Analysis of G-LOC incidents during centrifuge training

Wg Cdr H Malik, Wg Cdr G Gomez, Wg Cdr R Kapur, Wg Cdr PD Navathe

Institute of Aerospace Medicine Vimanapura Bangalore 560 017 India

Seventy-two incidents of G-induced loss of consciousness (G-LOC) observed during the high-G centrifuge training of 134 aircrew were analysed. These incidents occurred in 50 (37.3%) aircrew and 18 aircrew experienced more than one G-LOC episode. Forty-seven occurred during rapid onset runs, 19 during gradual onset runs and 6 during simulated aerial combat manœuvres (SACM). Straining GOR, ROR and SACM tolerances were found to be significantly lower in the G-LOC group as compared to the non-G-LOC group. The absolute, relative and total incapacitation periods in the G-LOC incidents during GOR runs (mean of 21.63, 15.25 and 36.80 s, respectively) were significantly higher than in those which occurred during ROR runs (mean of 13.48, 9.95 and 23.50 s, respectively). This study provides some insight into the important aeromedical problems of G-LOC which may provide some basis for research towards minimizing its occurrence or reducing the resulting incapacitation.

Keywords: Anti-G straining manœuvre (AGSM), Gradual onset rate; Incapacitation period; Rapid onset rate; Simulated aerial combat manœuvres (SACM).

G-induced loss of consciousness (G-LOC) was recognized as a major flying threat in 1978 when its hazards were documented by pilots' reports of near-mishaps due to G-LOC in F-15 aircraft during air combat tactics evaluations and air combat training [1]. This was further corroborated by an anonymous survey of pilots experiencing G-LOC during increased-G manœuvres [2]. G-LOC was cited as a contributing cause for 18 Class A accidents in USAF from 1982 to 1990 [3]. Of these 18 accidents, 14 resulted in fatal injuries. An anonymous questionnaire survey conducted in the Indian Air Force (IAF) in 1990–92 revealed that 44 (10.8%) aircrew out of the 407 aircrew who responded had experienced at least one episode of G-LOC during their flying career [4].

A thorough understanding of the G-LOC phenomenon is essential to establish some basis for research towards decreasing the resulting incapacitation from G-LOC. With this aim in mind, all the G-LOC incidents which occurred during the centrifuge training at Institute of Aerospace Medicine (IAM), Bangalore, have been analysed and presented in this paper.

Material and methods

The fighter aircrew undergoing high-G centrifuge training at IAM formed the subjects of this study. They were exposed to gradual onset runs (GOR), rapid onset runs (ROR) and simulated aerial combat manœuvres (SACM) during the six days of the course [5]. All the runs were monitored by a medical officer on close-circuit TV monitor and also video-recorded for debriefing of the aircrew and analysis after the run. The end-points selected for the GOR and ROR profiles were peripheral light loss of 56–60° or disappearance of Doppler audio sounds from superficial temporal artery and fatigue for SACM runs. Though G-LOC was not intended to be an end-point, it did occur in a large number of aircrew due to delayed recognition of visual symptoms or fatigue, noise in the Doppler audio sounds at high levels of G or improper performance of anti-G straining manœuvre (AGSM) during high-G runs. The centrifuge was brought to a halt by the medical officer at a predetermined deceleration rate, immediately on recognition of a G-LOC episode. These G-LOC incidents were played back on a video cassette recorder and various features of G-LOC were quantified. Aircrew who underwent G-LOC were also asked to fill up a questionnaire to find out about their subjective impressions before, during and after the G-LOC incident.

G-LOC results in incapacitation which can be characterized by the unconscious period (absolute incapacitation) and a subsequent period of confusion/disorientation (relative incapacitation). The sum of the absolute and relative incapacitation periods represents the total incapacitation period, and may be extrapolated to the overall length of time a pilot would be in uncontrolled flight should G-LOC occur in flight. In this study, as soon as the G-LOC occurred, the medical controller switched on a continuous audio horn. The aircrew was supposed to switch off the horn as and when he perceived it, to determine the return of purposeful movement following G-LOC on the centrifuge. The absolute incapacitation period was calculated from the time the aircrew lost the muscle tone of his head and neck (rolling of head to one side with eyes closed, hyperextension or sudden flexion of the neck) to the time when he opened his eyes or pulled up his head and neck. The total incapacitation period was calculated from the time he lost consciousness to the time he switched off the horn. The time difference between the total and the absolute incapacitation periods, therefore, becomes a measure of the time of confusion and disorientation following the return of consciousness, the relative incapacitation period.

Results

Of the 134 aircrew who underwent centrifuge training since its inception in March 1991, 50 (37.3%) experienced at least one episode of G-LOC. Sixteen (32%) out of these 50 experienced two episodes each, whereas one (2%) aircrew each went to G-LOC three times and five times during the six days of the course. The remaining 32 (64%) experienced one G-LOC episode each. Thus, the total G-LOC incidents analysed during this study were 72. Nineteen (26.4%) of these incidents occurred during gradual onset runs (GOR), 47 (65.3%) during rapid onset runs (ROR) and the remaining 6 (8.3%) occurred during SACM. Relaxed and straining GOR and ROR tolerances and SACM tolerance (13°) of aircrew who went into G-LOC were analysed and compared with the tolerance values of aircrew who did not experience G-LOC and with the whole group (Table 1). Straining GOR and ROR tolerances and SACM tolerance were found to be significantly lower in the G-LOC group as compared to the non-G-LOC group. However, relaxed GOR and ROR tolerances, although lower, were not statistically significant.

The effect of onset rate on the incapacitation periods was evaluated by separating the data into GOR (0.1 G/s), ROR (1 G/s) and SACM (1 G/s with multiple peaks). The mean absolute incapacitation period for the GOR subgroup ($n = 19$) was 21.63 s and significantly higher compared to those for the ROR subgroup ($n = 47$) and SACM ($n = 6$), which were 13.48 and 14.80 s, respectively (Table 2). The total incapacitation as measured by the auditory end-point also revealed a significant difference ($p < 0.05$) between the GOR subgroup (36.80 ± 27.40 s) and the ROR subgroup (23.50 ± 8.83 s).

Table 1. Tolerance values of aircrew with and without G-LOC

Type of run	With G-LOC ($n = 50$)	Without G-LOC ($n = 84$)	Total
GOR (REL)	4.67 ± 0.66	4.92 ± 0.63	4.81 ± 0.65
GOR (STR)*	7.25 ± 0.86	7.82 ± 0.79	7.65 ± 0.85
ROR (REL)	4.15 ± 0.52	4.29 ± 0.52	4.26 ± 0.51
ROR (STR)*	7.98 ± 0.92	8.70 ± 0.60	8.50 ± 0.60
SACM (13°)*	149.46 ± 53.90	185.10 ± 69.80	174.93 ± 70.65

*Z-test $p < 0.01$

Table 2. Period of incapacitation vs type of run

Type of run	No.	Incapacitation period (s) Absolute	Relative	Total	p value for diff. between total means
GOR	19	21.63 ± 13.11	15.25 ± 16.50	36.80 ± 27.40	<0.05 (GOR & ROR)
ROR	47	13.48 ± 6.63	9.95 ± 3.98	23.50 ± 8.83	>0.05 (GOR & SACM)
SACM	6	14.80 ± 6.51	8.65 ± 6.57	23.50 ± 12.10	>0.05 (GOR & ROR)
All	72	15.55 ± 9.28	11.10 ± 9.22	26.70 ± 16.60	

	Absolute	Relative
GOR vs ROR	3.22*	2.01*
GOR vs SACM	1.17	0.92
ROR vs SACM	0.45	0.68

*p < 0.05

Table 3. Period of incapacitation vs type of run (G-LOC during ROR)

	No.	Incapacitation period (s) Absolute	Relative	Total	p value for diff. between total means
Type I	27	14.08 ± 8.24	9.96 ± 4.39	24.00 ± 10.50	>0.5 (Type I & II)
Type II	19	12.94 ± 3.06	10.39 ± 2.85	23.30 ± 4.74	
Slow offset	21	14.57 ± 9.02	9.86 ± 4.31	24.40 ± 11.70	>0.05 (slow & fast)
Fast offset	25	12.54 ± 3.04	10.04 ± 3.68	22.50 ± 4.94	

There were a total of 47 incidents during ROR runs. Five of these were during 7 G ROR runs, 15 during 8 G and 11 during 9 G runs. Sixteen of these incidents occurred during ROR runs at G levels varying from 3.8 to 7.7 and out of these 16 incidents, 5 occurred during relaxed runs carried out to determine the relaxed ROR tolerance. Average peak G at which G-LOC occurred was 7.39 G with SD of 1.37 G. The average duration spent at peak G when G-LOC occurred was 4.66 s with SD of 3.35 s (range 1–15 s). The G-LOC incidents were separated into two groups, Type I (without convulsions) and Type II (with convulsions). They were also grouped, depending upon the rate of offset when G-LOC occurred, as slow offset group (mean 0.3 G/s) and fast offset (mean 0.5 G/s). Incapacitation periods were separately determined for these groups (Table 3). There was no significant difference in the incapacitation periods during Type I and Type II and slower offset and faster offset groups.

Nineteen incidents of G-LOC occurred during GOR runs at mean peak G of 7.11 G with SD of 2.02 G and range of 4–9 G. The period of incapacitation under various groups (Type I vs Type II, slow offset vs fast offset) was determined in these 19 also (Table 4) and no significant difference in periods was observed. Only 6 incidents of G-LOC were seen during SACM, all at peak G of 8 G with time spent at peak G of 5.17 ± 3.02 s. The average duration of SACM at the time of G-LOC occurrence was observed to be 113.8 s. Periods of incapacitation were determined in these 6 also under grouping Type I, Type II, slow offset (mean 0.27 G/s)

Table 4. Period of incapacitation vs type of run (G-LOC during ROR)

		Incapacitation period (s)		
	No	Absolute	Relative	Total
Type I	14	22.00 ± 13.66*	14.50 ± 18.69*	36.50 ± 30.20*
Type II	5	20.50 ± 11.30	17.50 ± 5.90	38.00 ± 16.10
Slow offset	10	26.50 ± 14.20*	19.50 ± 19.40*	46.00 ± 31.00*
Fast offset	09	13.50 ± 4.07	8.10 ± 4.25	21.60 ± 4.92

*One aircrew had absolute relative and total period of 55, 75 and 130 s, respectively
p value for difference between total means >0.05 for Type I and II and slow and fast offset groups.

Table 5. Period of incapacitation vs type of run (G-LOC during SACM; peak G: 8G; time at peak G: 5.17 ± 3.02 s; duration of SACM: 113.8 s)

		Incapacitation period (s)		
	No	Absolute	Relative	Total
Type I	5	15.00 ± 7.15	8.80 ± 7.19	23.80 ± 13.20
Type II	1	14.00	8.00	22.00
Slow offset	3	20.30 ± 4.64	13.30 ± 6.18	33.70 ± 9.00
Fast offset	3	9.30 ± 1.89	4.00 ± 2.16	13.30 ± 2.36

p value for difference between total means <0.05 (slow and fast).

and fast offset (mean 0.5 G/s) (Table 5). Although the groups were small (three each in slower offset and faster offset), the incapacitation periods were significantly higher in the slower offset group.

Discussion

G-induced loss of consciousness (G-LOC) occurs following a critical reduction of blood flow due to +Gz forces. Without sufficient blood flow to the brain, oxygen supply to the brain tissues ceases and the brain cells rapidly use their small oxygen and energy reserves to maintain consciousness. Following this latent period, if the brain continues to be deprived of blood supply, and hence oxygen, G-LOC occurs.

Stewart [6] was the first to attempt characterizing G-LOC in an aircraft early in World War II. He photographed the entire G-LOC event and was, therefore, able to develop a timed sequence of events involving G-LOC. He grouped G-LOC incidents into two types: (a) complete unconsciousness and (b) impairment of consciousness. He also recognized that functional recovery from G-LOC required an additional 10–20 s following physical recovery that had already lasted 12 s.

The duration of G-LOC and its recovery has received considerable research attention during the past decade. The duration of G-LOC is generally defined as the period of time during which the subject loses muscular control, particularly as it affects posture and head positioning. This time of absolute incapacitation following unexpected G-LOC in subjects on the centrifuge is generally considered to be 15–17 s [7, 8]. This was observed to be 15.55 ± 9.28 s (mean ± SD) in our group of 72 G-LOC incidents (Table 4).

The subject remains disorientation and generally unaware of the situation for some time after regaining consciousness. This period, known as the relative incapacitation period, begins at the end of absolute incapacitation and continues until the individual can voluntarily turn off a horn or light response to an auditory or visual stimulus. It lasts for 15 s and its duration is independent of the nature of the arousing stimulus [7]. We used a loud auditory tone as the stimulus and this period was observed to be 11.10 ± 9.22 s (mean ± SD) in our subjects (Table 4). Incapacitation periods (absolute, relative and total) were found to be significantly more when G-LOC develops during GOR runs as compared to those during ROR runs (Table 4). This is in conformity with the earlier findings [7, 9]. Incapacitation periods during ROR would be more realistic for extrapolation to in-flight G-LOC incidents since onset rates in fighter aircraft are of the order of 1–10 G/s (ROR). Thus, absolute incapacitation period of 13.48 s (SD 6.63) during ROR runs is more akin to absolute period of 12 s seen in an actual F-16 G-LOC incident [10]. It is of vital importance to know the length of incapacitation accurately for development of aircraft physiologic auto recovery systems. The relative incapacitation is an area deserving much attention from aeromedical researchers since aircrew may be more likely to have positive reorienting interaction during this period, thus reducing the time necessary for recovery [6]. The optimal stimulus for achieving recovery in the minimum time possible is thus a highly desirable goal. The relative incapacitation period during ROR was found to be 9.95 s (SD 3.98 s) in our group and much less than that seen earlier [7].

The occurrence of convulsions by a subject during recovery after G-LOC has led to the grouping of G-LOC into two types: (a) Type I G-LOC, which is characterized by a short duration and absence of convulsive type movements. (b) Type II incidents associated with convulsions indicating greater central nervous system embarrassment [11]. In our study, we observed 44 (61.1%) cases of Type I and 28 (38.9%) cases of Type II G-LOC incidents. Convulsions were first described in detail in 1945 by Franks *et al.*, who noted their presence in 52% of the 230 test subjects. More recent data [7] have shown that 31% experienced convulsive-like flail movements during recovery from G-LOC.

Convulsive-type or flail movements of the extremities during the absolute incapacitation period have been seen earlier during G-LOC in centrifuge [7] and aircraft [12]. These flail movements have the potential of causing inadvertent operation of any flight controls or switches besides causing bodily injury in an in-flight G-LOC incident. In our group, 28 (38.9%) incidents out of the total of 72 were associated with flail movements. However, we did not find any significant difference in incapacitation periods between G-LOC incidents associated with flail movements (Type II incidents) and those not associated with flail movements (Type I incidents). Earlier studies [7, 8] reported that individuals suffering flail movements (31% of all subjects) had prolonged periods of absolute, total and relative incapacitation. We did not observe any tongue biting or incontinence of urine or feaces during any episode of G-LOC. Twenty-four cases (33.3%) of G-LOC incidents were associated with amnesia and 30 (41.7%) with dream sensation.

In an earlier study, 69 (9.3%) out of the 741 trainees had one or more G-LOC episodes during the centrifuge training [13]. Of these, 44 incidents occurred during GOR runs. The reasons given for more G-LOC incidents during GOR include a tendency to relax immediately after reaching one's straining tolerance limit or some trainees pushing themselves beyond their straining tolerance trying to reach the 9 G run limit. We had higher percentage (37.3%) of aircrew going into G-LOC and more cases (65.3% of G-LOC incidents) during ROR runs. This may be because of the difference in rates of onset and offset in the two studies. The rate of onset for GOR runs (0.1 G/s) is the same in Indian Air Force (IAF) and USAF, whereas it is much lower (1 G/s) in IAF compared to USAF (6 G/s) during ROR runs. This was mainly due to the limitation of the capabilities of the centrifuge at IAM, IAF. Similarly, rates of offset, once a case of G-LOC was detected, were also lower (0.2 G/s during the first few courses to 0.7 G/s in later courses) in IAF as compared to USAF (2 G/s). These lower rates of onset and offset result in much longer periods spent at higher G values, and could have resulted in a higher incidence of G-LOC during ROR runs as well as higher overall incidence (37.3%) in our group. It has been seen earlier also that incapacitation periods following G-LOC with a lower offset rate (0.97 G/s) were much more compared to those with a higher offset rate (2.75 G/s) [14].

There was no significant difference in the relaxed GOR and ROR tolerances of the aircrew who experienced G-LOC during centrifuge training compared to those who did not (Table III). However, straining GOR, ROR and SACM tolerances were significantly lower ($p < 0.01$) in aircrew with G-LOC episodes (Table 3). This is a significant finding, and probably indicates that either the anti-G straining manœuvre (AGSM) performed by these aircrew at higher G values was not optimal, or they developed fatigue earlier due to repeated performance of AGSM. It may also suggest that aircrew with lower straining G tolerances are more prone to G-LOC.

Conclusion

G-induced loss of consciousness episodes are unavoidable during high-G centrifuge training. These result in varying periods of absolute, relative and total incapacitation based on onset rate, offset rate, the presence or absence of convulsions and many other factors. All the incidents should be video-recorded for gaining a complete understanding of this important aeromedical problem to enhance recovery and optimum safety of the fighter aircrew in the flight environment.

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