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## Short-term effects of +Gz exposure on respiratory functions: results from human centrifuge training

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### ABSTRACT

**Aims:** Military jet pilots are mandated to undergo human centrifuge training (HCT) to experience the adverse effects of +Gz acceleration during flight. The present study aimed to analyze short-term respiratory changes following +Gz exposure via pulmonary function testing (PFT) among jet pilots.

**Methods:** This single-center, cross-sectional study was conducted among healthy military jet pilots. Participants were classified as smokers or non-smokers. Each participant underwent PFTs immediately before and after the HCT. Forced vital capacity (FVC), forced expiratory volume in 1 second (FEV<sub>1</sub>), FEV<sub>1</sub>/FVC, maximal voluntary ventilation (MVV), peak expiratory flow rate (PEFR), and forced expiratory flow at 25-75% (FEF<sub>25-75%</sub>) have been measured. The participants' PFT parameters were evaluated to assess potential +Gz-related alterations.

**Results:** The study included 21 male pilots with a mean age of 27.95±3.60 years. Ten (47.6%) pilots were active smokers. After HCT, significant improvements were observed in the mean values of FEV<sub>1</sub> (4.45±0.55 vs. 4.55±0.57, p=0.001), FEV<sub>1</sub>/FVC (80.0±0.6 vs. 83.0±0.7, p=0.002), FEF<sub>25-75%</sub> (4.72±1.43 vs. 4.96±1.52, p=0.007), and MVV (169.3±28.6 vs. 181.5±32.4, p=0.002); however, no significant changes were observed in FVC or PEFR (p>0.05). Among smokers, significant post-training improvements were observed in FEV<sub>1</sub>, the FEV<sub>1</sub>/FVC ratio, and PEFR (p<0.05), whereas no significant changes were detected in FVC, FEF<sub>25-75%</sub>, or MVV (p>0.05). In non-smokers, significant increases were observed in FEV<sub>1</sub>, FEV<sub>1</sub>/FVC, and MVV (p<0.05), while the remaining parameters showed no significant changes.

**Conclusions:** This study revealed that +Gz exposure was associated with short-term improvements in expiratory flow parameters and effort-dependent ventilatory performance in jet pilots. Additionally, subgroup analysis demonstrated that smokers predominantly exhibited significant increases in flow-dependent parameters.



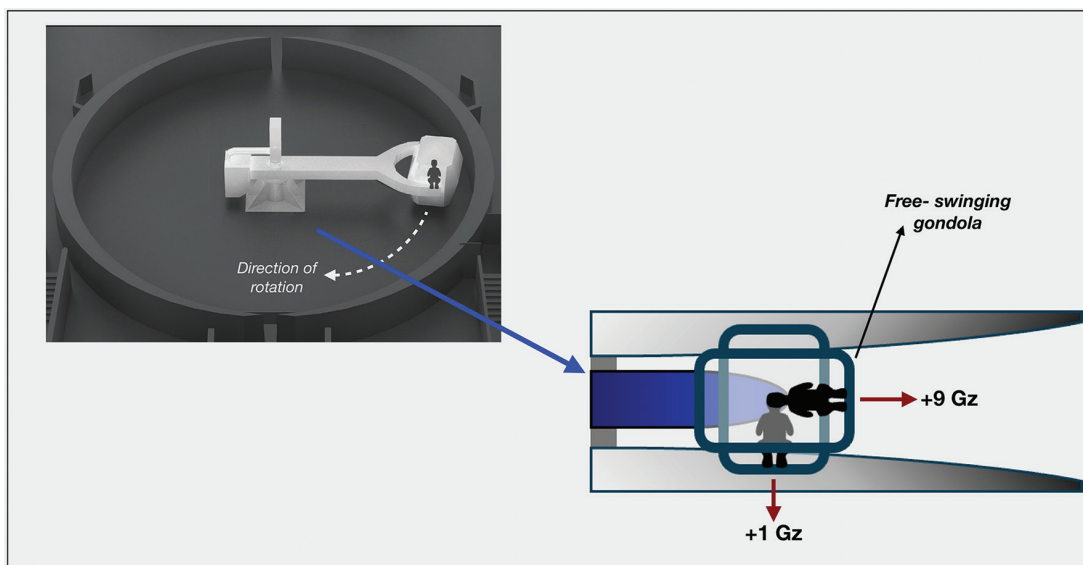
## Introduction

While the human physiology is well-suited to a gravity of 1 G ( $9.8 \text{ m/s}^2$ ), it is barely adapted to cope with numerous unusual conditions during flight, including discrete flight maneuvers that create “G” forces with varying amplitudes and directions. The +Gz force, generated during an inside loop maneuver, is a force experienced from the head to the feet, resulting in a downward displacement of intrathoracic and intra-abdominal organs and the redistribution of bodily fluids. In the initial moments of elevated +Gz, arterial blood pressure declines due to a decrease in total peripheral resistance induced by passive dilation of the lower extremity arteries and a reduction in venous return due to venous dilation. Stimulation of baroreceptors triggers sympathetic activation within 6-10 seconds, leading to an increase in arterial blood pressure due to elevated heart rate and peripheral resistance. This adjustment requires a few additional seconds at cardiac level compared with sympathetic activation. A delay during high +Gz loads (up to 9 G) results in an acute reduction of cerebral blood flow, which eventually results in a temporary condition of unconsciousness, G-induced loss of consciousness (G-LOC) (1,2). These effects may pose a significant risk during flight, potentially leading to incapacitation and jeopardizing flight safety.

During air combat maneuvers with high-performance aircraft, such as the F-16, Jet pilots are generally exposed to forces of +7 to +9 Gz for about 5-10 seconds and to levels beyond +5 Gz for over one minute. A significant quantity of medical incapacitations and military jet accidents has resulted from the hazardous effects of G-forces, especially during high-performance missions that involve maneuvers characterized by rapid onset and sustained high G levels (3,4). +Gz additionally causes various adverse effects including respiratory

impairments and musculoskeletal injuries (1). To raise pilots' awareness of these G-related consequences, a ground-based human centrifuge training (HCT) platform with a free-swinging gondola is used to generate +Gz by rotational motion (Figure 1). During this training, pilots are taught how to cope with the hazardous physiological effects of G forces.

+Gz alone has various effects on the pulmonary system, potentially causing alterations in lung volume and capacities. A rise of about 500 mL is observed at +3 Gz. Total lung capacity and vital capacity remain unchanged at accelerative forces up to +3 Gz; however, they undergo a 15% decline when accelerative forces exceed +5 Gz. The diaphragm and intra-abdominal organs also descend, which results in a rise in the functional residual capacity (6). Increased +Gz exposure also improves respiratory efforts and minute ventilation (7,8). Acceleration of +5 Gz may cause a 5 cm reduction in the heart and diaphragm level (2). To achieve effective respiration and adequate cerebral perfusion under high +Gz load, pilots execute the Anti-G Straining Maneuver (AGSM), which involves a rapid inspiration lasting less than one second, a forceful expiration against a partially closed glottis, and simultaneous contraction of all abdominal and limb muscle groups. Each respiratory cycle last for 2.5-3.0 seconds, providing the stability of intrathoracic pressure and respiratory regulation, thereby mitigating the negative respiratory effects of acceleration while supporting cardiovascular responses to increased +Gz. The anti-G suit provides another protective measure against +Gz. The suit provides full bladder coverage around the lower extremities and abdomen, inflating in response to increasing +Gz to apply pneumatic pressure that minimizes pooling of blood in the limbs (2). The inflation of the abdominal component additionally prevents the descent of the diaphragm to ensure adequate respiration (2,9). Contrary to the alterations



**Figure 1.** Human centrifuge training device. The device has a free-swinging gondola and is capable of producing high acceleration forces of up to 9 Gs [Adapted from the author's previously published presentation (5)]

caused by +Gz alone, vital capacity, functional residual capacity, and tidal volume have been shown to decline with the inflation of anti-G suit due to its restrictive mechanism (10,11). As is seen, hypergravity independently, as well as in conjunction with anti-G suit compression and AGSM, generates various physiological alterations within the respiratory mechanics.

While most of the research has focused on the changes occurring during high +Gz exposure (6,7,8,10,11), there is a lack of information about the persistence of these changes following the exposure. In this study, we aimed to analyze respiratory alterations immediately after exposure to +Gz acceleration using pulmonary function testing (PFT) in jet pilots.

## Methods

### Study design and participants

This single-center, cross-sectional study included military jet pilots who attended HCT at the Aeromedical Research and Training Center between December 2023 and March 2024.

The inclusion criteria were active military jet pilots who attended HCT and who consented to participate in the study. All these pilots were assessed to be in optimal health, having been deemed medically fit for flight duties and HCT following comprehensive aeromedical examinations (12). The exclusion criterion was the refusal to attend. Additionally, pilots who were unable to complete the HCT protocol and therefore did not experience the anticipated +Gz exposure were excluded from the post-training PFT. A total of 22 military jet pilots were enrolled in the study. One pilot suffered G-LOC during the training. The training was immediately stopped, and the HCT was rescheduled for another date. The pilot was excluded from the study procedures and post-training PFTs due to his incomplete HCT. Consequently, the PFT parameters of 21 pilots were measured both prior to and following HCT, and the statistical analysis was conducted on these pilots who completed the HCT and PFTs.

Ethical approval was taken from the University of Health Sciences Türkiye, Gülhane Training and Research Hospital (approval number: 2023/265, date: 22.11.2023). The study was conducted in accordance with the principles of the Declaration of Helsinki. Participants in the study provided informed consent after receiving thorough information via the consent forms.

### Study protocol

Before PFT, a basic questionnaire was applied for collecting data, involving age, sex, height and weight, history of medication, and smoking status. A pilot was identified as a smoker who had smoked a minimum of 100 cigarettes in their lifespan and smoked regularly in the period of 30 days before the centrifuge training. A non-smoker was identified as an individual who had not smoked within the thirty days before the training day, had not consumed 100 cigarettes in their lifetime, or smoked over

100 cigarettes in their lifespan but had not smoked in the last 30 days (13).

The PFTs were performed using the Quark PFT device (Cosmed, Rome, Italy). An experienced technician conducted PFTs for each pilot in a sitting position. Just before (pre-training) and immediately after (post-training) the HCTs, each pilot performed PFTs. Forced vital capacity (FVC), forced expiratory volume in 1 second ( $FEV_1$ ),  $FEV_1/FVC$ , maximal voluntary ventilation (MVV), peak expiratory flow rate (PEFR), and forced expiratory flow at 25-75% ( $FEF_{25-75\%}$ ) values were measured and recorded. Pilots met the standardization requirements by performing a minimum of three PFT cycles, and the most accurate cycle was evaluated (14). The PFT unit and the HCT platform were adjacent within the same facility. Therefore, the pilots were immediately transferred to the PFT unit following the HCT, and PFTs were performed without delay.

The HCT protocol consisted of three profiles: the initial profile involved a +4.0 Gz load, starting from baseline with an onset rate of  $0.1 \text{ G}\cdot\text{s}^{-1}$ . The following profile included a +4.5 Gz load, administered at an onset rate of  $3 \text{ G}\cdot\text{s}^{-1}$ , and maintained for a 30-sec peak. The last profile included a +7.0 Gz load, administered at an onset rate of  $3 \text{ G}\cdot\text{s}^{-1}$ , and maintained for a 15-sec peak. Each pilot completed the training successfully, did not experience any G-related alterations, and had no pathological symptoms. Pre- and post-training PFT values were statistically compared.

### Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, version 29 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was utilized to determine the normality of numerical data. For within-group comparisons of pre- and post-training pulmonary function test parameters, paired t-tests were applied to normally distributed variables, while the Wilcoxon signed-rank test was applied to non-normally distributed variables. Changes in mean post-pre-training values were compared between smokers and non-smokers using Independent Samples t-tests or Mann-Whitney U tests, depending on the distribution of the data. Categorical variables were presented as percentages and frequencies. A p-value of less than 0.05 was considered statistically significant, and the data were evaluated at a 95% confidence level.

## Results

### Demographics and clinical measures

The mean  $\pm$  standard deviation age of the 21 pilots was  $27.95 \pm 3.60$  years. After HCT, significant improvements were observed in the mean values of  $FEV_1$  ( $4.45 \pm 0.55$  vs.  $4.55 \pm 0.57$ ,  $p=0.001$ ),  $FEV_1/FVC$  ( $80.0 \pm 0.6$  vs.  $83.0 \pm 0.7$ ,  $p=0.002$ ),  $FEF_{25-75\%}$  ( $4.72 \pm 1.43$  vs.  $4.96 \pm 1.52$ ,  $p=0.007$ ), and MVV ( $169.3 \pm 28.6$  vs.

181.5±32.4, p=0.002). No significant changes were observed in FVC or PEFR (p>0.05) (Table 1).

Among smokers, significant post-training improvements were observed in the mean values of FEV<sub>1</sub> (4.35±0.47 vs. 4.42±0.45, p=0.012), FEV<sub>1</sub>/FVC (80%±0.06 vs. 83%±0.06, p=0.007), and PEFR (9.48±1.10 vs. 10.10±1.45, p=0.032), whereas no significant changes were detected in FVC, FEF<sub>25-75%</sub>, or MVV (p>0.05). In non-smokers, significant increases were observed in FEV<sub>1</sub> (4.54±0.61 vs. 4.68±0.67, p=0.008), FEV<sub>1</sub>/FVC (80%±0.6 vs. 83%±0.7, p=0.05), and MVV (175.7±36.0 vs. 190.1±37.8, p=0.01), while the remaining parameters showed no significant changes.

No statistically significant differences were observed in the magnitude of pre-post training changes for FVC, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC, FEF<sub>25-75%</sub>, PEFR, or MVV between smokers and non-smokers (all p>0.05).

### Intragroup comparisons

Ten (47.6%) pilots were active smokers. The analysis comparing PFT values between smokers and non-smokers revealed distinct PFT response patterns to HCT. Among smokers, significant post-training improvements were observed in FEV<sub>1</sub>, FEV<sub>1</sub>/FVC ratio, and PEFR, while FVC, FEF<sub>25-75%</sub>, and MVV exhibited non-significant increases. Within non-smokers, significant increases were observed in FEV<sub>1</sub>, FEV<sub>1</sub>/FVC, and MVV; other variables exhibited no significant alteration (Table 2).

### Discussion

This study suggests that short-term exposure to +Gz is correlated with rapid improvements in specific PFT measures in healthy military jet pilots. The observed changes in FEV<sub>1</sub>, FEV<sub>1</sub>/FVC, FEF<sub>25-75%</sub>, and MVV, primarily involving expiratory flow parameters and effort-sensitive lung volumes, reveal that high +Gz exposure induces temporary functional changes in

**Table 1. Pulmonary function parameters measured before and after human centrifuge training among 21 pilots**

Parameters	Pre-training	Post-training	p
FVC (L), mean ± SD	5.51±0.59	5.59±0.59	0.767
FEV <sub>1</sub> (L), mean ± SD	4.45±0.55	4.55±0.57	<b>0.001*</b>
FEV <sub>1</sub> /FVC (%), mean ± SD	80±0.6	83±0.7	<b>0.002**</b>
PEFR (L/sec), mean ± SD	10.12±1.63	10.33±1.4	0.237
FEF <sub>25-75%</sub> (L/sec), mean ± SD	4.72±1.43	4.96±1.52	<b>0.007**</b>
MVV (L/min), mean ± SD	169.3±28.6	181.5±32.4	<b>0.002**</b>

\*: Wilcoxon signed-rank test, \*\*: Paired t-test

FVC: Forced vital capacity, SD: Standard deviation, FEV<sub>1</sub>: Forced expiratory volume in 1 second, PEFR: Peak expiratory flow rate, FEF<sub>25-75%</sub>: Forced expiratory flow at 25-75%, MVV: Maximal voluntary ventilation

**Table 2. Comparison of pre- and post-training pulmonary function test parameters and magnitude of change among smoker and non-smoker pilots**

Parameters	Group	Pre-training	Post-training	p1	p2
FVC (L), mean ± SD	s	5.39±0.43	5.33±0.44	0.386	0.372
	ns	5.63±0.71	5.64±0.69	0.722	
FEV <sub>1</sub> (L), mean ± SD	s	4.35±0.47	4.42±0.45	<b>0.012*</b>	0.289
	ns	4.54±0.61	4.68±0.67	<b>0.008**</b>	
FEV <sub>1</sub> /FVC (%), mean ± SD	s	80±0.06	83±0.06	<b>0.007*</b>	0.982
	ns	80±0.6	83±0.7	0.05	
PEFR (L/sec), mean ± SD	s	9.48±1.10	10.10±1.45	<b>0.032*</b>	0.051
	ns	10.70±1.86	10.53±1.39	0.657	
FEF <sub>25-75%</sub> (L/sec), mean ± SD	s	4.65±1.44	4.91±1.45	0.074	0.307
	ns	4.79±1.50	5.00±1.64	0.083	
MVV (L/min), mean ± SD	s	162.3±16.6	172±23.6	0.059	0.613
	ns	175.7±36.0	190.1±37.8	<b>0.010*</b>	

\*: Paired t-test, \*\*: Wilcoxon signed-rank test

p1: Within-group comparison between pre-training and post-training values (paired analysis)

p2: Between-group comparison of mean post-pre training values among smokers and non-smokers

FVC: Forced vital capacity, SD: Standard deviation, s: Smoker, ns: Non-smoker, FEV<sub>1</sub>: Forced expiratory volume in 1 second, PEFR: Peak expiratory flow rate, FEF<sub>25-75%</sub>:

Forced expiratory flow at 25-75%, MVV: Maximal voluntary ventilation

respiratory dynamics. Furthermore, significant improvements have been observed in expiratory flow-related parameters, particularly  $FEV_1$  and  $FEV_1/FVC$ , in both smokers and non-smokers, along with a substantial increase in MVV among non-smokers and in PEFR among smokers.

In our study,  $FEV_1$ ,  $FEV_1/FVC$ ,  $FEF_{25-75\%}$ , and MVV exhibited significant improvements, while FVC and PEFR demonstrated non-significant increases following HCT. These parameters are considered as effort-sensitive lung volumes, which are primarily determined by physical exertion, expiratory muscle strength, and air flow rate (15,16). Exposure to +Gz and performing AGSM can be considered as a form of physical exercise since it requires strong muscular effort and circulatory stress, resulting in higher levels of oxygen consumption and lactate generation in a short time, both of which are characteristic indicators of physical activity (17). The observed increase in plasma adrenaline levels during +Gz exposure was interpreted as indicative of the excessive physical exertion associated with hypergravity conditions (18). High +Gz load has also been shown to affect lung stretch receptors, regulating cardiovascular responses and enhancing respiratory dynamics, as well as increasing breathing effort through deeper and more rapid breathing cycles and a rise in minute ventilation (2,7,11). The AGSM involves a quick and deep inspiratory gasp and an expiration phase after the forced expiration stage, thereby serving as a short, intense physical exertion, which is suggested to improve pulmonary functions and cause larger lung volumes throughout this period (19,20). The anti-G suit concurrently exerts additional restrictions, causing physical strain (10,11). All these alterations eventually boost sympathetic response which in turn impacts respiratory dynamics inducing bronchodilation and thereby improving the ventilatory process (2). However, these physiological conditions alter immediately upon cessation of +Gz exposure. Upon the completion of +Gz loading and the deflation of the anti-G suit, external pressure is alleviated, resulting in a decline in stress levels and a rapid restoration of chest wall mobility to baseline levels. During this post-exposure period, the physical burden diminishes, while the physiological activation induced by +Gz load may persist. Miyamoto et al. observed increases in adrenaline and noradrenaline levels during and after a 1-minute exposure to +5 Gz, with a sustained increase lasting for 110 seconds post-exposure (18). In order to benefit from the short-term G tolerance gain induced by catecholamines, pilots are advised to execute maneuvers that generate short-term G exposures before conducting high-G maneuvering (21). A study evaluating pulmonary functions via impulse oscillometer revealed a significant decrease in small-airway resistance and the reactance area, indicating the stiffness or flexibility of the airways following high-Gz exposure (22). In the same study, these findings have been linked to a temporary increase in intrathoracic pressure during AGSM, which momentarily dilates and expands the small airways—offering a

probable physiological rationale for the increases in  $FEV_1$ ,  $FEV_1/FVC$ ,  $FEF_{25-75\%}$ , and MVV observed in our study. Therefore, the elevated +Gz levels in our HCT protocol likely resulted in a short-term improvement in G tolerance via catecholamines, which in turn led to enhanced airway capacity, increased muscular effort, slight bronchodilation, and increased motivation, all of which caused a prolonged increase in respiratory dynamics following HCT.

Besides catecholamines, increased levels of serum cortisol have also been observed during +Gz exposure (23), mirroring those encountered during physical exercise and training (24,25). Any kind of stress triggers a cascade of physiological reactions, including an increase in heart rate due to the baroreceptor response- and cortisol levels in the blood (24). Although it takes longer than the baroreceptor reaction does, the endocrine response appears to play a greater role as G exposure intervals increase. Cortisol secretion was indicated to be “dose-dependent,” implying that increased +Gz acceleration correlates with higher cortisol release (26). Substantial data indicate that even short periods of vigorous resistance exercises can induce an immediate rise in blood cortisol levels that continues following exercise (27,28). Various research indicates that salivary cortisol levels significantly increase 15 to 30 minutes following brief +Gz exposures of around 6 +Gz lasting less than 1 minute (29,30). Given that +Gz exposure constitutes a form of physical exertion and that various hormone levels rise rapidly following intense physical activity, transient hormonal increases may have influenced post-training PFT outcomes in our study. The present study did not acquire hormonal measures or blood samples; thus, no endocrine inferences could be derived from our findings. The hormonal mechanisms discussed are conjectural, rely entirely on existing research detailing physiological responses to hypergravity and strenuous physical activity, and help to explain the observed pulmonary alterations following exposure, rather than to establish a proven causal relationship. Further studies utilizing repeated endocrine biomarkers with subsequent pulmonary evaluations would be helpful to find out if hormonal responses significantly influence pulmonary dynamics following HCT.

Subgroup analysis indicated that HCT provided small but significant increases in expiratory metrics, especially  $FEV_1$  and  $FEV_1/FVC$  for both smokers and non-smokers, MVV considerably increased just in non-smokers, and PEFR in smokers. Considering the physiological similarities between +Gz loading and physical exertion, the current literature does not specifically compare the impact of smoking status on PFT alterations with respect to +Gz exposure, although it supports such a comparison in the context of physical exertion. While smoking was shown to have significant effects on the PFT parameters, indicating airflow restriction ( $FEV_1$ ,  $FEV_1/FVC$ , PEFR, etc.) (31,32), respiratory muscle training and physical

exercise have been demonstrated to improve pulmonary functions among smokers. A study involving both smokers and non-smokers participating in an 8-week respiratory muscle training program revealed substantial improvements in basic spirometry measurements -FVC, FEV<sub>1</sub>, PEF, and FEV<sub>1</sub>/FVC- with smokers exhibiting greater increases in FEV<sub>1</sub>/FVC (33). In another study, smokers who underwent six weeks of pulmonary muscle training had notable improvements in FVC, although starting with lower baseline levels compared to non-smokers, who demonstrated considerable improvements in FEV<sub>1</sub> (34). While smoking is linked to progressive and mostly irreversible airflow restriction, especially in chronic obstructive pulmonary disease (COPD) (35), the observed increases in FEV<sub>1</sub>, FEV<sub>1</sub>/FVC, and PEF values among smokers may be said to indicate temporary and acute physiological modifications of airway functions that are triggered by sympathetic stimulation and effort-dependent respiratory mechanics, instead of structural airway alterations related to smoking. Additionally, the study cohort consisted of young, healthy, active pilots without any pulmonary disease (e.g., COPD), suggesting preserved basal respiratory reserve despite smoking. On the other hand, the MVV improvement observed in non-smokers may be indicative of a more enhanced baseline pulmonary reserve (36). Moreover, MVV is strongly influenced by respiratory muscle strength (37), and short-term high +Gz exposure might have functioned as a strong ventilatory stimulant, rapidly improving the efficacy of the ventilatory muscle and expiratory flow efficiency. Therefore, it is likely that the higher MVV increases among non-smokers may be said to demonstrate improved ventilatory muscle function on a normal airway background, while significant improvements in effort-dependent flow metrics in smokers indicate a temporary restoration of impairment in small airways due to smoking.

The long-term effects of repetitive or extended +Gz exposure have primarily been studied concerning cardiovascular functions (38,39), however, there is a lack of research specifically assessing whether repeated +Gz exposure results in cumulative improvements, fatigue-related impairments, or morphological alterations in the respiratory system. Although exposure to high +Gz likely results in significant improvements in effort-dependent flow metrics, airway capacity, and muscular effort, such exposure generally lasts for very short periods of 5 to 15 seconds, with prolonged durations barely exceeding 20 to 30 seconds and total cumulative exposure mostly not exceeding five minutes due to structural, operational, and physiological restrictions during aerial combat maneuvers in each sortie (1,2). On the other hand, considering the physiological similarities between high +Gz loads and intense physical activity, recurrent high-intensity physical exercise may induce respiratory muscle fatigue within minutes (40,41). It was shown that diaphragmatic fatigue develops in after just eight to ten minutes of high respiratory need with full-body exercise at or near peak effort (VO<sub>2</sub>max >85%)

and that both inspiratory and expiratory muscles become significantly fatigued several minutes after sustained excessive ventilation, which reduces the capacity for exercise and changes breathing patterns (40,42). In such a healthy population, these short exposure periods of high +Gz load appear inadequate to induce significant respiratory muscle fatigue that could lead to clinically relevant respiratory incapacitation, and are more likely to result in just mild, temporary fatigue levels as scientifically confirmed fatigue of the respiratory system typically needs longer periods of prolonged high ventilatory effort (1). Nonetheless, given the transient autonomic and hormonal responses that are likely to cause temporary changes in spirometry measurements following exposure, these alterations might be considered as acute physiological adaptations rather than actual improvements in the respiratory system. Consequently, it might be suggested that these improvements could obscure any underlying respiratory issue, especially among those with reduced pulmonary reserve, such as smokers or those with pre-existing subclinical airflow restrictions, whose impairments might only be observed under repeated stress or extended ventilatory exertion. While single episodes of high +Gz load are short-lasting, the cumulative mechanical strain on the respiratory system resulting from multiple exposures in a single sortie could otherwise unmask insidious physiological constraints which are not apparent following a single maneuver. In addition to +Gz, Pollock et al. (43) investigated the transient aftereffects of +Gx using a human centrifuge. Their findings revealed that sustained exposure to high-Gx acceleration- a force experienced from the chest to the back- during commercial suborbital spaceflight might cause substantial and rapidly developing respiratory mechanical stress, even in healthy individuals. This was stated to suggest that any temporary improvements observed in spirometry measurements could obscure underlying respiratory issues in individuals with medical conditions, such as coexisting cardiopulmonary disease and obesity. Therefore, further research involving extended or repeated high-Gz profiles, real-time ventilation assessments, and a wider range of aircrew populations would be useful to better and more comprehensively understand those mechanisms, and to identify how transient post-G changes obscure early signs of respiratory susceptibility.

Although such short-term respiratory improvements might not represent prolonged advancement in ventilatory capacity, they may provide a temporary boost in pulmonary functions that could assist individuals to execute maneuvers that require increased oxygenation, better ventilation, or more physical effort. Since moderate exercise was shown to improve cognitive and physical performance (44,45), high-Gz exposures can be beneficial in maintaining cognitive abilities, reaction times, and physical endurance throughout crucial mission periods by triggering an immediate burst in catecholamines and associated hormonal reactions. Understanding the short-term nature of

the respiratory improvements could benefit training supervisors in effectively regulating maneuver effectiveness, arranging sufficient recovery periods, and minimizing the overestimation of respiratory tolerance depending simply on acute post-G measurements. Furthermore, integrating regular respiratory measurements into HCT protocols may assist in identifying aircrew- even including passengers for commercial space flights- with insidious underlying conditions who might be at increased risk due to prolonged exposure patterns or inadequate recovery. Future operational investigations are needed to identify the optimal integration of these physiological responses into training procedures to improve both performance and safety.

### Study Limitations

The present study has various limitations. First, the cohort size was relatively small, which might have limited the statistical power and generalizability of the results. Given the operational difficulties, this was the maximum achievable sample size. Pilots generally either leave the training center shortly after completing their physiological training tasks or continue to other modules of training (such as ejection seat, spatial disorientation, or night vision training), making their attendance in subsequent PFTs challenging. Second, PFT was performed immediately following centrifuge exposure, increasing the likelihood that the observed effects were short-term rather than long-term physiological alterations. However, additional testing was not possible due to the same practical concerns. Potential residual effects of +Gz exposure could be studied more thoroughly by conducting follow-up PFTs at specific subsequent time points. Another limitation of this study is the absence of a control group that did not undergo +Gz exposure. Without a control cohort, it is challenging to definitively attribute the observed improvements in pulmonary function solely to the high-G exposure, as opposed to other factors such as testing familiarity, psychological effects, or natural variability in respiratory function. Including a control group in future studies—such as pilots undergoing identical testing without +Gz exposure—would strengthen the causal inference and help distinguish true physiological changes from test-retest effects or placebo influences. Moreover, a control group could facilitate assessment of baseline stability of PFT parameters, thereby ensuring that the observed modifications are specifically related to the high-G stress.

### Conclusion

Overall, respiratory responses to +Gz acceleration exposure resulted in improvements in several PFT values. Expiratory flow-dependent parameters ( $FEV_1$ ,  $FEV_1/FVC$ ,  $FEF_{25-75\%}$ ) and MVV exhibited significant post-training improvements. Subgroup analysis demonstrated that non-smokers showed significantly greater increases in flow-dependent measures, while smokers had smaller yet significant improvements.

Acute high-Gz exposure may be said to temporarily improve respiratory dynamics, especially in those who have preserved basal pulmonary reserve, through sympathetic stimulation, and improved activation of respiratory muscle groups. To confirm these outcomes and explain the mechanisms at work, further studies should better include larger cohorts, additional analyses of hormonal biomarkers' responses, and repeated post-exposure measures.

### Ethics

**Ethics Committee Approval:** Ethical approval was taken from the University of Health Sciences Türkiye, Gülhane Training and Research Hospital (approval number: 2023/265, date: 22.11.2023).

**Informed Consent:** Participants in the study provided informed consent after receiving thorough information via the consent forms.

### Footnotes

#### Authorship Contributions

Surgical and Medical Practices: M.S.İ., N.K., Ş.H.G., Concept: A.E.D., M.S.İ., N.K., Ş.H.G., Design: A.E.D., M.S.İ., N.K., C.T., Data Collection or Processing: A.E.D., M.S.İ., Ş.H.G., Analysis or Interpretation: C.T., Literature Search: A.E.D., Writing: A.E.D., Ş.H.G., C.T.

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