G-Induced Loss of Consciousness: Case-Control Study of 78 G-LOCs in the F-15, F-16, and A-10

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Introduction: This study determined the trends of reported G-induced loss of consciousness (G-LOC) mishaps from 1980–1999, and determined potential risk factors in pilot characteristics; specifically, 30/60/90-h and sortie history, total flight hours, total hours in the aircraft, age, height, weight, and BMI. ***Methods:*** Using aircraft malfunction mishaps to reflect a cross-section of USAF pilots, potential risk factors were determined using a case-control method; cases were all G-LOC mishaps and controls were aircraft malfunction mishaps. The data consisted of 2002 mishap pilots in the history of the F-16, F-15, F-15E, and A-10 from 1980–1999. ***Results:*** During this time, G-LOCs represented only 2.5% of all mishaps. The mean engagement number for G-LOC mishaps was three at an average of 8 Gs. A poor anti-G straining maneuver was cited in 72% of the mishaps, fatigue and G-suit malfunction in 19%, low G-tolerance at 14%, and 37% were student pilots. Within pilot characteristics, only two factors were found to be statistically significant: the time in the aircraft and pilot age. In the F-16, there was a 3.5 times greater chance of experiencing a G-LOC mishap if the pilot had less than 600 h in the aircraft [3.5 (1.7–7.2, 95%CI)], and a 9.5 times greater chance in the F-15 [9.5 (2.2–41.9, 95%CI)]. There was a 4.5 times greater chance of experiencing a G-LOC mishap if under the age of 30 in the F-16 [4.5 (2.3–8.5, 95% CI)] and a 3 times greater chance in the F-15 [2.8 (1.2–6.8, 95% CI)]. ***Discussion:*** Though it is difficult to predict who will experience G-LOC, emphasis on prevention must be concentrated in training and in pilots new to the aircraft.

Keywords: acceleration, age, centrifuge, G-LOC, F-16, F-15, COMBAT EDGE.

THE UNITED STATES Air Force (USAF) has continually improved aircraft design to exceed the normal G-force tolerance capabilities of the human body. There is no debate that anti-G devices and an effective anti-G straining maneuver (AGSM) can maintain a pilot functioning through 9-G maneuvers. These methods have been well established in preventing G-induced loss of consciousness (G-LOC) (1–3,7,8,11). Through the history of high performance aircraft (above 6 $G \cdot s^{-1}$ onset rate), prevention programs have been established to reduce G-LOC. These include mandatory training of the AGSM within a centrifuge, annual AGSM review, use of the anti-G suit, and in many cases, use of the Combined Advanced Technology Enhanced Designed G-Ensemble (COMBAT EDGE) in the F-16, F-15, and F-15E. Several studies conclude that proper use of the equipment and the AGSM will improve an individual's tolerance to G-forces. However, improper use of any of these may result in an incapacitated pilot through gray-out, blackout, and/or G-LOC.

Despite the anti-G equipment and training, the Air Force continues to have a number of reported and unreported G-LOC mishaps. Since G-LOC is known to cause amnesia, an individual may experience G-LOC without remembering and thus not report it, or may choose not to report it (9). However, the Air Force expects equipment and training to decrease the rate of G-LOC mishaps. Limited operational studies have been conducted to determine the effectiveness of these programs. In 1992 Lyons et al. reported findings that revealed a decrease in the rate of G-related mishaps from 4 per million single-seat flying hours in 1982–1984 to 1.3 per million flying hours for 1985–1990, and they suggest this was due to the USAF initiation of the anti-G-LOC training program (6). They further found that only higher systolic BP and shorter aircraft-specific flying hours contributed to a pilot's risk for G-LOC mishaps. Other research to determine risk factors has been conducted in the centrifuge setting. (4,5,10).

Hull et al. suggested a positive correlation between age and G-tolerance to rapid-onset G-forces and a positive correlation between age and weight with gradual-onset G-tolerance (4). They found no significant negative correlations. Webb et al., on the other hand, found an inverse correlation with height and a direct correlation with age, weight, and diastolic BP. However, they concluded that pilots cannot be reliably separated into categories of G-tolerance or susceptibility to G-LOC on the basis of height, weight, diastolic BP, systolic BP, resting heart rate, age, and lipid levels. They further suggested that the AGSM remains the most important factor in establishing a pilot's operational G-tolerance, and its effectiveness apparently overrides any suspected physiological or anthropometric advantage that may exist (10).

This research study determines the trends and rates of reported operational G-LOC mishaps from 1980–1999 and evaluates potential risk factors, specifically aircrew characteristics (age, weight, height, experience, recency of flying), using a case-control method. Aircraft

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malfunction mishaps were used as a control group under the assumption that aircraft malfunction mishaps might happen to any pilot regardless of characteristics. Aircraft malfunction mishaps thus reflect a cross-section of typical Air Force pilots within the same aircraft and years. Cases are all reported G-LOC mishaps, whether the pilot self-reported, it was reported by other flight members, or was determined by a mishap board in the event of a loss of life or aircraft. The cases when compared to the controls, predicted certain reasonable risks. Recommendations are made regarding training focus and anti-G techniques based on the risks found to be significant. Though other studies have addressed variables of when and who are G-LOCing in an operational environment, this study is unique in that it establishes specific risk analysis of those variables. Furthermore, it may validate centrifuge results of pilot characteristics in comparison to the average operational pilot.

METHODS

The USAF Safety Center database provided information on all USAF aircraft mishaps. All mishaps with pilot involvement were queried in the history of the F-16, F-15, F-15E, and A-10 from 1980–1999. For the purpose of the study, G-LOC mishap pilots were treated as cases and aircraft malfunction mishap pilots as controls. All other mishaps, such as those attributed to spatial disorientation, situational awareness, hypoxia, or birdstrikes, were excluded due to potential human factor issues that may have biased the results. Since the study specifically examines the characteristics of a pilot, any mishap that was potentially attributed to the human was excluded. If human factors mishaps were included, specific characteristics, such as recency of exposure and experience, might have biased the results. Controls were specifically chosen to represent a randomized sample of Air Force pilots and determine which characteristics, if any, specifically stood out during a G-LOC. All G-LOCs were included in the cases and not represented in the controls.

G-LOC mishaps do not necessarily reflect loss of life or loss of aircraft. Class A aviation mishaps include: 1) mishaps with a cost of over $1 million; 2) mishaps involving a fatality or permanent total disability; or 3) mishaps involving complete destruction of an aircraft. Class P mishaps include any episodes that could potentially affect the physical or mental capabilities of the primary aircrew to safely perform the mission. Both Class A and Class P G-LOC mishaps were included.

The final database consisted of 2002 pilots involved in the specified aviation mishaps and contained the following variables for analysis: year; aircraft type; one line narrative; mishap type; mishap class; time of mishap; and pilot characteristics (rank, gender, age, height, weight, 30/60/90 flight hour and sortie history, total flying hours, and total flying hours within the mishap aircraft). For G-LOC mishaps other variables were included: engagement number (engagement is defined as a set of maneuvers by opposing aircraft attempting to achieve/prevent weapons firing positions) in which the G-LOC occurred; G level; reported time to aircraft recovery; causal findings; and student status. All data were excluded on ground personnel and incentive flyers (non-pilots who were granted an aircraft flight). SPSS for Windows (Version 10.0.5, 27 Nov 1999, SPSS, Chicago, IL) was used to manage the data and conduct statistical analysis. The data were stratified by aircraft and then controlled for year. All G-LOC mishap pilots were compared with a sample of the flying population (aircraft malfunction mishap pilots, **Table I**) to gain an estimation of relative risk in the form of an odds ratio.

TABLE I. DATA BY CATEGORY AND AIRCRAFT (1980–1999).

	A-10	F-15	F-15E	F-16	Totals
G-LOC	4	25	0	49	78
Malfunctions	234	661	364	665	1924
Totals	238	686	364	714	2002

The data contained reporting bias between 1983 and 1993, since during this time individual data did not have to be collected if the mishap did not involve human factors. This does not affect the data in the G-LOC cases, but affects the data within the aircraft malfunction controls. Individuals who had an aircraft malfunction did not necessarily have to report their personal information such as height, weight, and experience. The database thus had some blanks in it before 1993. However, in most cases, personal data was collected and the database had sufficient individuals with reported data to make a risk assessment. Furthermore, since the data was controlled for by year, the effect was minimal.

Further bias may be included in the cases. As reported in the literature, the number of reported G-LOC mishaps does not accurately reflect the number of actual G-LOCs occurring in the Air Force, and it has been suggested that 12% of tactical pilots admit to possibly experiencing a G-LOC during flight (9). G-LOCs are a reportable mishap whether or not a crash occurs. The discrepancy between actual and reported G-LOCs may be due to a number of factors including reluctance to report a G-LOC or amnesia of a G-LOC happening. Not every G-LOC that has occurred was expected to be in the database due to this reporting bias.

RESULTS

Descriptive Statistics of G-LOC Cases

Within the database, G-LOC mishaps constituted 2.5% of all mishaps in these aircraft while aircraft malfunction mishaps represent 61%. Separately by aircraft, G-LOC comprised 4.0% of all mishaps within the F-16, 2.5% in the F-15, 0.9% in the A-10, and 0% in the F-15E. **Fig. 1** shows the number of reported G-LOC mishaps by aircraft and year. As depicted, the A-10 has not reported a G-LOC mishap since 1984 and has had only a total of four G-LOC mishaps in its history. No reports of G-LOC mishaps have occurred with the F-15E. Both the A-10 and the F-15E fly primarily air-to-ground missions. The operational parameters of these missions involve a lower G exposure, which contributed to their lack of reported G-LOC mishaps.

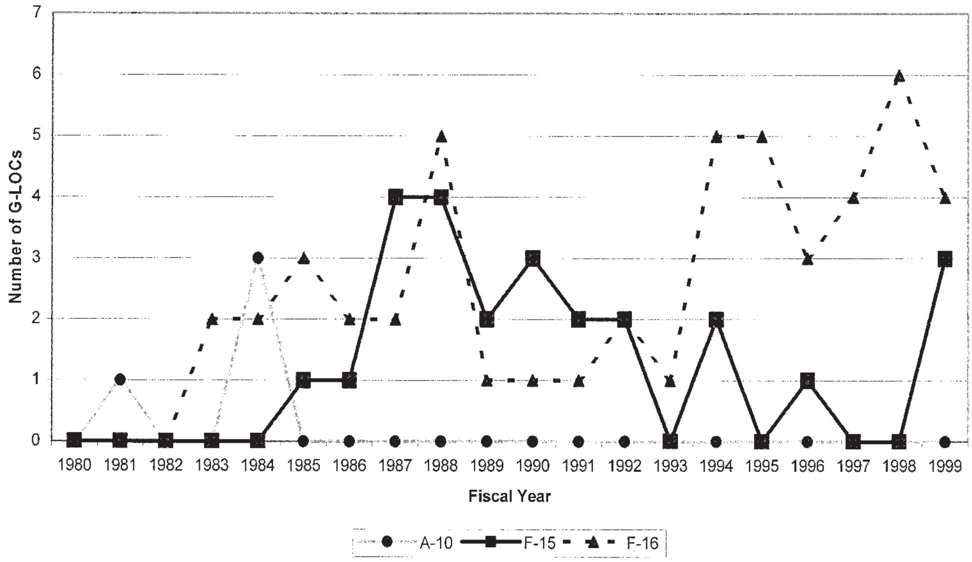

Fig. 1. Number of G-LOC mishaps by aircraft.

After 1988, the F-15 has steadily decreased its G-LOC mishap numbers until 1999. The F-16, however, seems to have had an increase of G-LOC mishap occurrence since 1993. **Fig. 2** depicts the trend in G-LOC mishap rates for the F-16 and F-15, shown as mishaps per 100,000 flying hours. The start of mandatory centrifuge training is noted. In 1988 the USAF prioritized pilots for centrifuge training based on presumed risk factors of low resting heart rate, low sitting systolic BP, height, and total flying time (6). In 1989, the Department of the Air Force issued a policy that all tactical pilots train in the centrifuge. The Air Force operationally tested the COMBAT EDGE system 1 yr later. In 1991, the F-16 community began fitting the system into all of their aircraft and the F-15 community began the fitting in 1996.

Table II displays all G-LOC mishaps by class. Class A mishaps constitute only 28% of all G-LOC mishaps. For F-16s, Class A G-LOC mishaps make up 31% (15 of 49) of all F-16 G-LOC mishaps, while the F-15's have only 16% (4 of 25). No Class A mishap was reported among the 17 G-LOC mishaps involving dual-seated aircraft; the remaining 61 G-LOC mishaps occurred in single-seat aircraft.

The mishap reports list factors that potentially caused the G-LOC. **Table III** lists the most common causal factors. Many of the accidents listed multiple factors. However, most accidents faulted a poor AGSM, which is specifically listed in 53 (72%) of 74 mishaps. Fatigue and G-suit malfunction are equally listed for 14 mishaps each. Low G-tolerance, usually due to illness, lack of recent flying, dehydration, or other physiological condition, was listed for 10 of the mishaps. Experience level was not listed as a factor, but of all G-LOC mishaps, 37% involved a student pilot.

A total of 14 variables were evaluated for trends and risks factors. **Table IV** notes the means of those variables categorized by aircraft. All variables are later compared with a control group, except for G level, engagement, and recovery time. The average G level in which a G-LOC occurred was approximately 8 G, with the lowest G-LOC occurring at 4 Gs and the maximum at 16 Gs. The engagement number ranged from zero (G-LOCs during the G-awareness exercise) to seven (if the

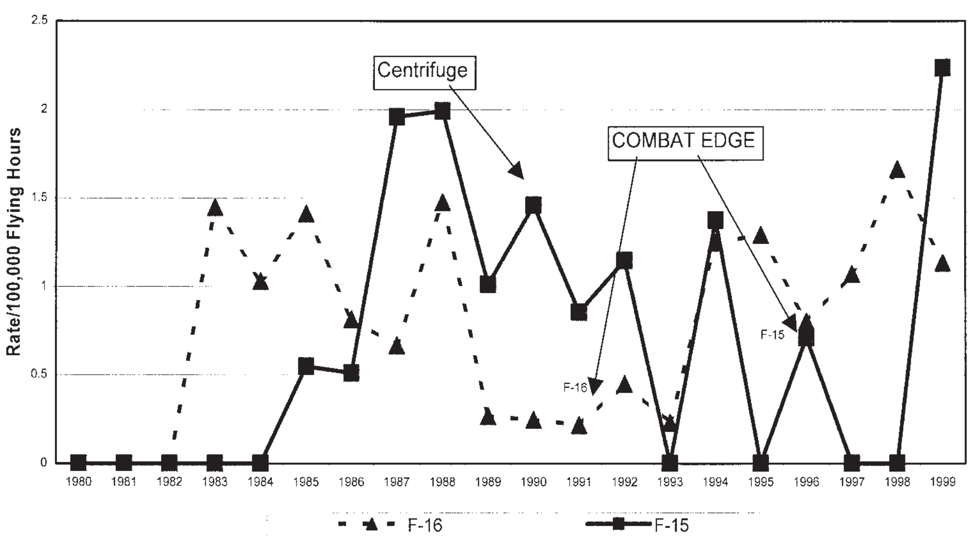

Fig. 2. F-16/F-15 G-LOC rates.

TABLE II. G-LOCS BY CLASS TYPE.

	F-16	F-15*	A-10	Total	%
Class A	15	4	3	22	28
Class P	34	21	1	56	72
Totals	49	25	4	78	100

* Does not include F-15E data.

G-LOC occurred during the second sortie of the day, after filling the aircraft with gas, either on the ground or during an air-refueling, the previous engagements were counted and the engagement number continued during subsequent sorties). An F-15 G-LOC usually occurred during the second engagement while an F-16 G-LOC most frequently occurred during the third. If a pilot was able to recover the aircraft before impact or ejection, the recovery time took an average of 12 s in the F-16 and 13 s in the F-15.

Analyses of G-LOC Mishaps

The aircraft malfunction mishaps category was used as a control group under the assumption that aircraft malfunction mishaps might happen to any pilot regardless of exposure. Only F-16 and F-15 pilots were compared since no G-LOC mishaps occurred in the F-15E and only four in the A-10. **Table V** depicts the odds ratios for G-LOC mishap pilots in the F-15 and F-16 compared with aircraft malfunction mishap pilots.

The control group, aircraft malfunction mishaps, was dichotomized into two groups: comparing those less than the control median vs. those at or above the control median for each factor, separated by aircraft type. If there was no difference in the population in comparing the two groups, the odds ratios would equal 1. For F-16 and F-15 pilots the only risk factors found significant were lower total flying time in the F-16 and younger pilot age. When the control group was dichotomized, further analyses were done to the nearest mean whole number. Results indicated an odds ratio of 3.5 (1.7–7.2, 95% CI) when the individual has less than 600 h in the aircraft and an odds ratio of 4.5 (2.3–8.5, 95% CI) when the individual is younger than 30 yr of age. For F-15 pilots the significant risk factors mirrored those of their F-16 counterparts: lower total flying time within the aircraft and younger pilot age. Further analysis showed an odds ratio of 9.5 (2.2–41.9, 95% CI) when the individual has less than 600 h in the F-15 and an odds ratio of 2.8 (1.2–6.8, 95% CI) when the individual is younger than 30 yr of age.

Most other flying history and physical characteristics

TABLE III. CAUSAL FACTORS LISTED IN F-16 & F-15 MISHAP REPORTS (N = 74).

	Number	Percentage
Poor AGSM	53	72%
Fatigue	14	19%
G-Suit Malfunction	14	19%
Low G-Tolerance	10	14%
Student*	27	37%

* Not a causal factor stated in mishap reports.

TABLE IV. MEANS OF G-LOC MISHAPS BY AIRCRAFT.

	F-16	F-15	A-10
G-Level	8	8	N/A
Engagement	3	2	N/A
Recovery Time	12	13	N/A
30-d Flt Hours	14	16	12
60-d Flt Hours	25	24	40
90-d Flt Hours	36	30	59
30-d Sorties	11	13	8
60-d Sorties	20	18	23
90-d Sorties	27	23	33
Total Flt Hours	1448	1397	2109
Total Flt Hours-A/C	297	135	577
Age	31	31	31
Height	72	72	71
Weight	182	189	170
Body Mass Index	25	26	24

showed no significant differences in risk for the G-LOC mishap pilot compared with the aircraft malfunction mishap pilot. Although 90-d flight hour history showed significantly higher risk for those with lower hours, the higher risk for those with a lower 90-d sortie count was minimal. In addition, no significant difference was found in these analyses when controlled for age or year.

DISCUSSION

Our study suggests that the rate of G-LOC mishaps has not shown a steady decline throughout the years. In fact, the rates increased in the late 1990s. However, the rates are comparatively low and represent only a handful of G-LOC mishaps. An addition or subtraction of just one G-LOC mishap per aircraft would greatly change the rate. Compared with the other mishaps in this data set, G-LOCs represent a very small proportion (2.4%). However, there is an obviously greater danger of having a Class A mishap in a single-seat aircraft whenever the pilot is incapacitated, including from G-LOC. Fortunately, only 28% of reported G-LOCs have

TABLE V. UNADJUSTED RISK OF G-LOCS IN THE F-16 AND F-15 (95% CONFIDENCE INTERVAL).

	F-16	F-15	Control Median†
30-d Flt Hours	1.26 (0.64–2.49)	0.18 (0.02–1.46)	14 h
60-d Flt Hours	1.56 (0.78–3.12)	3.05 (0.58–15.91)	29 h
90-d Flt Hours	2.06 (1.00–4.29)	8.56 (1.04–70.26)*	44 h
30-d Sorties	0.51 (0.24–1.06)	0.19 (0.02–1.59)	10 sorties
60-d Sorties	0.87 (0.44–1.73)	1.05 (0.21–5.29)	19 sorties
90-d Sorties	1.23 (0.62–2.44)	1.24 (0.27–5.61)	29 sorties
Total Flt Hours	1.56 (0.82–2.94)	1.36 (0.54–3.45)	1715 h
Total Flt Hours-A/C	3.47 (1.63–7.39)*	8.76 (1.99–38.56)*	637 h
Age	2.71 (1.40–5.24)*	2.75 (1.06–7.13)*	32 yr
Height	0.79 (0.29–2.16)	0.48 (0.05–4.74)	71 in
Weight	0.70 (0.25–1.90)	0.33 (0.03–3.24)	175 lb
Body Mass Index	1.04 (0.39–2.81)	0.22 (0.02–2.1)	25

† Odds Ratio: Comparing those less than the control median vs. those at or above the control median for each factor separated by aircraft type in G-LOC vs. aircraft malfunction mishaps.
* Significant odds ratio

resulted in Class A mishaps as determined by a Safety Investigation Board.

Among those with G-LOC mishaps, the mean engagement number was three. This suggests that G-LOC mishaps may be related to fatigue and/or complacency. If an individual had a malfunction in the G-suit or another technical problem, that should have been noticed during the G-awareness exercise or during the first two engagements. The sortie should have terminated without incident. After a G-awareness exercise, which physiologically prepares a pilot to tolerate high G-forces, that individual needs the addition of a properly conducted and timed AGSM. After the third engagement, the use of COMBAT EDGE should help in combating fatigue (1). However, the addition of positive pressure breathing will not supplement an inefficient lower body strain (3). Efforts should be made to fine-tune the AGSM to reduce the effects of fatigue, specifically starting the AGSM before the onset of G, and maintaining a constant 3-s breathing cycle. A late start on the muscle tension along with rapid or deep breathing may fatigue the individual, compounding the stress caused by G forces.

All pilots must successfully demonstrate an adequate AGSM technique during centrifuge training at 9 Gs. According to the data, only 29% of the G-LOCs occurred during a 9-G maneuver, 43% occurred at 8 Gs, and 28% occurred at 7 Gs or lower. Training should concentrate on long sorties and an efficient AGSM in addition to high-G maneuvers. Until improved equipment can supplement an inadequate AGSM, training should concentrate on maintaining a proper AGSM at all G levels. Efforts should be made to highlight equipment limitations, since the currently used equipment cannot prevent a G-LOC without a proper AGSM.

The operational F-16 and F-15 G-LOC mishap pilot is very difficult to predict. The pilot will not necessarily be one that has been grounded for several weeks or be tall and thin. Neither of these factors was found to be significant among those individuals that experienced a G-LOC. After several analyses, only two factors were found to be consistently important: the time in the aircraft and pilot age. A younger pilot is more likely to experience G-LOC. Previous centrifuge studies have also supported that aging may offer some protection from G-stress, which may also be due to arterial BP, rigidity of blood vessels, or limitation of diaphragmatic descent (4). Though age may also affect flying style, total flying experience was not a significant factor. Flying history or recency of exposure is not as important as experience in the aircraft.

CONCLUSIONS

The goal of training is to reduce the number of mishaps to zero. Centrifuge training is extremely important to expose pilots to proper AGSM techniques in a non-life-threatening environment. It may be just as important to include COMBAT EDGE training in the centrifuge to ensure pilots do not have an inappropriate reliance on the equipment but ensure focus on developing and maintaining the proper AGSM at all G levels, even when fatigued. Furthermore, due to the increasing capabilities of the aircraft, pilots may be asked to fly longer and more aggressively, increasing the risk of G-LOC. The concentration in training should be on proper and efficient use of AGSM to prevent G-LOC and the proper and efficient use of equipment to reduce the fatigue associated with AGSM. Training can also emphasize the necessity of both anaerobic and aerobic fitness training to combat fatigue during a demanding sortie. Furthermore, efforts need to be made into perfecting technology to potentially remove the pilot's need to rely on an AGSM. It is obvious that years of effort to perfect and train the AGSM have not eliminated G-LOC mishaps any more than the current technology. Until G-LOC mishaps cease to occur, both areas need to be emphasized.

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