Original Article

Human tolerance to high sustained +Gz during simulated aerial combat manoeuvre

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Simulated Aerial Combat Manoeuvre (SACM) tolerance was determined in 126 healthy male aircrew who reported for high 'G' centrifuge training at Institute of Aerospace Medicine (IAM) IAF. Mean SACM tolerance of the whole group was 174. 13 seconds with a standard deviation of 66. 80 seconds. SACM tolerance was not significantly related to age, weight, height and flying experience of the aircrew. A significant and direct correlation was found between SACM tolerance and G-level tolerance both relaxed and straining Gradual Onset Rate (GOR) tolerance and relaxed and straining Rapid Onset Rate (ROR) tolerance.

Keywords:+Gz induced loss of consciousness (G-LOC), Gray out, Black out,High sustained +Gz, Aerial combat manoeuvres (ACM), Anti -G straining manoeuvre (AGSM).

For the first time in the long history of combat aircraft, it has become evident that man is the limiting factor in achieving better aircraft performance and better aircraft manoeuverability. Modern generation combat aircraft with their high airframe agility and high thrust to weight ratios expose aircrew to high levels of sustained +Gz. The operational requirements of the present and future dictate that not only has the pilot to withstand this high G stress but he also has to perform effectively at that level for achieving mission success. Thus ground based training and research on human centrifuge in the field of acceleration physiology has assumed great importance.

The word "tolerance" is used in acceleration research on the centrifuge to identify the G level and duration at which specific physiologic systems are significantly altered. There appear to be many endpoints which limit the pilot's ability to withstand acceleration stress and they are different for each acceleration stress [1]. There are widespread differences in the technique of threshold determination but historically most centrifuge groups refer to Peripheral Light Loss (PLL) or Central Light Loss (CLL) as a threshold level that can be determined experimentally [2].

In the human centrifuge at Institute of Aerospace Medicine Bangalore, relaxed +Gz tolerance norms for large number of Indians using visual endpoints and three segment profile have been evolved during the past 25 years [3]. Although relaxed +Gz tolerance gives repeatable results, they are not necessarily relevant to a subject's performance during exposure to higher G levels or the aerial combat maneuvres. +Gz tolerance in the Aerial Combat Manoeuvres (ACM) arena is, to a large measure, determined by fatigue of the pilot, who is eventually unable to continue with the G manoeuvres because the energy used to maintain an adequate Anti-G Straining

Manoeuvre (AGSM) finally exhausts the pilot [4].

The ACM is an environment of multiple G – levels(2 to 9 G) which continues for an indefinite period of time (few seconds to few minutes). Tolerance to ACM with fatigue as an endpoint is determined on a centrifuge using a variable G (multi-segment) profile called Simulated Aerial Combat Manoeuvre (SACM) [5]. The multi-segment profile enables us to simulate ACM to as near a realistic simulation as of the actual combat manoeuvres of the aircraft. No study had been carried out earlier to determine tolerance of our population to such G profiles. The present study was undertaken to establish the tolerance norms for SACM which will help in carrying out applied research and training in the field of high sustained +Gz.

Material and methods

126 healthy male aircrew who had reported for high 'G' centrifuge training at IAM were selected for this study. The subjects were highly motivated. They were explained the experimental protocol in detail and had voluntarily consented to take part in this study.

The subjects were given Gradual Onset Rate (GOR) and Rapid Onset Rate (ROR) runs to determine their relaxed and straining tolerances, using PLL as the end point, on the first 2-3 days of the course as per the established training schedule [6]. Rates of onset employed for GOR and ROR runs were 0.1 G/sec and 1.0 G/sec respectively. The relaxed and straining GOR tolerances were determined again with the AGSM taught and perfected during the centrifuge training.

The aircrew were then subjected to the standard SACM profile at 13 degree tilt employed at IAM for high-G centrifuge training on 4th - 5th day of the course [7]. A warm - up run was given with an onset rate of 1 G/sec to a peak of 4 G for 15 sec and offset rate of 0.5 G/sec. This run enabled the subject to test the anti-G suit and practice the AGSM. The SACM consisted of a Rapid Onset Run (ROR) with onset rate of 1 G/sec up to 4 G for 15 seconds then again a build up at the rate of 1 G/sec up to 8 G for 10 seconds followed by a deceleration at the rate of 1 G/sec up to 4 G. This profile continued till the subject felt fatigued and gave a call to terminate the run or there occurred a Peripheral Light Loss (PLL 52-56 Degrees) or G-LOC, when the centrifuge was then stopped. The subjects performed AGSM while accelerating from 4 G to 8 G and continued throughout, till they were returned to 4 G. The anti-G suit was kept inflated throughout the SACM. SACM tolerance was taken as the total duration in seconds from the start of the run till its termination. The aircrew were given only one SACM profile in a day to avoid the effect of carry-over of fatigue.

Results

The age of the subjects (aircrew) ranged from 22 to 37 years, with a mean age of 26.81 years. Height ranged from 164 to 190 cm. The minimum weight recorded was 51 kg while the maximum weight was 89 kg. Flying experience ranged from 240 hours to 3080 hours (Table I). 36 subjects had current experience on Mirage 2000 and MiG 29 fighters. The rest of the 90 subjects were current on MiG 27, Jaguar, Ajeet and variants of MiG 21 aircraft, which lack the rapid onset, high sustained +Gz capability.

Table I : Vital Parameters and Flying Experience (n =126)

	Age (yrs)	Height (cm)	Weight (Kg)	Flying Exp. (Hrs)
Mean	26.81	173.38	65.53	857.96
S.D	3.29	5.83	6.44	593.59
Min	22	164	51	240
Max	37	190	89	3080

SACM tolerance was divided into two groups; one group was aircrew who went into one or more G-LOC episodes during the centrifuge training and the second group in which the aircrew had no G-LOC episode during the training. These tolerances (mean ± SD) were found to be 149.46 ± 53.9 sec (n = 46) and 185.1 ± 69.8 sec. (n = 80) respectively in the two groups. The difference of the tolerance in the two groups was statistically significant (z test; $p<0.01$).

The SACM tolerance range of the whole group (n = 126) was from 57 sec. to 435 sec. with a mean tolerance of 174.13 sec. and standard deviation of 66.80 sec. Seven aircrew had SACM tolerances of more than 300 sec. Endpoint of SACM in 6 aircrew was G-LOC which occurred after mean SACM duration of 113.8 sec. In 11 cases, SACM had to be terminated due to neck muscle fatigue/ abdominal discomfort from inflated anti - G suit/ severe pain in legs or feet. Endpoint in rest of the cases (109 cases) was generalized fatigue with inability to carry on with the AGSM and consequently the SACM run.

Relaxed and straining ROR and GOR tolerance were also determined in the subjects. Mean relaxed and straining ROR tolerances were 4.26 G and 8.6 G respectively (Table II). Straining G tolerance was determined wearing anti-G suit which was inflated as per the standard schedule by the Russian anti-G valve fitted in the gondola. Mean relaxed and straining GOR tolerances were 4.78 G and 7.74 G respectively (Table II).

Table II : Acceleration Tolerances

	SACM Tolerance (Seconds)	ROR Tolerance		GOR Tolerance	
		Relaxed (G)	Straining with anti -G Suit (G)	Relaxed (G)	Straining (G)
n	126	123	126	126	126
Max	435	5.6	9.0	6.7	9
Min	57	3.0	7.0	3.4	5.6
Mean	174.13	4.26	8.6	4.78	7.74
S.D.	66.8	0.49	0.6	0.66	0.86
AGSM Protection (Mean + SD)		4.30 ± 0.78		2.95 ± 0.75	

Protection afforded by the AGSM was calculated by subtracting relaxed tolerances from the straining tolerances separately for GOR and ROR. AGSM protection during ROR thus includes the protection by anti - G suit (1.2-1.4G) also and was found to be 4.30 ± 0.78 (Mean ± SD). Protection afforded by AGSM alone during GOR was 2.95 ±0.75 G only (Table II).

Table III : Age vs SACM Tolerance

Age	n	SACM (Sec) Mean +/- SD
20 - 24	12	176.75 ± 51.51
24 - 28	73	169.09 ± 69.09
28 - 32	28	173.67 ± 73.04
32 - 38	13	198.00 ± 42.54

Table IV : Flying Experience Vs SACM Tolerance

Flying Experience	n	SACM (Sec) Mean +/- SD
< 500	36	160.25 ± 60.67
500 - 1000	63	180.96 ± 74.36
1000 - 1500	9	176.00 ± 41.27
1500 - 2000	6	164.50 ± 48.60
2000 - 2500	9	173.00 ± 61.32
> 2500	3	214.33 ± 30.32

r value = 092647 (Not Significant)

Table V : Type of Aircraft vs. SACM Tolerance

Aircraft	n	SACM Tolerance Mean ± SD
MiG 29/Mirage 2000	36	180.00 ± 80.70
Other Aircraft	90	163.00 ± 65.70

Table VI : Regression outputs of SACM tolerance vs. Age, Weight & Height

	SACM		
Parameters	Age	Weight	Height
Constant	123.6257	88.83368	178.36940
Std Err of Y Est	67.04771	66.80630	67.33882
R Squared	0.008632	0.01578	0.000004
No. of Observations	126	126	126
Degrees of Freedom	124	124	124
X Coefficient (s)	1.884001	1.301678	-0.029578
r-Value	0.092908*	0.125531	0.002130

* : Not Significant

Relationship of SACM tolerance with age, flying experience and type of aircraft were tabulated (Tables III to V). Aircrew in the higher age group (32-38 years) showed higher SACM tolerance (Table III). Aircrew having maximum flying experience (>2500 hours) had much higher SACM tolerance than those with lesser flying experience (Table IV). Aircrew flying MiG-29/Mirage 2000 aircraft had higher SACM tolerance

Table VII : Regression outputs of SACM tolerance vs. Relaxed tolerances (GOR & ROR)

Parameters	SACM vs.	
	GOR Relaxed Tolerance	ROR Relaxed Tolerance
Constant	22.22302	35.34945
Std Err of Y Est	63.92526	65.95911
R Squared	0.098818	0.058139
No. of Observations	126	126
Degrees of Freedom	124	124
X Coefficient (s)	31.75331	32.85991
Std Err of Coefficient	8.611211	0.923831
r- value	0.314354*	0.125531 $

* p < 0.01 (Significant) p < 0.05 (Significant)

Table VIII : Regression outputs of SACM tolerance vs. Straining tolerances & AGSM protection

Parameters	SACM Vs.		
	GOR Straining Tolerance (GOR)	ROR Straining Tolerance	AGSM Protection
Constant	5.85639	- 48.76850	161.8988
Std Err of Y Est	64.63018	65.22150	67.26722
R Squared	0.078834	0.061901	0.002129
No. of Observations	126	126	126
Degrees of Freedom	124	124	124
X Coefficient	6.672234	9.049430	8.040714
r - Value	0.280774 *	0.248799*	0.046151$

* : p < 0.05 (Significant $: Not Significant

than those flying aircraft of lower performance viz. MiG-21, MiG 23 etc (Table V). Regression output between SACM tolerance and age, weight, and height (Table VI) were separately calculated to determine the effect of these variables on SACM tolerance significantly (r values not significant). Correlation of relaxed and straining GOR and ROR tolerances with SACM were also determined (Tables VII and VIII). It was found that there is a significant and direct correlation between the SACM tolerance and relaxed and straining GOR and ROR tolerance (r values less than 0.05). However, r values were not significant in the regression output of AGSM protection

(GOR) Vs SACM tolerance (Table VIII).

Discussion

The 'G' tolerance in a high sustained +Gz environment is dependent on two dimensions viz. intensity (G level) and time (exposure duration) [8,9].

Tolerance of G levels above +5 Gz, even with the aid of an inflated anti-G suit, requires well co-ordinated muscle tensing and straining while performing the L1 or M1 anti-G straining manoeuvres (AGSM)[8,9]. Their effective performance and concomitant development of fatigue are considered as the principal limiting factors of G-duration tolerance. During actual or simulated aerial combat manoeuvering, psychological stress is imminent as the pilot has not only to survive the high G, but also to perform optimally in this environment [3,6,10].

The finding, in the present study, of statistically lower SACM tolerance in the group who went into G-LOC during the centrifuge training vis-a-vis those who tolerated the similar G-profiles without going into G-LOC is a significant one. It indicates that aircrew having lower SACM tolerance are more likely to go into G-LOC. It may form the basis of selection criteria for inducting aircrew into the fighters with high sustained +Gz capability like Mirage-2000 and MiG 29 aircraft.

Range of the SACM tolerance in our fighter aircrew was between 57-435 sec. with mean of 174.13 sec. and SD of 66.8 sec. Seven aircrew were able to sustain more than 300 sec. of SACM and could have much higher G-tolerance but the centrifuge was brought to halt by the medical controller at the pre-determined rate. This limit was fixed as aircrew do not sustain more than 5 minutes (300 sec.) of high sustained G during 2-3 situations in the aerial combat manoeuvres [7].

The mean SACM tolerance (174.13 sec.) determined in our subjects was higher than or equal to that found in some of the earlier studies [11,12] and lower than in other studies [13,14,15] although the SACM profiles used in various studies were slightly different. However, SACM tolerance in the earlier studies was determined only in limited number of subjects ranging from 5 to 11, whereas number of subjects in our study was 126 making it more comprehensive and reliable. Moreover, SACM tolerance in our subjects were determined in highly motivated aircrew in the younger age group (26.81 ± 3.29 years) who were given adequate AGSM training and high G training profiles as reported earlier [7] during the preceeding 3-4 days. The SACM tolerance was determined in them on the 4th - 5th day of their centrifuge training and the SACM was the only centrifuge run given on the day to prevent any effect of fatigue on the SACM tolerance.

A regression output between age and SACM tolerance showed the value to be not significant indicating that age is not significantly related to SACM tolerance. This was in contrast to an earlier study in IAF [3] which showed that relaxed +Gz tolerance showed increasing trend with the age. The differences between two studies is that the present study related age to the SACM tolerance which is more relevant from operational flying point of view than relaxed +Gz tolerance and secondly the range of age of the aircrew in our study varied

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between 22 and 37 years only whereas the age groups considered in the earlier study were 20-35 years, 35-40 years and 41-55 years. However, we also grouped age in four groups viz. 20-24, 24-28, 28-32 and 32-38 years and tabulated the SACM tolerance under these groups (Table III). It was seen that the aircrew in the highest age group (32-38 years) showed much higher SACM tolerance than in the younger age groups as was also seen in the earlier study [3]. It also confirms the finding of another study [11] of higher age of 37 ±5 years in a high tolerance group and age of 32 ±8 years in a low tolerance group, although the difference was not significant.

SACM was not found to be significantly correlated by regression output to weight, height and flying experience (Tables IV and IV). It is in contrast to the earlier study [11] in which using the USAFSAM aeromedical evaluation protocol, a series of clinical parameters were found to be associated with +Gz tolerance. The high +Gz prototype individual was found to have less height (68.4 ± 1.6 inches), more weight (172 ±24 lbs) and more flying experience (3196 hours) as compared to low tolerance group (Height : 71.3 ± 2.3 inches, Weight : 157 ±19 lbs; mean flying experience of 1798 hours). However in that study also, only relationship of +Gz tolerance with height was seen to be significant.

Flying experience was also grouped in subsets of 500 hours (Table IV). Though the number (n=3) of aircrew having flying experience more than 2500 hours was less, it was seen that they had much more SACM tolerance as compared to those having less experience. This is in conformity with the finding of an earlier study [11]. This may be due to their higher flying experience resulting in giving more attention as well as better performance of AGSM. They may also have learnt to titrate the amount of effort required as per the +Gz load with the increase in flying experience. Similarly, aircrew flying aircraft with high sustained +Gz capability viz. MiG 29 or Mirage 2000 were found to have higher SACM tolerance (Table V) probably due to the similar reasons.

A significant and direct correlation was found between the SACM tolerance and relaxed and straining tolerances (Tables VII to VIII). This indicates that an individual with a higher G-level tolerance will also have higher G-duration tolerance. Similar results (relaxed tolerance vs SACM tolerance) were also seen by Burton and Shaffstall [12] who determined the relation between fatigue tolerance and G-level tolerance in subjects using reclined seats to increase their G-level tolerance [12]. They found that as relaxed light loss tolerance increased and less AGSM was required at 7 G, tolerance to fatigue also increased but at a complex exponential rate. The physiological basis for this complex relationship between fatigue and the cardiovascular requirements (G level) of the ACM was not completely known. However, a predictive model had been proposed that relates fatigue to G-level tolerances. It has been validated with published data and appears to be reasonably accurate [4].

No correlation was seen between protection afforded by AGSM to an individual and SACM tolerance (Table VIII). It could be that most of the individuals may perform AGSM cyclically for a few times during the determination of AGSM protection (difference between straining and relaxed tolerance) but performing it for 3-7 minutes (till fatigue level) under high +Gz loads during SACM is altogether a different experience. This confirms the findings that high G levels (+6 to +10 Gz) of very short duration may be tolerated by the use of almost any type of straining effort requiring only minimal co-ordinated skeletal muscular tensing [9]. However to tolerate the levels and duration of +Gz in a HSG exposure, especially during SACM, the aircrew must perform repeated co-ordinated straining manoeuvers in combination with an anti-G suit. Interruption of failure of any of these protective mechanisms viz., straining manoeuvers and anti-G suit, will lead to loss of vision and probably unconsciousness [8,9,10].

Conclusion

Increased +Gz tolerance demands will continue to be placed on aviators flying high performance fighter aircraft. Because of the high +Gz stress, it has become increasingly important to accurately define human +Gz tolerance limits. G-duration tolerance is an important determinant of G-tolerance of an individual. Simulated Aerial Combat Manoeuver (SACM) profiles on a centrifuge forms an important tool and near real environment for determination of G-duration tolerance. The present study has analyzed the SACM tolerance (n=126) in the largest number of subjects reported in the literature so far.

The mean SACM tolerance of the whole group (n=126) was 174.13 seconds with standard deviation of 66.8 seconds. It was seen that age, weight, height and flying experience were not significantly correlated with SACM tolerance. An important finding of the study was a significant and direct correlation between the SACM tolerance and relaxed and straining GOR and ROR tolerances. It demonstrates that G – duration and G-level tolerances are related to each other in some way.

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