$+G_z$ Standards for the Indian Air Force

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INTRODUCTION: $+G_z$ tolerance is an important aspect for the success of fighter aircrew as it reflects the ability of the neuro-cardiovascular response to compensate and prevent adverse manifestations such as gray-out, black-out, and G-induced loss of consciousness (G-LOC) under high-G stress.

METHODS: The data for aircrew taking the Operational Training in Aerospace Medicine for Fighters course at the Institute of Aerospace Medicine Indian Air Force (IAF) from January 2017 to December 2020 were analyzed to assess the effectiveness of the existing training goal to recommend a G-tolerance standard for fighter aircrew.

RESULTS: During the study period, 334 aircrew took the Operational Training in Aerospace Medicine for Fighter course. Only three aircrew failed to achieve the training goal of the course (failure rate <1%). There was a significant difference in the relaxed gradual onset rate tolerance of aircrew experiencing G-LOC and not experiencing G-LOC during the training. The odds of experiencing G-LOC at 9 G after clearing the 7-G and 8-G profiles were 4.4 and 4.7, respectively.

DISCUSSION: It is generally accepted that aircrew having higher G tolerance have less chance of G-LOC in the air. There is a need to have an operational definition of G tolerance for fighter aircrew that aligns with the operational training goal of the organization. The G tolerance of IAF aircrew is as per the institutional definition of the IAF Institute of Aerospace Medicine. The high-G training has stood the test of time and has served well for the IAF.

KEYWORDS: G tolerance, high sustained G, fighter aircrew, Operational Training in Aerospace Medicine, Indian Air Force.

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Fighter aircrew get exposed to $+G_z$ acceleration frequently during aerobatics and combat. The effect of $+G_z$ acceleration is known to manifest most commonly in the form of visual symptoms like tunnelling of vision or gray-out (also known as peripheral light loss or PLL) and blackout or central light loss (CLL) and not so commonly in the form of neurological symptoms such as G-induced loss of consciousness (G-LOC). These manifestations depend on the tolerance of an individual and have been reported to be 4.47 G ± 0.69 for a relaxed Indian aircrew for gray-out at a gradual onset rate (GOR).[16] Tolerance is defined as the G level or duration at G by which a specific body system starts manifesting signs of failure (e.g., PLL or CLL for vision and G-LOC for the central nervous system). Tolerance measurement of the high-G environment should, therefore, measure both this component G level as well as G duration. Tolerance criteria for component G level usually involve the ability of a subject to maintain vision or consciousness, which is classically determined on subjects who are "relaxed" and is considered an individual's basic G tolerance, which measures the cardiovascular response to an increased G exposure. For G duration, the usual tolerance criterion is a subjective fatigue endpoint that can be validated with blood lactate level.[1] The G-tolerance parameter is required for the selection and training of aircrew as well as the evaluation of aircrew and G-protective equipment. The most used parameter is G-level tolerance under GOR with PLL as the endpoint.

The Institute of Aerospace Medicine, Indian Air Force (IAM IAF), has conducted high-G training of Indian fighter aircrew and aircrew from 12 friendly foreign countries since 1991. The Institute is also responsible for evaluating aircrew (with suspected low G tolerance) and G-protective equipment (e.g., anti-G suit or AGS). Traditionally, relaxed GOR tolerance has been used for such evaluation. However, the nonavailability of a

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well-defined G-tolerance standard has led to wide variation in such an approach. This is also the fact that the values of GOR tolerances vary among various centers with different centrifuges as well as the target population. These variations could be due to different arm lengths of the centrifuges, different protocols (PLL to 52–56° of the lightbar, 100% PLL, 50% CLL, 100% CLL, etc.), and different onset rates ($0.1\,G \cdot s^{-1}$, $1/15\,G \cdot s^{-1}$, $0.25\,G \cdot s^{-1}$, etc.). Hence, it is important for every center to develop its own G-tolerance standard.

The reported relaxed G-tolerance values for Indian aircrew appear to be significantly lower than their U.S. Air Force counterparts.[16] Despite this, they have been successfully meeting the high-G training requirements of 9G for 5s during Operational Training in Aerospace Medicine for Fighters (OPTRAM-F). This is because relaxed G tolerance does not correlate well with G-level tolerance, especially when it is determined while using an AGS and/or an anti-G straining maneuver (AGSM).[1] The traditional way of identifying low G tolerance by means of GOR ($0.1\,G \cdot s^{-1}$) or rapid onset rate (ROR; $1\,G \cdot s^{-1}$) may not be reliable as these parameters fail to predict performance in a high sustained G environment. Parkhurst et al. demonstrated that individuals with normal G tolerances can be trained to endure 9G for up to 45s or more safely.[19] The aim of this paper was to study the G tolerance of the pilots reporting to IAM IAF for high-G training and recommend optimal standards for the high-G training based on the data available from the training experience.

METHODS

Subjects

The training data available in the Department of Acceleration Physiology and Spatial Orientation from January 2017 to December 2020 was used for the purpose of the study. Approval was received from the Institute Ethical Committee for this retrospective analysis of the G tolerance of fighter pilots who underwent training during this period in the department.

Equipment

The high-G exposure was given to all aircrew using an 8-m arm, high-performance human centrifuge with three degrees of freedom. The specification and technical details are available in the article published earlier by this author.[16]

High G Training Profiles

During high-G training in the OPTRAM-F, aircrew are gradually exposed to 4 G_z for 60s, 6 G_z for 30s, 7 G_z for 15s, 8 G_z for 10s, and 9 G_z for 5s in the target tracking mode after initially checking their relaxed GOR tolerance at $0.1\,G \cdot s^{-1}$ with the endpoint of PLL of 52–56° on the lightbar over the period of 3 d. Optionally, they are also subjected to a simulated aerial combat maneuver of 4 G_z for 10s and 8 G_z for 10s with onset/offset rates of $6\,G \cdot s^{-1}$, with a maximum of six such exposures in the pilot out-of-loop profile. Additionally, the "push-pull effect" is demonstrated where relaxed GOR tolerance at $0.1\,G \cdot s^{-1}$ with the AGS not inflated is checked before and after exposure to -1.5 G_z. The reduction in the relaxed GOR tolerance after exposure to -1.5 G_z is explained as the result of the "push-pull effect".[18] All aircrew sign a consent for the use of their training data for research and academic purposes.

The training goal of OPTRAM-F is 9G for 5s and exposure to a simulated aerial combat (SACM) profile of 4G for 10s and 8G for 10s of six loops is an optional profile. The training data for all aircrew who underwent training up to 9G and their relaxed GOR tolerance data available in the system were included in the study. The incidence of almost loss of consciousness has been included as G-LOC as it is considered part of the G-LOC syndrome rather than a separate entity.[15] The success of training at any G level was analyzed based on G-LOC episodes experienced during the subsequent exposures.

Statistical Analysis

The data obtained were tabulated and descriptive analysis, *t*-test for relaxed GOR tolerance of aircrew experiencing G-LOC and not experiencing G-LOC during the training, and odds ratio for G-LOC during various G profiles were calculated using SPSS 26.

RESULTS

During the study period, a total of 334 pilots underwent high-G training. However, not all of them were exposed to the full OPTRAM-F profiles of up to 9G for 5s. Hence, these aircrew were not included in the study. Further, three aircrew experienced G-LOC during the relaxed GOR tolerance assessment. Although they successfully completed the remaining portions of the OPTRAM-F profile, their relaxed GOR tolerance data for gray-out was unavailable. Consequently, these three aircrew were excluded from the study.

The remaining dataset comprised the training data of 302 pilots, which was deemed suitable for further analysis. However, one pilot's relaxed GOR data at 7.9G was identified as an outlier and subsequently removed from the study. Interestingly, this

Table I. The Descriptive Parameters for the Pilots Included in the Study.

PARAMETERS	*N*	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION
Age (yr)	300	19.22	44.23	26.91	4.75
Height (cm)	300	162	205	174.51	5.62
Weight (kg)	301	53	94	72.11	7.54
Flying hours	301	15	2900	638.38	598.94
GOR tolerance	301	2.9	7.02	4.56	0.71

N = number of pilots and GOR = relaxed gradual onset rate tolerance at $0.1\,G \cdot s^{-1}$ with PLL of 52–56° as endpoint.

Table II. The Descriptive Parameters for the Pilots Experiencing G-LOC at Various G Levels.

G LEVEL	*N*	AGE (YR) (MEAN ± SD)	HEIGHT (cm) (MEAN ± SD)	WT (kg) (MEAN ± SD)	FLYING HOURS (MEAN ± SD)	GOR (MEAN ± SD)
6 G TT	7	24.86 ± 3.60	174 ± 5.41	68.43 ± 10.49	412 ± 429	4.31 ± 0.68
7 G TT	21	25.26 ± 4.25	177.48 ± 4.99	72.24 ± 8.20	537.86 ± 642	4.33 ± 0.68
8 G TT	39	25.54 ± 3.20	175.03 ± 5.34	71.26 ± 7.58	524.69 ± 484	4.40 ± 0.69
9 G TT	36	26.11 ± 4.47	174.97 ± 5.21	72 ± 7.43	530.31 ± 434	4.46 ± 0.55
SACM	11	23.93 ± 2.26	175.64 ± 5.56	70.45 ± 5.50	317.72 ± 224	4.35 ± 0.74
Mean	80	25.68 ± 3.98	174.98 ± 5.08	70.65 ± 6.74	505.2 ± 491	4.34 ± 0.60

N = number of pilots; GOR = relaxed gradual onset rate tolerance at $0.1\,G \cdot s^{-1}$ with PLL of 52–56° as endpoint; TT = target tracking; SACM = simulated aerial combat maneuver.

particular pilot experienced G-LOC at 9 G. Therefore, the final dataset analyzed for the study consisted of the training data of 301 pilots.

The mean age, height, weight, flying hours, and GOR tolerance of the pilots in the study experiencing G-LOC at various G levels and not experiencing G-LOC are found in **Table I**, **Table II**, and **Table III**, respectively.

A total of 80 pilots in the study experienced G-LOC at various G levels during the training. None of the pilots experienced G-LOC during the 4.5 G target tracking run. The GOR tolerance of pilots not experiencing G-LOC (Table III) was significantly higher than the pilot experiencing G-LOC ($P < 0.001$). However, there was no significant difference in GOR tolerance among pilots experiencing G-LOC at various G-levels (Table II). As reported in our previous study,[16] it appears from the data (Table II and Table III) that older pilots and those with more flying hours may have a lower frequency of experiencing G-LOC. However, no statistical analysis was conducted to confirm these findings, as it was beyond the scope of the study.

Fig. 1 shows the number of pilots experiencing G-LOC during various high-G training profiles. The number of pilots experiencing G-LOC tripled from 6 G (2.3%) to 7 G (7%) and doubled from 7 G to 8 G (12.9%). It remained similar at 8 G and 9 G (12.3%). Of the pilots undergoing training, 88% (267) volunteered for the SACM profile, and 4.1% of those pilots suffered G-LOC during the training. The mean G-duration tolerance of successful aircrew was 44.8 s. The success rate for the SACM profile was 95.9%.

Fig. 2 shows the distribution of relaxed GOR tolerance among pilots experiencing G-LOC and not experiencing G-LOC during the high-G training. As expected, G-LOC incidences are higher for people with lower relaxed GOR tolerance which stagnates at 4.5 G and beyond.

Of the pilots who experienced G-LOC at 6 G, 43% (3 out of 7) also suffered G-LOC at 7 G. A similar percentage of pilots (43%, i.e., 9 out of 21) suffering G-LOC at 7 G also suffered G-LOC at 8 G, whereas approximately 29% of pilots experiencing G-LOC at 7 G and 8 G also suffered G-LOC at 9 G. The odds of experiencing G-LOC at 9 G for these pilots were 4.4 and 4.7, respectively. At the same time, 28% of aircrew experiencing G-LOC during the course did not experience G-LOC at 7 G and below, but experienced G-LOC at 9 G. Only three aircrew failed to achieve the training goal of the course (failure rate <1%), implying failure in the course to be <1%.

DISCUSSION

Defining G tolerance is important for the selection of aircrew for high performance fighter aircraft, comparing G protection provided by an AGS or other G-protective methods, and disposal of cases of low G tolerance. Japan, Korea, and many Warsaw Pact air forces (Serbia, Denmark, Netherlands, and Germany, etc.) have used centrifuges for the evaluation of G tolerance as a part of their selection process for high performance fighter aircraft.[10] GOR tolerance with PLL as an endpoint has been most widely used for these purposes, with the premise that this defines the best G protection available to a subject due to the baroreceptor response. This is also due to the simplicity of assessment and availability of continuous data that allows the use of the parametric test. However, Ludwig and Krock caution that a single determination has a very high standard error (±0.78 G, 95% confidence interval, range 1.5 G) and low reliability, making it unacceptable for most scientific and clinical applications.[17] Relaxed G tolerance in ROR is assessed using an epoch pattern which is ordinal data, resulting in nonparametric tests for any statistical analysis, which has lower strength than parametric tests. Other than this and the concern raised by Ludwig and Krock, it is also observed that a high relaxed G-level tolerance is not necessary for tolerating high G levels when customary AGS and AGSM are used, as only 16% of the high-G straining tolerance is dependent upon a person's relaxed ROR tolerance.[9] The G tolerance at higher rapid onset

Table III. The Descriptive Parameters for the Pilots Not Experiencing G-LOC During High-G Training.

PARAMETERS	*N*	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION
Age (yr)	220	20.51	44.23	27.35	4.93
Height (cm)	220	162	205	174.35	5.80
Weight (kg)	221	53	94	72.64	7.76
Flying hours	221	15	2900	686.59	627.49
GOR tolerance	221	2.9	7.02	4.63	0.73

N = number of pilots and GOR = relaxed gradual onset rate tolerance at $0.1\,G \cdot s^{-1}$ with PLL of 52–56° as endpoint.

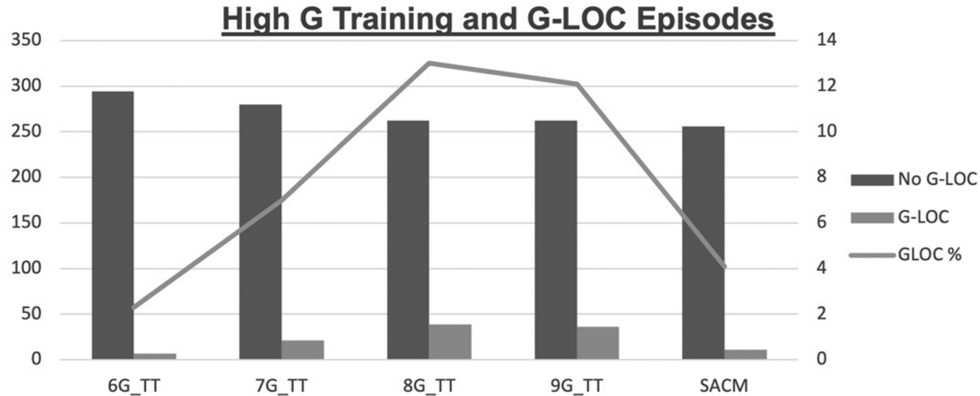

Fig. 1. G-LOC experienced by pilots during high-G training profiles.

rates such as high rapid onset rates (defined as $>3\,G \cdot s^{-1}$) and very high rapid onset rates (defined as $>6\,G \cdot s^{-1}$) reduces further.[1] Since the G tolerance estimated through these means may not accurately predict pilot performance at higher G levels, it is prudent to test aircrew for the G level and G duration in which the pilot is required to operate. G-level tolerance of IAF aircrew with fully operational anti-G trousers and AGSM was 9 G for 5 s and G-duration tolerance using the SACM profile was 45 s, which meets the institutional definition of G tolerance. The success rate was 99% for G-level tolerance and 96% for G-duration tolerance as per the institutional definition. G-duration tolerance may be higher as most of the trainees did not continue for more than two loops, which was the optional minimum requirement during the course.

Analysis of G-LOC data at various G levels revealed that the incidence of G-LOC was lowest at 6 G (2.3%), tripled at 7 G (7%), was 5.6 times at 8 G (12.9%), and was 5.3 times at 9 G (12.3%). Further, a significant number of aircrew (28%) who did not experience G-LOC at 6 G or 7 G experienced G-LOC at 9 G. Hence, it is amply clear that performance at 6 G and 7 G did not predict performance at higher G levels. This has a significant implication in setting high G training goals for fighter aircrew. This study suggests that it should never be less than the capability of the aircraft being flown (the G level which is likely to be encountered in a worst case scenario), even if that G level is not routinely encountered, as the basic aim of the high G training is to make an aircrew aware of his/her G tolerance and allow the practice of good AGSM. Assuming 100% effort is taken to perform a good AGSM at 9 G, one cannot realize this potential without getting exposed to it.[1]

Since 1977 the U.S. Air Force School of Aerospace Medicine adopted an informal "G-tolerance standard" of +7.0 G_z, applied at a rate of $1\,G \cdot s^{-1}$ or greater and sustained for 15 s, for subjects seated in an upright seat (13° seatback angle), wearing a functioning AGS, and performing an AGSM. The rationale for this G-tolerance criterion was based on analyses of G-tolerance distribution data available in the U.S. Air Force School of Aerospace Medicine Acceleration Stress Data Repository in 1977 and upon reports of subsequent G-LOC in flight occurring in pilots not tested to the 7-G, 15-s tolerance level.[10,12] In 1981, a NATO Standardization Agreement (STANAG 3827) adopted this as the definition of "low G tolerance."[5] However, Gillingham observed that this would be an "extremely lenient standard" for an actively flying aircrew.[11] Currently, STANAG 3827 has dropped the definition of low G tolerance and instead recommends high-G training of aircrew which should be commensurate to the aircraft being flown by them.[3,4]

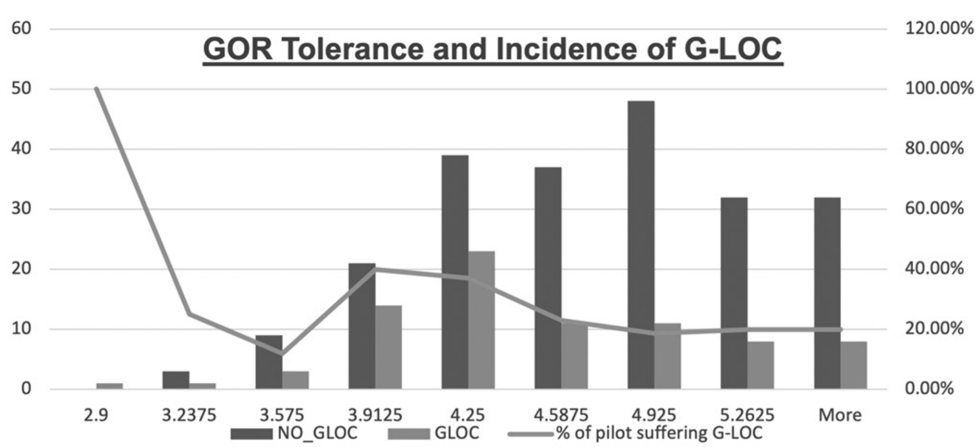

Fig. 2. Distribution of GOR tolerance among pilots experiencing G-LOC and not experiencing G-LOC during the high-G training at IAM.

The Indian Air Force does not use any G-tolerance standard for the intake of candidates for fighter flying. Only those pilots or cadets who experience repeated episodes of G-LOC are evaluated for low G tolerance at the IAM IAF. In 2018, IAM IAF defined the G-tolerance standard as an attempt to standardize institutional protocol, where the definition of low G tolerance was adopted as "failure to maintain consciousness at 9 G for 5 s while wearing functional AGS and performing AGSM; low G duration tolerance as failure to complete two peaks of SACM (4 G × 10 s and 8 G × 10 s) while wearing AGS and performing AGSM." The rationale for this G-tolerance criterion was based on the requirement of the IAF for all fighter aircrew to complete OPTRAM-F, where these were the qualifying criteria for passing the course as well as our experience with actively flying aircrew, where 99% of aircrew could meet these requirements (failure rate ≤1%). In the last 5 yr, 12 hypertensive fighter aircrew on medication have also been evaluated using these criteria. All of them could successfully clear the profiles. One case of syncope was upgraded based on these criteria in the last 2 yr and continues to fly fighters without any in-flight episodes of G-LOC. One case of a trainee pilot (after full medical evaluation) who failed to meet this requirement was declared unfit for fighter flying as a case of low G tolerance.[20] There has been no report of in-flight G-LOC among trained aircrew in the last 3 yr. Hence, it can be safely assumed that these criteria have served us well.

Gillingham recommended that eventually a higher G-tolerance standard, designed to optimize the match between the G load-generating capability of a particular aircraft and the G tolerance of the pilot selected to fly that aircraft, will probably be indicated.[11] Though our definition of G tolerance is serving the purpose at present, this may be considered lenient, as tolerating 9 G for 5 s is within "the physiological reserve (5 s)" of an individual and may give a false sense of confidence of tolerating 9 G. It is also evident from this study that, contrary to our expectation, there was a lower incidence of G-LOC at 9 G in comparison to 8 G, which is a 10-s profile (Fig. 1). The odds of experiencing G-LOC at 9 G for pilots clearing 7 G and 8 G training profiles were similar (4.4 and 4.7, respectively). The incidence of G-LOC is 1.5 times more at 9 G than at 7 G in centrifuge training (Fig. 1). This suggests that the G-tolerance standard of 7 G for 15 s of the 1981 STANAG 3827 is inadequate to predict performance at 9 G.[5] Our adversaries and contemporaries are training for 9 G for 15 s, which makes IAF aircrew flying 4^{th}/4.5 generation aircraft inadequately prepared in comparison.[12,22] The Advisory Group of Aerospace Research and Development also recommends that the high-G training goal for pilots of high performance aircraft should be 9 G for 15 s.[1] The incidence of G-LOC during SACM is even less than that at 7 G and 96% of pilots could meet the current requirement of this profile without experiencing G-LOC. As IAF aircrew are flying highly agile and super maneuverable platforms of 4^{th} and 4.5 generations, where variable sustained G during aerial combat is a routine requirement, the SACM profile may be made a mandatory training goal rather than an optional profile during the high-G training as it prepares and tests aircrew for G-duration tolerance rather than the G-level tolerance. The Royal Air Force (UK) uses a dynamic flight simulator as an actual flight simulator where a pilot undergoes high-G training while wearing full aircrew flying clothing ensembles (AGS, helmet, and mask).[21] With the upgrade of high performance human centrifuges to dynamic flight simulators, the possibility of imparting high-G training in a more realistic manner like the Royal Air Force may be explored.

Traditionally, aircraft designers have placed a rigid or fixed G limit on various types of aircraft based on dynamic load requirements and depending on how the aircraft was to be used, e.g., fighter, bomber, trainer, aerobatic, transport, etc. The traditional 7.33-G design load limit which applied to some of the earlier century series fighters has been raised under recent design criteria to as high as 8.7 G for some modern fighter aircraft.[6] Pilots have long known that the design load limit can be exceeded by 150% to the ultimate load limit and have used this safety factor while under the stress of combat. Short duration loads of 10 G and higher have been reported in actual aerial engagements during and since World War II.[14] The current fighter aircraft in the IAF inventory has been designed for modern-day requirements. Hence, they can sustain 9 G and beyond, even though their operational role is limited to lower G levels during peacetime. Parkhurst et al. demonstrated that a normal human being can be safely trained to tolerate 9 G for up to 45 s and even higher.[19] Burns et al. demonstrated that G protection is available up to +12 G_z using existing G-protection methods.[8]

The super maneuverable aircraft with thrust vectoring in IAF inventory may expose aircrew simultaneously to multiaxial G stress which can either enhance or reduce relaxed $+G_z$ tolerance (simultaneous G_y and G_z enhances, whereas simultaneous G_x and G_z reduces). However, these differences have been estimated to be too small to be operationally relevant.[7] These super maneuverable aircraft with thrust vectoring do not expose pilots to greater $+G_z$ than current legacy aircraft and the air combat techniques rely more on beyond visual range techniques rather than the erstwhile dogfight. High linear and angular velocities and accelerations will be needed to avoid adverse weapons during beyond visual range combat. In close combat situations (within visual range), vectored thrust gives high maneuverability at low speed and these pilots will thereby have better possibilities to win and survive.[2] However, this comes with additional challenges of its own. Since these aircraft have the capability to generate sustained variable $+G_z$ without any limit for the duration (theoretically endless), it exposes pilots to a unique variable G environment as acceleration, in this case, means sustained high G_z, other G-vectors, and push-pull effects. All these acceleration stresses combined with a lot of vestibular peculiarities may result in loss of situational awareness, spatial disorientation, and motion sickness. Besides the acceleration effects on the cardiovascular system, the spine, assisting muscles, and joints are heavily stressed.[2] This cocktail of aeromedical stressors is likely to compromise the performance of an aircrew more if he/she is not confident in handling this G stress. The push-pull effect has been implicated as an important cause of G-LOC, ranging from 29–31% in different studies.[13,18] IAF aircrew is exposed to a push-pull profile during the OPTRAM-F course where $+G_z$ GOR tolerance is measured before and after exposure to $-1.5\ G_z$, demonstrating a reduction in $+G_z$ GOR tolerance and explaining its significance. It is reasonable to conclude that there is no operational justification for at least reducing the current standard of high-G training in the IAF.

This study reaffirms that the search for a G-tolerance standard to predict performance at higher G levels remains elusive. The data indicates that no performance at lower G levels can reliably predict performance at higher G levels or duration. Hence, aircrew should be exposed to the G level that he/she is likely to experience in a worst-case scenario. The IAF's decision to use 9 G as a standard for all aircrew appears reasonable as it allows every aircrew to experience and test their AGSM skill in the most demanding conditions. This also allows flexibility in using the aircrew across all fleets of fighter aircraft without the need for a refresher in high-G training. However, 9 G for 5 s as a standard may not be better than 8 G for 10 s as the incidence of G-LOC was similar or somewhat higher in the 8-G profile (Fig. 1), possibly due to the higher exposure time in the 8-G profile. It would be prudent to replace the 9 G for 5 s profile with a 9 G for 15 s profile, which would allow the practice of at least two AGSM cycles beyond the physiological reserve (physiological reserve of 6 s and each AGSM cycle of 4 s), thus allowing assessment of the effectiveness of AGSM performed at its peak. Considering the performance of IAF aircrew at 8 G for 10 s, 9 G for 5 s, and SACM profiles, it is reasonable to assume that they should be able to train for 9 G for 15 s as well without much difficulty.

In conclusion, the G tolerance of IAF aircrew is as per the institutional definition and meets the current operational goal of the IAF. The current high-G training profile has stood the test of time and appears to serve well.

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