ARTICLE

DOI 10.52781/cmm.a104

Pulmonary function of combat pilots: What are the chronic effects of exposure?

Función pulmonar en pilotos de combate: ¿Cuáles son los efectos crónicos de la exposición?

Abstract: The effects related to work at high altitudes and acceleration force overload can generate physiological compensation mechanisms and eventual short-, medium- and long-term changes in lung function. Therefore, this study aimed to describe the chronic changes in lung function in combat pilots of the Brazilian Air Force. The sample consisted of 19 combat pilots and 20 controls. For pulmonary function measurements, we observed an increase in the mean values of Forced Vital Capacity (FVC) and Forced Expiratory Volume in the First Second ($FEV_{1)}$, a decrease in lung volume, an increase in resistance and work of breathing, in the exposed group compared to the control, with significant modifications to Residual Volume (RV) by Total Lung Capacity (TLC) in liters (L) and percentage (%). Similar behavior when evaluated according to flight hours, with an increase proportional to the increase in exposure time. Discrete changes, such as those observed in this research, may reflect adaptations of the respiratory system, bringing a complementary view to changes in chronic conditions.

Keywords: pilots; military; high altitude; acceleration force; lung function.

Resumen: Los efectos inherentes al trabajo en altitudes elevadas y sobrecarga de la fuerza de aceleración pueden generar mecanismos de compensación fisiológica y eventuales modificaciones de la función pulmonar a corto, mediano y largo plazo. Ante eso, el objetivo de este artículo fue describir las modificaciones crónicas de la función pulmonar en pilotos de combate de la Fuerza Aérea Brasileña (FAB). La muestra estuvo compuesta por 19 pilotos de combate del grupo expuesto y 20 voluntarios del grupo control. Para las medidas de función pulmonar se observó un aumento de los valores medios de Capacidad Vital Forzada (CVF) y Volumen Espiratorio Forzado en el Primer Segundo (VEF_1), disminución del volumen pulmonar, aumento de la resistencia y del trabajo respiratorio. En el grupo expuesto, en comparación con el grupo control, observamos cambios significativos para el Volumen Residual (RV) por Capacidad Pulmonar Total (TLC) en litros (L) y porcentaje (%), es decir, VR/CPT. Comportamientos similares cuando se evalúan según las horas de vuelo, con aumento proporcional a la elevación del tiempo de exposición. Las modificaciones sutiles, según las observadas en esta investigación, pueden ser reflejo de adaptaciones del sistema respiratorio, trayendo una mirada complementaria para los cambios en condiciones crónicas.

Palabras clave: piloto; militar; altitud elevada; fuerza de aceleración; función pulmonar.

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Received: Aug 30, 2023
Approved: Mar 14,2023

COLEÇÃO MEIRA MATTOS
ISSN on-line 2316-4891 / ISSN print 2316-4833
http://ebrevistas.eb.mil.br/index.php/RMM/index

1 INTRODUCTION

The pilot is exposed to the adverse effects of working at high altitudes during air activity. Extreme vibrations, dysbarism, hypoxia, the action of acceleration loads (G-Force), and other environmental stressors are frequent, especially in flights above 15,000 feet (GÜL; SALMANOĞLU, 2012). This air segment requires supplemental oxygen, the cabin environment can present controlled pressurization, and the effects of working at altitude may seem more evident (ALVES *et al.*, 2008; GÜL; SALMANOĞLU, 2012; PETRASSI *et al.*, 2012).

The literature describes that reducing air pressure with increasing altitude leads to hypoxia, also known as hypobaric hypoxia (ALVES *et al.*, 2008). Lowering the alveolar partial pressure of oxygen lowers arterial blood pressure. Thus, in an acute ventilatory response, the body works to recover homeostasis of oxygen concentration, causing hypocapnia and respiratory alkalosis (PETRASSI *et al.*, 2012). This compensation causes respiratory muscle fatigue (BUSTAMANTE-SÁNCHEZ; DELGADO-TERÁN; CLEMENTE-SUÁREZ, 2019; POLLARD *et al.*, 1997), with possible psychomotor impairment in acute hypobaric patients, which may affect the postural control of the crew. Therefore, it increases proportional postural sway as altitude increases (NORDAHL *et al.*, 1998).

In addition, acceleration force tolerance in the aerospace context is considered a particular factor and may have physiological effects related to the respiratory system, vision (commonly called blackout – complete loss of vision), and the level of consciousness (with loss of consciousness, known as Induced Loss of Consciousness – G-LOC) (RUSSOMANO; CASTRO, 2012).

In addition to these, with the G-Force overload acting on the thorax, the airways in the lower third of the lung may collapse, evolving up to 50% of the lung as the acceleration force progresses, generating consequent changes in the distribution of lung blood flow (WEST, 2013). Pulmonary capillaries must be thin and exposed directly to the alveolar space for efficient gas exchange. Thus, changes in ambient pressure are transmitted to the alveolar capillaries, impacting pulmonary circulation both by lung deformation and by changes in the distribution of hydrostatic pressure in the lung (PRISK, 2011).

Additionally, individual biopsychological factors can be decisive when engaging in aerial combat. Aviation troops must be able to deal with these conditions, whether in routine situations or a high workload (GINDHART, 1999; GÜL; SALMANOĞLU, 2012; SAUVET *et al.*, 2009). The acclimatized subject may experience less deleterious effects on the body, which makes it possible to carry out daily work even at very high altitudes (4400 to 5500 meters), with efficiency close to that of the subject working at sea level. However, the possibility of developing diseases or adaptations due to continuous exposure should be considered (ARISTIZABAL *et al.*, 2019; DUISHOBAEV *et al.*, 2018).

External offsets can be used in high-performance military aviation to reduce the deleterious effects of exposure during flight. In addition to personalized training and acclimatization, oxygen supplementation between 70 and 100% can occur to solve the effects of hypoxia, which can occur from 15,000 feet of altitude or 4,572 meters (BUSTAMANTE-SÁNCHEZ;

DELGADO-TERÁN; CLEMENTE-SUÁREZ, 2019). Mechanical assistance measures are used to maintain adequate venous return. Anti-G suits, positive breathing pressure, and anti-G effort maneuvers, such as the Anti-G Strain Maneuver (AGSM), are seen as fundamental means to tolerate acceleration (ÖZTÜRK; İLBASMIŞ; AKIN, 2012).

Some instruments are commercially available to estimate pulmonary function assessment indices, among which spirometry and plethysmography are the most established (MUNGOGE *et al.*, 2016; SOCIEDADE BRASILEIRA DE PNEUMOLOGIA E TISIOLOGIA, 2009; TRINDADE; SOUSA; ALBUQUERQUE, 2015). In addition, the Forced Oscillation Technique (FOT), described by DuBois *et al.* in 1956, stands out for being complementary to traditional instruments and has the advantage of being a method performed in spontaneous ventilation (OOSTVEEN *et al.*, 2003).

A more detailed analysis of lung function under exposure conditions described above may contribute to better coping and improvement of human performance and the man-machine relationship in the Brazilian armed forces, providing parameters for diagnostic evaluation and longitudinal follow-up of these subjects.

Thus, this article aimed to (1) compare changes in lung function between volunteers in the control group and fighter pilots of the Brazilian Air Force (FAB); (2) analyze the effects of the flight exposure period on the lung function of combat pilots; (3) analyze the effects of work at high altitudes considering the particularities of exposure with low and high exposure to the G-load.

2 MATERIAL AND METHODS

The proposed protocol was carried out at the Biomedical Instrumentation Laboratory of the State University of Rio de Janeiro (UERJ), based on applying a sociodemographic questionnaire and pulmonary function tests performed by duly trained technicians. The sequence in which the tests were carried out was FOT in the multifrequency version, spirometry, and full-body plethysmography.

The sample was selected for convenience. The group of exposed subjects enrolled volunteer fighter pilots from the First Group of Fighter Aviation (1st GavCa) and pilots from Transport Squadrons from Santa Cruz Air Force Base and Galeão Air Force Base. All could fly according to the criteria proposed by the current military legislation – ICA 160-6/2016 (BRASIL, 2016) and identified for this research according to the abbreviations: GFighter and GTransport, respectively. For the control group, the subjects were: non-flying personnel, military or not, non-sedentary, and similar to the exposed group in age, weight, and height. The exclusion criteria for all groups were respiratory infections in the last 30 days, chest diseases, and smoking.

Lung flow and volume were measured using the BPd full-body plethysmograph (nSpire Health, Inc., 1830 Lefthand Circle, Longmont, CO 80501). The tests followed the guidelines for pulmonary function tests (GRAHAM, 2019; NEDER *et al.*, 1999; PEREIRA; MOREIRA, 2002; SOCIEDADE BRASILEIRA DE PNEUMOLOGIA E TISIOLOGIA, 2009). The FOT was previously described in detail (MELO; WERNECK;

GIANNELLA-NETO, 2000) and follows international standards (NAVAJAS e FARRÉ, 2001; OOSTVEEN *et al.*, 2003; SÁ *et al.*, 2013).

Results were presented using mean and standard deviation. Commercial software was employed to compare group differences (STATISTICA for Windows, release 5.0). The analysis between the two groups used the independent t-test for samples with normal distribution and Mann-Whitney for non-parametric samples. The comparisons between the three groups used the Analysis of Variance (ANOVA), followed by Tukey's test when the distribution presented a parametric characteristic, and Kruskal Wallis ANOVA, followed by Mann Whitney when non-parametric. Results with $p < 0.05$ were considered statistically significant. Finally, Pearson and/or Spearman correlation coefficients determined correlation analyses.

3 RESULTS

The study involved 37 volunteers, 18 from GControl and 19 from GPilots (6 from GTransport; 13 from GFighter). The analysis based on the biometric parameters showed a homogeneous distribution (Table 1).

Table 1 – Anthropometric data of the analyzed volunteers – GControl × GTransport × GFighter

Parameters	GControl N = 18	GTransport N = 6	GFighter N = 13	p
Age (years)	33.27 ± 5.63	30.16 ± 2.31	31.46 ± 1.98	ns*
Weight (kg)	80.22 ± 8. 62	82.61 ± 6.19	82.6 ± 8.32	ns*
Height (cm)	175.16 ± 5.28	178.16 ± 7.67	177.25 ± 5.71	ns*
BMI (kg/m^2)	26.06 ± 2.13	26.60 ± 1.95	26.01 ± 2.14	ns*

Note: Results presented as mean ± standard deviation. *Anova/Tukey test, **Kruskal Wallis Anova/and Mann Whitney. P < 0.05. Ns = not significant.

Source: Prepared by the authors, Soares *et al.* (2022).

In the evaluation of pulmonary function based on spirometry, in the comparison between the GControl, GTransport, and GFighter, we observed slightly higher mean values in the Forced Vital Capacity (FVC), Forced Expiratory Volume in One Second (FEV_1), and Forced Expiratory Flow ($FEF_{25\text{-}75\%}$) in the groups of fighter pilots compared with the other groups, although without significant changes (Table 2).

Table 3 presents the pulmonary function results from the plethysmographic parameters, in which Residual Volume (RV), Total Lung Capacity (TLC), and RV/TLC showed lower mean values in the group of fighter pilots compared with the other groups. Significant RV and RV/TLC modifications were observed in the analysis between the control and fighter groups. Resistance, whether measured using plethysmography or FOT (Table 4), showed progressively higher mean values, with a proportional drop in conductance.

In addition, we also saw an increase in ventilatory workload measured through Z4Hz, although without statistically significant changes.

Table 2 – Spirometric measurements of the studied groups – GControl × GTransport × GFighter

Parameters	GControl	GTransport	GFighter	p
FVC L	4.97 ± 0.22	5.11 ± 0.34	5.47 ± 0.61	ns*
FVC %	98.39 ± 7.24	96.46 ± 7.35	102.52 ± 7.44	ns*
FEV$_1$ L	3.97 ± 0.49	4.36 ± 0.47	4.32 ± 0.55	ns*
FEV$_1$ %	95.59 ± 10.70	98.76 ± 8.10	97.91 ± 9.55	ns*
FEV$_1$/FVC L	80.8 ± 5.87	85.48 ± 8.72	79.11 ± 5.39	ns*
FEV$_1$/FVC%	96.95 ± 7.37	102.46 ± 10. 70	95.23 ± 6.70	ns*
FEF $_{25-75}$ % L	4.02 ± 1.20	4.69 ± 25. 47	4.1 ± 0.97	ns*
FEF $_{25-75}$ %	86.84 ± 23.99	95.07 ± 25. 47	85.96 ± 20.25	ns*
FEF $_{25-75}$/FVC L	0.82 ± 0.24	0.92 ± 0.27	0.75 ± 0.17	ns*
FEF $_{25-75}$/FVC %	88.27 ± 23.58	99.85 ± 31. 30	84.17 ± 20.94	ns *

Subtitle: FVC – Forced Vital Capacity; FEV$_1$ – Forced Expiratory Volume in One Second;
FEF – Forced Expiratory Flow. Results presented as mean ± standard deviation.
*Anova/Tukey test, **Kruskal Wallis Anova/and Mann Whitney. P < 0.05. Ns = not significant.
Source: Prepared by the authors, Soares *et al*. (2022).

Table 3 – Plethysmography measurements of the studied groups – GControl × GTransport × GFighter

Parameters	GControl (0)	GTransport (1)	GFighter (2)	p
RV L	2.63 ± 0.98	1.91 ± 1.05	1.79 ± 0.82	ns*
RV %	147.3 ± 53.36	105.46 ± 61. 81	100.16 ± 46. 101	0-2 *
TLC L	7.49 ± 1.29	6.65 ± 0.88	7.23 ± 0.99	ns*
TLC %	110.25 ± 15.79	93.46 ± 13. 65	100.71 ± 12. 55	ns**
RV/TLC L	33.96 ± 9.28	27.57 ± 11. 42	24.2 ± 9.05	0-2*
RV/TLC %	130.2 ± 37.08	108.56 ± 46. 75	93.96 ± 35. 64	0-2*
Raw L	2.54 ± 1.25	2.61 ± 1.93	3.08 ± 1.27	ns*
Raw %	186.7 ± 94.28	190.4 ± 132. 30	229.63 ± 93. 70	ns*
Sgaw L	0.15 ± 0.08	0.14 ± 0.05	0.1 ± 0.03	ns**
Sgaw %	68.33 ± 39.30	64.05 ± 26. 98	46.89 ± 14. 81	ns**

Subtitle: RV – Residual Volume; TLC – Total Lung Capacity; Raw, Resistance of the respiratory system;
Sgaw, Conductance of the respiratory system. Results presented as mean ± standard deviation.
*Anova/Tukey test. **Kruskal Wallis Anova/and Mann Whitney. P < 0.05. Ns = not significant.
Source: Prepared by the authors, Soares *et al*. (2022).

Table 4 – FOT measurements of the studied groups – GControl × GTransport × GFighter

Parameters	GControl (0)	GTransport (1)	GFighter (2)	p
fr	12.80 ± 3. 62	10.69 ± 2.91	11.13 ± 3.43	ns **
Xm	0.38 ± 0.33	0.53 ± 0.31	0.54 ± 0.36	ns *
R0	2.86 ± 0.74	2.33 ± 0.75	3.08 ± 0.82	ns *
S	2.83 ± 16.73	3.23 ± 18.41	10.44 ± 16. 59	ns **
Rm	2.89 ± 0.77	2.37 ± 0.64	3.18 ± 0.81	ns*
Cdyn	0.02 ± 0.00549	0.025 ± 0.009	0.02 ± 0.005	ns*
Z4Hz	3.57 ± 0.99	2.93 ± 1.10	3.72 ± 0.98	ns*

Subtitle: fr, Resonance Frequency; Xm, Mean Reactance; R0, Total Respiratory System Resistance; S, Slope Coefficient of the Resistance Curve; Rm, Mean Resistance; Cdyn, Dynamic Compliance of the Respiratory System; Z4Hz, Impedance Module of the Respiratory System. Results presented as mean ± standard deviation. *Anova/Tukey test, **Kruskal Wallis Anova/and Mann Whitney. $P < 0.05$. Ns = not significant.

Source: Prepared by the authors, Soares *et al*. (2022).

We analyzed the subjects based on subgroups of flight hours to clarify whether the changes found would be related to exposure to the G-load alone or to the time of exposure to altitude. For this characterization, the sample lost homogeneity for anthropometric parameters, with a significant change for age (Table 5). Furthermore, we identified a significant inverse correlation in comparing flight hours and the spirometric parameters FEV_1/FVC and $FEF_{25\text{-}75\%}$ in their absolute values (Table 6). For correlations between plethysmography and FOT parameters, there were no significant changes.

Table 5 – Anthropometric data from characterization by flight hours

Parameters	GControl	GPilots			P
	(N = 18) (0)	Up to 1000 h (N = 4) (1)	1000 to 1500 h (N = 10) (2)	> 1500 h (N = 5) (3)	
Age (years)	33.27 ± 5.63	28.75 ± 0.5	30.77 ± 1.56	33 ± 1.78	1-2, 1-3, 2-3**
Weight (kg)	80.22 ± 8. 62	80 ± 5.58	85.96 ± 7.10	79.31 ± 8.14	ns*
Height (cm)	175.16 ± 5.28	178 ± 9.20	178.36 ± 5.46	176 ± 5.93	ns*
BMI (kg/m^2)	26.06 ± 2.13	25.94 ± 2. 13	26.98 ± 1.40	25.2 ± 2.62	ns*

Note: Results presented as mean ± standard deviation. *Anova/Tukey test. **Kruskal Wallis Anova/and Mann Whitney. $P < 0.05$. Ns = not significant.

Source: Prepared by the authors, Soares *et al*. (2022).

In Tables 7, 8, and 9, we observe the behavior of lung function with the progression of time of exposure to air activity given the results of spirometric, plethysmographic, and FOT parameters, respectively.

Overall, we observed a slight increase in the average values of FVC in liters (L) and percentage (%) and FEV$_1$ (L and %) with increasing flight hours. We also noted increased mean values of FEV$_1$/FVC (L and %), FEF$_{25-75\%}$ (L and %), and FEF/FVC (L and %) when comparing the GControl and subjects with up to 1000 flight hours, with a subsequent decrease in the subjects with 1000 to 1500 and those with more than 1500 flight hours. However, values were within normal limits. The plethysmographic parameters RV, TLC, and RV/TLC (L and %) decreased when comparing GControl with GPilots, with increasing exposure in flight hours. The resistance progressively increased compared with the GControl, with a slight decrease in conductance observed only in the groups with more than 1000 flight hours. The increase in the work of breathing was seen when comparing GControl with Pilots, with increased mean values with increasing exposure in flight hours.

Table 6 – Correlation between flight hours and spirometric parameters

Horas de voo	FVC L	FEV$_1$	FEV/FVC	FEF$_{25-75\%}$	FEF/ FVC
R	.042	-.318	-.498	-.468	-.476
p	.865*	.184*	.030*	.044*	.039*

Note: Results presented in correlation. P < 0.05 was considered significant.

* Pearson correlation, **Sperman correlation.

Source: Prepared by the authors, Soares *et al*. (2022).

Table 7 – Spirometric results with the characterization by flight hours

Parameters	G Control		GPilots		P
	(N = 18) (0)	Up to 1000 h (N = 4) (1)	1000 to 1500 h (N = 10) (2)	> 1500 h (N = 5) (3)	
FVC L	**4.97 ± 0.22**	5.08 ± 0.21	5.46 ± 0.62	5.37 ± 0.62	ns*
FVC %	98.39 ± 7.24	95.95 ± 8.58	102.08 ± 8.25	101.4 ± 5.91	ns*
FEV$_1$ L	3.97 ± 0.49	4.53 ± 0.47	4.32 ± 0.57	4.21 ± 0.49	ns*
FEV$_1$ %	95.59 ± 10.70	102.07 ± 7.85	97.47 ± 9.93	96.5 ± 8.28	ns*
FEV$_1$/FVC L	80.8 ± 5.87	89.20 ± 8.17	79.12 ± 5.22	78.67 ± 5.45	ns*
FEV$_1$/FVC %	96.95 ± 7.37	106.45 ± 11.17	95.25 ± 6.63	94.9 ± 6.17	ns*
FEF $_{25-75}$ % L	4.02 ± 1.20	5.275 ± 1.34	4.095 ± 0.97	3.89 ± 0.92	ns*
FEF $_{25-75}$ %	86.84 ± 23.99	104.25 ± 27.24	84.78 ± 19.99	84.64 ± 19.21	ns*
FEF $_{25-75}$/FVC L	0.82 ± 0.24	1.03 ± 0.25	0.75 ± 0.16	0.73 ± 0.18	ns*
FEF $_{25-75}$/FVC %	88.27 ± 23.58	110.32 ± 34.26	83.36 ± 20.78	83.7 ± 19.29	ns*

Subtitle: FVC, Forced Vital Capacity; FEV$_1$, Forced Expiratory Volume in One Second; FEF, Forced Expiratory Flow. Results presented as mean ± standard deviation. *Anova/Tukey test, **Kruskal Wallis Anova/and Mann Whitney. P < 0.05. Ns = not significant.

Source: Prepared by the authors, Soares *et al*. (2022).

Table 8 – Plethysmographic results with the characterization by flight hours

Parameters	G Control		GPilots		P
	(N = 18) (0)	Up to 1000 h (N = 4) (1)	1000 to 1500 h (N = 10) (2)	> 1500 h (N = 5) (3)	
RV L	2.63 ± 0.98	2.23 ± 1.19	1.76 ± 0.67	1.6 ± 1.07	ns*
RV %	147.39 ± 53.36	124.77 ± 69. 20	97.94 ± 33.82	91.3 ± 65.66	ns*
TLC L	7.49 ± 1.29	6.85 ± 1. 06	7.2 ± 0.98	6.91 ± 1.07	ns*
TLC %	110.25 ± 15.79	96.75 ± 16.31	99.71 ± 10.17	97.2 ± 17.84	ns**
RV/TLC L	33.96 ± 9.28	31.26 ± 12. 54	24.22 ± 7.13	22.57 ± 11.84	0-2, 0-3**
RV/TLC %	130.22 ± 37.08	124.47 ± 50. 38	93.88 ± 28.04	87.24 ± 46.95	0-2, 0-3**
Raw L	2.54 ± 1.25	2.60 ± 2. 32	3.01 ± 1.31	3.06 ± 1.32	ns*
Raw %	186.78 ± 94.28	183.65 ± 151. 24	223.92 ± 93.06	230.76 ± 108.12	ns*
Sgaw L	0.15 ± 0.08	0.15 ± 0.06	0.10 ± 0.03	0.10 ± 0.03	ns**
Sgaw %	68.33 ± 39.30	70.12 ± 31.34	46.86 ± 14.38	48.96 ± 16.08	ns**

Subtitle: RV, Residual Volume; TLC, Total Lung Capacity; Raw, Resistance of the respiratory system; Sgaw, Conductance of the respiratory system. Results presented as mean ± standard deviation. *Anova/Tukey test. **Kruskal Wallis Anova/and Mann Whitney. $P < 0.05$. Ns = not significant.

Source: Prepared by the authors, Soares *et al*. (2022).

Table 9 – FOT results with the characterization by flight hours

Parameters	G Control (0)	Up to 1000 h (1)	1000 to 1500 h (2)	> 1500 h (3)	P
fr	12.80 ± 3. 62	10.32 ± 2.48	11.45 ± 3. 96	10.74 ± 2.70	ns**
Xm	0.38 ± 0.33	0.56 ± 0.24	0.45 ± 0.36	0.65 ± 0.37	ns*
R0	2.86 ± 0.74	2.18 ± 0.92	2.98 ± 0. 76	2.96 ± 0.68	ns*
S	2.83 ± 16.73	0.97 ± 22. 70	11.57 ± 17.57	7.84 ± 13.29	ns**
Rm	2.89 ± 0.77	2.19 ± 0.75	3.09 ± 0.75	3.05 ± 0.61	ns*
Cdyn	0.02 ± 0.00549	0.029 ± 0.009	0.02 ± 0.003	0.01 ± 0007	ns*
Z4Hz	3.57 ± 0.99	2.75 ± 1. 12	3.62 ± 0.87	3.73 ± 1.23	ns*

Subtitle: fr, Resonance Frequency; Xm, Mean Reactance; R0, Total Respiratory System Resistance; S, Slope Coefficient of the Resistance Curve; Rm, Mean Resistance; Cdyn, Dynamic Compliance of the Respiratory System; Z4Hz, Impedance Module of the Respiratory System. Results presented as mean ± standard deviation. *Anova/Tukey test, **Kruskal Wallis Anova/and Mann Whitney. $P < 0.05$. Ns = not significant.

Source: Prepared by the authors, Soares *et al*. (2022).

4 DISCUSSION

We will begin the discussion by considering the first and second objectives of this article, in which we seek to compare changes in lung function between GControl and GPilots volunteers and analyze exposure to flying in its different spheres, i.e., the transport pilot with low exposure to G-load, and the fighter pilot with high exposure.

Initially, we believed that exposure of the respiratory system to all the undesirable effects of aviation could trigger some process of lung damage. However, this was not identified in this study.

Despite the non-significant results, we must consider that all the subjects analyzed are healthy and practitioners of regular activity, with physical fitness for flying regulated by ICA 54-1 (BRASIL, 2011) and inherent to military readiness. With these characteristics, our results showed parameters with a predicted cutoff point for pulmonary function behavior within normal limits, as described in the literature (GRAHAM, 2002; NEDER *et al.*, 1999; SOCIEDADE BRASILEIRA DE PNEUMOLOGIA E TISIOLOGIA, 2009).

In the sample studied, the specificity of physical training was not monitored. Aptitude for work was based on previously established norms for military service (BRASIL, 2011). However, Bateman *et al.* (2006) report in a review article that the effects of muscle strength training, aerobic fitness, and resistance to fatigue on G-force tolerance are still a complex subject to be discussed and without evident results. Previous analyses describe that neither aerobic training can be considered always harmful nor strength training can be regarded as universally effective in improving tolerance to the G force (BULBULIAN, 1986). For the respiratory system, there is an improvement in lung capacity and oxygen consumption rates by increasing the pulmonary vascular network with the practice of regular physical activity (MCKENZIE, 2012).

Subtle modifications such as those observed in this research, with a slight progressive increase in lung function in the comparison between GControl, GTransport, and GFighter, expressed with the help of spirometric parameters, may be a reflection of adaptations of the respiratory system to exposure in small doses and over many years of work and therefore must be considered. The reduction in RV for the same comparisons may be associated with an increase in FVC, optimizing the air volume available for ventilatory exchanges. Despite this, the mean values of TLC also decreased, countering this analogy.

Contradicting our results, other authors analyzed pulmonary function in athletes of different sports. They observed more significant static pulmonary volumes and greater pulmonary diffusion capacity in elite swimmers compared to runner athletes. These authors credited their findings to possible age differences between the combined controls in addition to genetic characteristics, suggesting further studies for clarification (CORDAIN; STAGER, 1988).

Aerial activity and swimming practice can be similar, especially regarding the combination of labor gestures, as the swimmer combines periods of immersion in water, exercises, and apnea, with evidence of subtle changes in the permeability of the lungs (DROBNIC *et al.*, 2018). For such high-performance swimming athletes, physical training at high altitudes is often used to increase physiological adaptations and, consequently, improve activity performance (LUNDBY; ROBACH, 2016; RODRIGUEZ *et al.*, 2015). These reflections, ultimately, shed light on the understanding that exposure to high altitudes can act as a modifying factor in lung performance even in the presence of adequate physical conditioning, that is, analyses aligned with the results presented in our study since GControl and GPilots differ only in the criterion of exposure to the flight, with physical fitness being common to both.

There are no reports in the literature about late adaptations of the respiratory system in exposure to high altitudes and G-force overload in combat pilots. In high-performance athletes, previously documented adaptations consider the pulmonary response to exercise much greater than the cardiovascular or peripheral muscular system (WARBURTON, SHEEL; MCKENZIE, 2008). Under conditions of acclimatization to work at high altitudes and G overload, the result may be similar.

In studies with elite athletes, minute ventilation can increase about 20 times compared with resting values, showing that the lung can handle heavy work demands (WARBURTON; SHEEL; MCKENZIE, 2008), despite suffering the consequences relating to such action.

However, in the air work environment, connotations of glory do not coexist, and the literature shows that flying in high G-load environments imposes strong cardiometabolic wear on the body (TESCH, HJORT; BALLDIN, 1983).

Bustamante-Sánchez; Delgado-Terán; Clemente-Suárez (2019) conducted a study with 23 male airmen in a hypobaric chamber, including pre- and post-exposure measurements. The sample comprised seven transport aviation crew members, three transport pilots, ten helicopter pilots, and three F-18 fighter pilots from the Spanish Air Force. The authors report that exposure to hypoxia increased the perception of stress and exertion and decreased respiratory muscle function regardless of the crew group. Transport pilots were more negatively affected than helicopter pilots and transport aircrew (BUSTAMANTE-SÁNCHEZ; DELGADO-TERÁN; CLEMENTE-SUÁREZ, 2019). Since the fighter pilot is led to experience moments of low oxygen, such as routine aerial activity, possibly, acclimatization conditions are established, which causes a better physiological response when the pilot is exposed to it again.

In that same study by Bustamante-Sánchez; Delgado-Terán; Clemente-Suárez (2018), FEV_1 and PEF were reduced in the studied population, with this drop being significant in PEF for helicopter pilots and in PEF and FEV_1, for transport crew members, suggesting that these may be associated with symptoms of muscle fatigue respiratory effects after hypoxic exposure (BUSTAMANTE-SÁNCHEZ; DELGADO-TERÁN; CLEMENTE-SUÁREZ, 2019; POLLARD *et al.*, 1997). Comparing the groups, the transport pilots had significantly lower FEV_1 values in the post-tests. FVC increased, and FEV_1 and PEF decreased for the group of fighter pilots, but with no significant changes for the pre- and post-test. The authors associate the result with the different profiles of physical training and technical preparation of these populations (BUSTAMANTE-SÁNCHEZ; DELGADO-TERÁN; CLEMENTE-SUÁREZ, 2019).

Aligned with these authors, Beer *et al.* (2017) observed a significant reduction in mean values of flows and lung capacities measured with the help of spirometry in ten US Air Force fighter pilots under conditions of confinement and high loads of oxygen supplementation. Measurements were made in the pre-flight and post-test 12 hours after the end of the flight.

Hormeño-Holgado; Clemente-Suárez (2019) evaluated 29 Spanish Air Force pilots' psychophysiological responses under combat and air defense exercise conditions lasting approximately 30 minutes each. Combat maneuvers were performed at altitudes between 8,000 and 18,000 feet (with oxygen supplementation) and with G-force between 0.5 and 5.9. Spirometry measurements were taken two hours before and 30 minutes after the flights. The results presented by the authors showed a slight reduction in FVC and an increase in FEV_1 and PEF, without significant changes, in the attack exercise condition. A similar result was seen for the defense exercise but with a significant modification for the FVC (HORMEÑO-HOLGADO; CLEMENTE-SUÁREZ, 2019).

The reduction in lung flows and volumes in acute situations such as those narrated by the studies mentioned above, under conditions of immediate post-flight assessment, conditions of fatigue of the respiratory muscles are plausible. Öztürk; Ilbasmiş; Akin (2012) describe that evidence of respiratory muscle fatigue may be associated with vigorous muscle maneuvers performed throughout the flight to provide mechanical assistance to minimize the effect of thoracic distortion and maintain adequate venous return (ÖZTÜRK; İLBASMIŞ; AKIN, 2012). However, in chronic situations, such as those evaluated in this research, long-term low-dose exposure seems to trigger an increase in respiratory performance.

The strength and resistance of the respiratory muscles improve with training, similar to what happens to the peripheral skeletal muscle. However, cellular changes in humans (WARBURTON; SHEEL; MCKENZIE, 2008) – or even the impact of this response on the pulmonary function of combat pilots – are not yet documented.

It is admissible that continuous exposure to thoracic deformations, pulmonary vascular alterations, airway closures, and other repercussions peculiar to the combat aviation environment lead to the reproduction of tissue, airway, and lung parenchyma adaptations. These facts were observed in this research through the increase in the mean values of respiratory system resistance measured with plethysmography and FOT, either for comparison between GControl and GPilots, or for the progressive mean increase in the Control, Transport, and Fighter groups, proportionally to the decrease in conductance, providing a measure of lung gas transfer.

Additionally, the Xm measured using FOT reflects changes in lung homogeneity based on the elastic characteristics of the system (MELO; WERNECK; GIANNELLA-NETO, 2000; OOSTVEEN *et al.*, 2003). More positive mean values were observed in this research, in the analysis between the Control and Pilots groups, and comparing GControl, GTransport, and GFighter. Despite the increase in resistance and decrease in conductance, a possible improvement in lung elasticity may be associated with long-term muscle gain, with better pressure variation and, thus, better ventilatory use.

While the effects described in previous studies with combat pilots have been observed in acute conditions and with fewer subjects, it is possible to infer that the singularity of each aviation profile can create different patterns of physiological responses.

In addition, our study highlights the late changes in exposure to the deleterious effects of aviation, bringing a complementary look to the behavior of the respiratory system in chronic conditions. Considering that it is part of the fighter's routine to use anti-G protection maneuvers and against the effects of G-LOC throughout the occupational flight journey (ÖZTÜRK; İLBASMIŞ; AKIN, 2012), it would be relevant to associate the improvement of lung function observed by our study in GFighter compared with the other groups to this specificity.

Healthy individuals living in these high-altitude regions have slightly better lung function than subjects residing at lower altitudes or sea levels (ARISTIZABAL *et al.*, 2019; DUISHOBAEV *et al.*, 2018).

Seeking to clarify whether the changes found would be related to the time of exposure to altitude or exposure to the G-load alone, we analyzed the subjects considering subgroups of flight hours, our third objective.

The change in sample homogeneity based on anthropometric parameters, with a significant difference in the age of the subgroups analyzed, was expected since subjects who recently joined the FAB have yet to have the opportunity to experience more significant moments of exposure to flying. However, the group with the longest flight time has an average age equivalent to that of the control group.

The inverse correlation between flight hours and FEV_1/FVC and $FEF_{25\text{-}75\%}$ parameters may clarify the possible occurrence of small airway dysfunction with increased exposure to flight. These results may reflect areas of entrapment and limitation of expiratory flow (AZEVEDO; SANTOS, 2018), which may be associated with changes in the pulmonary vascular network. Results are in line with the behavior of higher mean values of resistance and decreased conductance of the respiratory system, also observed in this article. However, parameters such as RV/TLC (L and %) showed reduced values, contradicting these findings (AZEVEDO; SANTOS, 2018). Thus, it is plausible that we are facing initial changes and that not all dysfunction markers are altered.

For this sample, exposure to work at high altitudes, based on the characterization of accumulated flight hours, seems to bring more harmful effects to the respiratory system in the analyzed combat pilots. Such occurrence is independent of the presence of G overload.

The literature lacks articles describing changes in lung function in populations similar to the one analyzed in this study. There are previous reports of populations residing in high-altitude environments, considering the temporary effects or long-term acclimatization (TALAMINOS-BARROSO *et al.*, 2020). The adaptation matches changes in respiratory control mechanisms (WEITZ; GARRUTO; CHIN, 2016), genetic adaptations that are transferred through generations, such as the development of larger lung volumes; changes in arterio-alveolar oxygen gradients; and increased uterine artery blood flow during pregnancy, thus suggesting a better efficiency in oxygen transport and consumption (TALAMINOS-BARROSO *et al.*, 2020). The increase in RV is also reported and justified by the improvement in the alveolar area and a moderate increase in the number of red blood cells (FRISANCHO, 2013). However, in this study, we observed a reduction in the mean RV values with the progression of exposure to flying.

While the changes in the respiratory system of subjects living in high-altitude regions aim to improve the efficiency of oxygen consumption and transport, these seem to follow different adaptation pathways among people (EICHSTAEDT *et al.*, 2014; LORENZO *et al.*, 2014).

Therefore, it is possible to infer that there is a sum of actions that influence the adaptations of the respiratory system of combat pilots in the face of the aerial activities that they carry out, from certain factors, such as exposure to high altitudes to the demands related to an overload of G-Force.

Indeed, more studies are needed to clarify the chronic changes in lung function in the population of combat pilots and if these changes remain after the exposure ends.

5 STUDY LIMITATIONS

During the data collection period, the volunteers who applied for this study were relocated to other bases in Brazil, given the renovation of the airstrip at Santa Cruz Air Base in Rio de Janeiro, where most of the pilots in this sample were. Subsequently, in resuming the collection flow, the lockdown began due to the COVID-19 pandemic, remaining for almost two years. These facts hindered data collection with these individuals, reducing the number of subjects per group.

Furthermore, it is necessary to point out the complexity of the scheduling and collection scale for this group of professionals since they belong to an elite group of aviators among the other FAB military personnel and, therefore, have an overloaded agenda of commitments and missions inherent to such a function.

While the possible characterization of the practice of physical activity carried out as a routine by each subject in the sample could provide further clarification about the results, it was not the object of study of this research.

Future studies should consider these issues and the possibility of reassessing these groups in situations at the beginning, middle, and end of a military career, such as for combat pilots, with the possibility of bringing up additional information for analysis.

6 CONCLUSION

We observed a slight increase in lung function in transport and fighter pilots compared with the control group. For this analysis, no changes indicative of abnormalities or obstructive and restrictive disorders were observed.

Concerning the period of exposure in flight, we noticed a slight increase in lung function as exposure progressed, with possible initial damage to the small airways. However, the parameters continued within normal limits.

Exposure to work at high altitudes over the long term seems to have more harmful effects on the respiratory system than the presence of G overload.

This study highlights the need to better understand chronic lung changes in combat pilots since there are no reports in the literature on such aspects. Indeed, better elucidation of gaps in the respective knowledge may provide strategies for improving human performance and the man-machine relationship.

As a future perspective, we present the research proposal on exposure to flying, analyzing the aviator from school to the most advanced levels of training. This strategy could provide relevant data for understanding long-term lung behavior and complement the results described in this research.

ACKNOWLEDGMENTS

We appreciate the support of the volunteer pilots and their commanders, who spared no effort for the proper development of this research.

AUTHORSHIP AND COLLABORATIONS

All authors participated equally in elaborating the article.

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