of those that cause LOC in some subjects of human
centrifuge studies.

    Maneuvers such as the outside-inside vertical eight subject pilots to
marked transition from negative to positive G's and this transition appears
to be most difficult to compensate for by cardiovascular responses. The
pilot is probably in greatest danger of LOC in performing such a maneuver.
Studies indicate that cardiovascular response is poorest, or may not be of
significant help, in counteracting G effects at the frequencies of G changes
experienced in many aerobatic maneuvers. Factors which reduce blood volume
or interfere with cardiovascular responsiveness probably lower tolerance to
G's.

30.

The occasional aerobatic pilot with lower G tolerance may experience LOC and be lost from this sport in a fatal accident. In order to make the sport safer there is a need to more precisely define, under laboratory conditions, human tolerance to transitions from positive to negative G's, negative to positive G's, and oscillating transitions at the frequencies encountered in aerobatic maneuvers. There is also a need to study, in flight, the G changes similar to those recorded and analyzed in this report along with careful monitoring of the cardiovascular responses. Finally, there is a need to correlate laboratory findings with in-flight findings so that pilots can be better advised as to the seriousness of the threat of G-induced LOC to their safety in this sport. Even without these more definitive studies, there is sufficient evidence to demonstrate that G-incapacitation is a threat in aerobatics. Pilots should be wary.

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