Association Between Anti-G Straining Maneuver Trainer Performance and G-Induced Loss of Consciousness in Centrifuge Training

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Abstract

Background: G-induced loss of consciousness (G-LOC) remains a major threat to flight safety during high +Gz exposure. The Anti-G Straining Maneuver (AGSM) is the primary countermeasure for improving G tolerance. However, the physiological components most strongly associated with successful AGSM performance remain incompletely understood. We evaluated physiological parameters of AGSM performance and their association with G-LOC during centrifuge training.

Methods: In a nested case-control study, second-year Israeli Air Force flight academy cadets underwent standardized centrifuge training and AGSM assessment using a dedicated monitoring system incorporating electromyography, a pneumograph, and near-infrared spectroscopy. For each cadet who experienced G-LOC during centrifuge exposure, one control cadet without G-LOC was randomly selected from the same training course. We obtained all measurements before centrifuge exposure.

Results: Cadets who experienced G-LOC had a higher mean open-glottis count than controls (5.33 vs. 1.50, P = 0.0338) and a longer mean breath duration (0.75 vs. 0.56 seconds, P = 0.0453), whereas left shin contraction stability was lower (-1.21 vs. 1.19, P = 0.0453). In regression analysis, open-glottis count was associated with G-LOC (odds ratio [OR] 6.24, 95% CI 1.12–119.94, P = 0.031), as was mean breath duration (OR 5.98, 95% CI 1.03–417.67, P = 0.044).

Conclusions: Respiratory coordination, particularly glottis stability during AGSM execution, was associated with G-LOC in this small sample. These findings suggest that internal respiratory mechanics may play a greater role in AGSM effectiveness than previously appreciated, and that respiratory monitoring during G-tolerance training warrants further evaluation.

Keywords: Anti G straining manoeuvre, Centreifuge, Aircrew, Respiratory, G induced loss of consciousness.

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Introduction

Under +Gz conditions, inertial forces redistribute blood volume from the head to the lower body, reducing cerebral perfusion. Consequently, the brain becomes susceptible to ischemic hypoxia, which may ultimately lead to syncope [1]. As +Gz increases, the earliest symptoms are typically visual. Pilots may initially experience peripheral visual dimming, progressing to gray-out and eventually complete vision loss ("blackout"). With further reductions in cerebral perfusion, G-induced loss of consciousness (G-LOC) may occur. G-LOC is defined as a transient loss of consciousness caused by a critical reduction in cerebral blood flow during exposure to increased Gz.

Human centrifuges, which expose trainees to high +Gz levels in a controlled environment, are commonly used for both training and studying the manifestations of G-LOC. A typical G-LOC episode consists of two phases: an absolute incapacitation phase lasting approximately 12 seconds, followed by a relative incapacitation phase lasting an additional 15 seconds, during which the pilot remains unable to control the aircraft adequately. At high +Gz onset rates, G-LOC may occur without preceding visual warning signs, posing a substantial threat to flight safety. Any intervention that safely increases arterial pressure at the aortic valve level may counteract the hydrostatic effects of +Gz and improve G tolerance. The most effective countermeasure is currently the Anti-G Straining Maneuver (AGSM). Proper execution of the AGSM can increase G tolerance by up to +3Gz in well-trained aircrew [2]. Owing to its established effectiveness in preserving aircrew performance in high-performance aircraft, systematic AGSM training has become an integral component of military aviation training programs.

In addition to AGSM, aircrew wear pneumatic anti-G suits with five air bladders that cover up to 85% of the lower body. These bladders inflate with pressurized air when increasing +Gz is detected, reducing venous pooling and enhancing venous return from the dependent regions, thereby providing up to approximately +3Gz of additional G-tolerance [3].

The optimal AGSM consists of two coordinated components. The first involves forced exhalation against a closed glottis, combined with rapid air exchange lasting approximately 0.5 seconds every 3 seconds. The second component involves sustained contraction of the lower limb and abdominal musculature to enhance venous return and maintain arterial pressure.

To investigate and optimize AGSM performance, we developed a dedicated device to measure and train the maneuver's physiological components. This study aimed to evaluate the physiological parameters of AGSM performance measured by this device and determine whether they were associated with G-LOC during centrifuge training.

Methods

Study population

The study population comprised 12 active-duty Israeli Air Force (IAF) flight academy cadets (second year), including both pilots and navigators, selected during 2025–2026 based on availability (convenience sample). Centrifuge training is mandatory during flight training in accordance with IAF regulations. All participants were healthy and medically qualified according to IAF Aeromedical Center criteria. For each cadet who experienced G-induced loss of consciousness (G-LOC) during centrifuge training, one control cadet without G-LOC was randomly selected from the same training course. We did not conduct individual matching because only limited baseline variables (sex) were consistently available, published centrifuge studies report modest and mixed sex-related differences in +Gz tolerance, and matching on a single factor was unlikely to substantially improve control of confounding. Random selection from the same cohort was therefore preferred [4]. All cadets underwent standardized training syllabi with comparable exposure to high +Gz flight profiles.

Centrifuge training

Centrifuge training was conducted at two locations. The training protocols were identical except for the final acceleration profile. At both locations, participants underwent a standardized G-training syllabus that included lectures on G physiology and instruction in the AGSM.

Training began with a relaxed G-tolerance run at an onset rate of 0.1 G/s without performing AGSM, to determine

each participant's relaxed G tolerance. The run ended when participants experienced visual symptoms such as gray-out or tunnel vision. Subsequently, participants completed three standard rapid onset rate (ROR) acceleration profiles. The first profile consisted of a ROR exposure to +6Gz for 30 seconds, followed by a ROR exposure to +8Gz for 15 seconds. The final profile consisted of either a ROR exposure to +9Gz for 10 seconds followed by +8Gz for 10 seconds, or a sustained +9Gz exposure for 10 seconds, depending on the training location. A 2-minute rest interval was allowed between runs.

AGSM trainer and data collection

Proper coordination and timing between the components of the AGSM require dedicated training and may be challenging to teach. To address this, we developed a dedicated AGSM training device designed to quantify maneuver performance. The system incorporated medical-grade electromyography (EMG), a calibrated pneumograph, and near-infrared spectroscopy (NIRS). EMG assessed the intensity and consistency of lower-limb muscle contractions. The pneumograph measured respiratory parameters, ventilatory airflow duration, and breath-holding periods. A NIRS sensor mounted on the forehead evaluated frontal cortical hemoglobin flow as a proxy for the maneuver's physiological effectiveness. Physiological data generated by the AGSM trainer, including pneumograph, EMG, and NIRS measurements, were collected during AGSM performance assessments conducted several weeks before centrifuge training.

Statistical analysis

We performed statistical analyses using R (version 4.4.3). Because of the small sample size (n=12) and the non-normal distribution of the physiological variables, we used Mann-Whitney U tests to compare the G-LOC and control groups across all measured parameters. To account for potential variability between training environments, we evaluated differences among the three training courses using the Kruskal-Wallis test. To assess the predictive value of significant physiological markers, we used Firth's penalized likelihood logistic regression. We selected this method to reduce bias in small samples and address complete separation, in which predictors perfectly distinguish outcomes and may produce unstable estimates in standard logistic regression.

Before regression analysis, we standardized (Z-scored) continuous variables. Accordingly, we report odds ratios per 1 standard deviation (SD) increase in the predictor variable. All statistical tests were two-tailed, and a P-value < 0.05 was considered statistically significant. P-values between 0.05 and 0.10 were considered suggestive of an association.

Ethics

The IDF Medical Corps Institutional Review Board (IRB) reviewed the study protocol and determined that it was exempt from IRB review. The IRB waived the informed consent requirement.

Results

Comparison of physiological variables revealed significant differences between the G-LOC and control groups across multiple variables (Table 1). Each group consisted of 6 flight cadets (G-LOC group: 2 females and 4 males; control group: 6 males). The G-LOC group demonstrated a significantly higher frequency of glottis opening, with a mean open-glottis count of 5.33 compared with 1.50 in the control group (P = 0.0338). In addition, the G-LOC group exhibited a longer mean breath duration (0.75 seconds vs. 0.56 seconds, P = 0.0453) and lower left shin contraction stability on EMG (-1.21 vs. 1.19, P = 0.0453). Based on the available data, we detected no differences in thigh contraction stability, airflow control, or the change in NIRS signal at 8 seconds (Table 1).

Distributions of the three variables that differed are shown in Figure 1.

To identify independent predictors of G-LOC, we performed Firth's penalized logistic regression analysis (Table 2). Open-glottis count was significantly associated with G-LOC occurrence, with an odds ratio (OR) of 6.24 (95% CI: 1.12–119.94, P = 0.031). Mean breath duration was also significantly associated with an increased likelihood of G-LOC (OR = 5.98, 95% CI: 1.03–417.67, P = 0.044). Reduced muscle control showed a potentially relevant association with G-LOC (OR = 0.20), although

Variable	G-LOC group (n=6)	Control group (n=6)	P-value
Shin contraction stability	−1.21 ± 2.13	1.19 ± 1.48	0.0453
Thigh contraction stability	−0.41 ± 1.06	0.28 ± 2.96	0.9362
Mean breath duration (s)	0.75 ± 0.18	0.56 ± 0.07	0.0453
Airflow control (L/s)	2.95 ± 1.17	1.90 ± 0.98	0.1735
Open-glottis count	5.33 ± 3.39	1.50 ± 1.38	0.0338
ΔNIRS 8 s	0.24 ± 2.21	1.36 ± 3.39	0.4225

Table 1. Comparison of physiological variables between the G-LOC and control groups.
Values are mean ± standard deviation; Mann-Whitney U test. Groups differed in shin contraction stability, breath duration, and open-glottis count; with the numbers available, no other differences were detected.

the wide confidence interval (95% CI: 0.00–1.03) and P-value (0.056) indicate substantial uncertainty.

To assess potential confounding by training course, we performed Kruskal-Wallis tests for all significant variables. Based on the available numbers, we detected no association between training course and either open-glottis count or shin contraction stability. In contrast, mean breath duration was associated with training course, suggesting potential variability related to the training environment.

Discussion

This study aimed to evaluate AGSM physiological parameters to distinguish trainees who experienced G-LOC from those who remained conscious during centrifuge exposure.

The strongest associations with G-LOC in this study came from respiratory measurements. Specifically, the mean duration of air exchange and the frequency of unintended glottis openings between breaths differed between the two groups. These findings contrast with our initial hypothesis that NIRS-based cerebral blood flow measurements would serve as the primary predictors of AGSM effectiveness [5].

Current literature primarily attributes AGSM efficacy to the mechanical effect of muscle contraction, which increases arterial pressure and improves cerebral perfusion during high +Gz exposure [6]. Consequently, previous investigations have largely focused on muscle activation and contraction quality [7]. Although muscle engagement remains a fundamental component of the maneuver, our findings suggest that respiratory coordination, particularly glottis control, may be an equally relevant marker of G-LOC susceptibility and one that is not routinely assessed.

Several physiological mechanisms may explain the observed association between glottis control and G-LOC. First, maintenance of a closed glottis is essential for generating the intrathoracic and intra-abdominal pressures required to preserve cerebral perfusion during AGSM execution [2]. Unintended glottis opening may reduce pressure stability and impair the maneuver's effectiveness. Second, frequent glottis openings may reflect impaired coordination during AGSM performance. Coordination difficulties during submaximal effort may be further exaggerated under high +Gz exposure, as both physical and cognitive demands increase [8]. Finally, unlike lower-limb muscle contractions, which instructors can often visually observe or physically assess, glottis activity is largely concealed during conventional training. As a result, deficiencies in respiratory coordination may remain undetected without a dedicated physiological monitoring system.

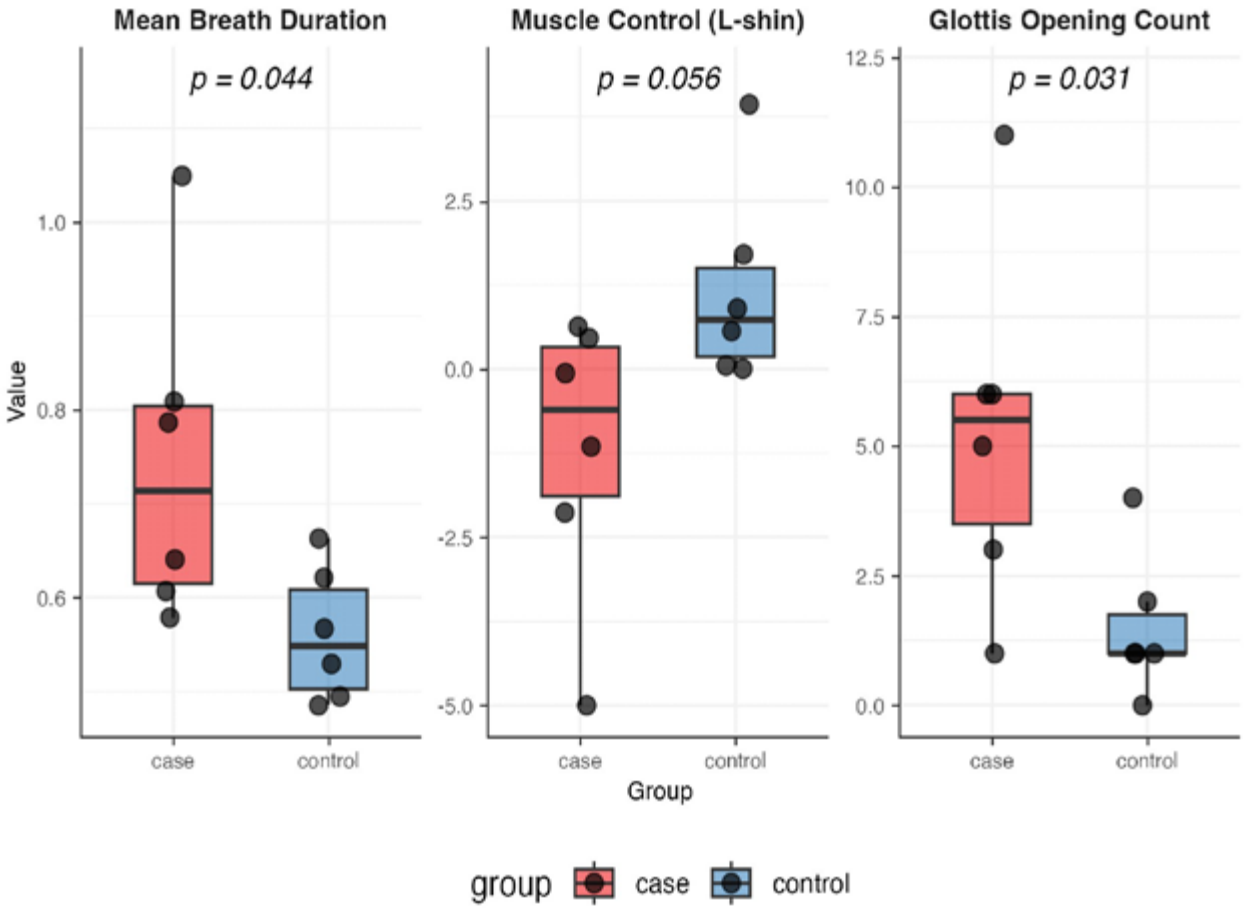


Figure 1. Physiological parameter distributions in the G-LOC and control groups at 50% effort.
Boxplots with individual data points (n=12) for (A) mean breath duration, (B) left shin contraction stability, and (C) open-glottis count, in the G-LOC and control groups.

Predictor	Odds ratio (OR)	95% CI	P-value
Open-glottis count	6.24	1.12–119.94	0.031
Mean breath duration	5.98	1.03–417.67	0.044
Left-shin contraction stability	0.20	0.00–1.03	0.056

Table 2. Firth logistic regression analysis of predictors of G-LOC at 50% effort level.
Odds ratios are per one standard deviation increase in the predictor, estimated by Firth's penalized likelihood method to allow for the small sample size and potential separation.

Several limitations should be acknowledged. First, the study was limited by a relatively small sample size. Because AGSM is generally an effective countermeasure, G-LOC incidence during training remains low, typically occurring in only one to two trainees per course. This inherently restricts the statistical power of comparative analysis and likely contributed to the wide confidence intervals observed in the regression models. In addition, we performed six group comparisons without adjustment for multiple testing, so the differences we report should be regarded as exploratory and hypothesis-generating rather than confirmatory.

Second, procedural variability existed between training courses. Participants were recruited from different courses instructed by different personnel, potentially introducing variability in instructional methods and feedback provided during AGSM training. In some courses, trainees were permitted to repeat simulator sessions, whereas in others they received only qualitative feedback, which may have affected baseline maneuver proficiency. Consistent with this, mean breath duration was associated with training course, so the difference observed in this variable cannot be separated from the training environment in which it was measured.

Another limitation was the non-standardized interval between AGSM training and centrifuge exposure, which may have influenced subsequent centrifuge performance. The two groups also differed in sex composition, and with six cadets in each group, this imbalance could not be adjusted for; therefore, the contribution of sex to the observed differences cannot be excluded.

Finally, the study did not assess the extent of corrective learning or technical adjustments trainees made between simulator training and centrifuge exposure. Consequently, suboptimal AGSM performance identified during simulator assessment may not necessarily have persisted during centrifuge testing if participants independently improved their technique. These findings also come from flight academy cadets undergoing mandatory training in a single air force and may not generalize to experienced aircrew or to other centrifuge profiles.

Conclusions

These findings suggest that existing training protocols and research may underemphasize the respiratory component of AGSM. Early identification of glottis instability may allow instructors to provide targeted feedback and improve trainee safety during high +Gz exposure. The present study further suggests that future investigations of G tolerance should evaluate internal respiratory mechanisms alongside traditional hemodynamic measures to characterize the physiological determinants of AGSM effectiveness better.

Conflict of interest

The authors declare no conflicts of interest.

Source of Support

None to declare.

Data availability

The IDF holds the data, which is not publicly available due to military data-security and confidentiality restrictions.

Disclaimer

The views expressed are the authors' own and not an official position of the institution, the funder, the IDF, or the IMA.

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