



The effect of smoking on lung function changes during a 16-week combined exercise program in middle-aged workers: a latent growth curve analysis

Fernanda M. Silva^{1,2} · José P. Ferreira¹ · Ana M. Teixeira¹ · Diogo Monteiro^{3,4} · Pedro Duarte-Mendes^{5,6}

Received: 13 February 2025 / Accepted: 8 May 2025

© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2025

Abstract

Purpose To investigate the longitudinal changes in lung function of sedentary middle-aged workers over a 16-week combined exercise training program.

Methods Thirty-six sedentary workers (53.70 ± 6.92 years old) were randomly allocated to either a combined aerobic and resistance training program ($n = 18$) or a control group ($n = 18$). Lung function was evaluated through spirometry using a portable flow spirometer (Spiropalm 6MWT, Cosmed, Italy). Predicted percentages of forced vital capacity (FVC), forced expiratory volume in the first second (FEV_1), FEV_1/FVC ratio, and mean forced expiratory flow between 25 and 75% of exhaled FVC (FEF_{25-75}) were analyzed. Assessments were performed at baseline (M1), after 8-week (M2) and 16-week follow-up (M3). The changes in lung function were analyzed using the Latent Growth Curve Modeling that estimated inter-individual and intraindividual growth paths.

Results Smoking status revealed a significant effect on lung function growth with significant paths to intercept and slope for all models in both groups. The exercise group participants who are non-smokers revealed higher increases in FVC% ($\beta = .22$), $FEV_1\%$ ($\beta = .08$), $FEV_1/FVC\%$ ratio ($\beta = .19$), and $FEF_{25-75}\%$ ($\beta = .06$) compared to those who are smokers from M1 to M3. The control group revealed a lower growth in lung function from M1 to M3, with a lower slope observed in smokers compared to non-smokers for FVC% ($\beta = -.44$), $FEV_1\%$ ($\beta = -.41$), $FEV_1/FVC\%$ ($\beta = -.98$), and $FEF_{25-75}\%$ ($\beta = -.52$).

Conclusion Our findings suggest that a 16-week combined training program is an effective strategy to improve lung function among sedentary workers, with a higher magnitude of improvement for non-smokers compared to smokers.

Trial registration Clinicaltrials.gov, NCT04868240. Registered April 30, 2021.

Keywords Spirometry · Exercise training · Smoking · Aging · Health promotion

Communicated by I. Mark Olfert.

✉ Fernanda M. Silva
geral.fernandasilva@gmail.com

- ¹ University of Coimbra, CIPER, Faculty of Sport Sciences and Physical Education, Coimbra, Portugal
- ² School of Education and Communication, University of Algarve, Faro, Portugal
- ³ ESECS—Polytechnic University of Leiria, Leiria, Portugal
- ⁴ Research Center in Sport Sciences, Health Sciences and Human Development (CIDESD), Vila Real, Portugal
- ⁵ Department of Sports and Well-Being, Polytechnic University of Castelo Branco, Castelo Branco, Portugal
- ⁶ Sport Physical Activity and Health Research & Innovation Center (SPRINT), Santarém, Portugal

Introduction

Poor lung function, characterized by reduced forced vital capacity (FVC) and forced expiratory volume in the first second (FEV_1), is associated with several major health issues, such as chronic lung disease prevalence (i.e., asthma and chronic obstructive pulmonary disease [COPD]) (Buist et al. 2007), lung cancer (Mannino et al. 2003), cardiovascular diseases (Silvestre et al. 2018), and predicts all-cause mortality (Sarycheva et al. 2022). Endogenous factors including age, sex, body size, and early life exposures are known to be the main determinants of lung capacity (Benadjaoud et al. 2019; Bui et al. 2018). According to previous evidence, above the age of 25 years, FEV_1 typically declines in healthy non-smokers by 30 mL per year (Oelsner et al. 2020). Chronic cigarette smoking is clearly a major cause

of accelerated airway obstruction (Postma et al. 2015), with smokers presenting a significantly steeper decline in lung function across adulthood compared to non-smokers (Oelsner et al. 2020). However, other modifying risk factors may influence the lung function decline. Previous cross-sectional analysis showed that sedentary behavior is inversely associated with FEV₁ and FVC both in current and never smokers, representing an important threat to respiratory health (Benadjaoud et al. 2019; Dogra et al. 2018).

In contrast, physical activity (PA) might positively modulate the immune system and can be a protective factor in lung function decline (Dogra et al. 2018; O'Donovan and Hamer 2018). The longitudinal results from the "Canadian Longitudinal Study on Aging" demonstrate that self-reported PA was associated with higher FVC and FEV₁, regardless of smoking status in adults without respiratory diseases (Dogra et al. 2018). Likewise, "The English Longitudinal Study of Aging" demonstrated that healthy community-dwelling adults who remained physically active or became active, maintained, or improved their lung capacity (O'Donovan and Hamer 2018). Importantly, studies suggest that the association between lung function and PA might depend on smoking history (Benadjaoud et al. 2019; Luzak et al. 2017). Despite this observational evidence, experimental research on the effects of a supervised exercise intervention on the lung function of middle-aged adults without respiratory diseases and their relationship with smoking status is scarce and remains unclear. A study (Tartibian et al. 2023) observed that a 6-week home-based combined aerobic and resistance exercise program was effective in improving FVC, FEV₁, FEV₁/FVC ratio, and the mean forced expiratory flow between 25 and 75% of exhaled FVC (FEF₂₅₋₇₅) parameters compared to the control group. According to the authors, the exercise protocol strengthened the endurance of respiratory muscles, particularly the diaphragm, and averted respiratory muscle fatigue. In turn, Silva-Reis et al. (2022) observed that a 12-week combined training program increased FVC% and peak expiratory flow but not FEV₁% and FEV₁/FVC% ratio in obese patients. Similarly, Nikniaz et al. (2021) verified that a 4-week aerobic program was effective in increasing FEV₁ and FVC but not the FEV₁/FVC ratio among sedentary male smokers. According to the authors, regular exercise might prevent lung function decline by reducing inflammatory markers and oxidative stress, and by strengthening respiratory muscles. However, these studies only included non-smokers (Silva-Reis et al. 2022; Tartibian et al. 2023) or smokers individuals (Nikniaz et al. 2021), which did not allow them to examine the role of smoking status as a predictor of lung function growth.

The methodological approaches used in lung function research to evaluate the changes over time in the context of exercise intervention are commonly based on mean difference-based approaches (Nikniaz et al. 2021; Silva-Reis et al.

2022; Tartibian et al. 2023). These approaches are useful for evaluating average change over time but are limited in the types of questions that can be answered (Herle et al. 2020). Public health investigations would benefit from individual-difference-based approaches that capture important group statistics while also capturing individual variations in continuous trajectories over time (Herle et al. 2020). The latent growth curve modeling (LGCM) is a structural equation modeling technique for longitudinal data that can help track the interindividual and intraindividual growth trajectories over time (Byrne 2016). Such models have been recently used in health sciences research for the evaluation of longitudinal changes in different health markers (Lucas et al. 2023). To our knowledge, this is the first study to investigate the interindividual and intraindividual variability growth trajectories in lung function over an exercise intervention. Thus, we aimed to evaluate the longitudinal changes in lung function (i.e., FEV₁, FVC, FEV₁/FVC ratio, and FEF₂₅₋₇₅) of sedentary middle-aged workers over 16 weeks of combined exercise training.

Methods

Study design, participants, and intervention

This study was designed as a single-blinded, parallel-group, randomized controlled trial. Eligible participants were randomized to control or exercise groups with a 1:1 ratio allocation, as per a computer random number generator. This study was approved by the Ethical Committee for Health, University of Coimbra (CE/FCDEF-UC/00512019) and was performed in accordance with the Declaration of Helsinki. The protocol of this study was previously registered at Clinicaltrials.gov (NCT04868240). Details regarding randomization/allocation, and intervention procedures are reported elsewhere (Ferreira et al. 2022). Eligible participants were adults aged 40 to 64 years old with sedentary occupations/jobs. Exclusion criteria were uncontrolled or abnormal blood pressure (i.e., systolic ≥ 140 mmHg or diastolic ≥ 90 mmHg) (Williams et al. 2018); diagnosis of major chronic diseases like cancer, metabolic or cardiovascular diseases as well as cognitive or mental disorders; history of myocardial infarction and heart failure; performing exercise 6-month before the beginning of the study and; an FEV₁/FVC ratio < 0.7 (airflow limitation) (Ferreira et al. 2022). Non-smokers and current smokers' individuals were included in this trial. Forty-six eligible sedentary workers were included in baseline screening and were posteriorly randomized. However, only 36 participants (age: 53.70 ± 6.92 years old; body mass index: 27.24 ± 3.92 kg/m²) of both sexes completed the study procedures ($n = 18$ in each group) (Fig. 1). All participants provided written informed consent before

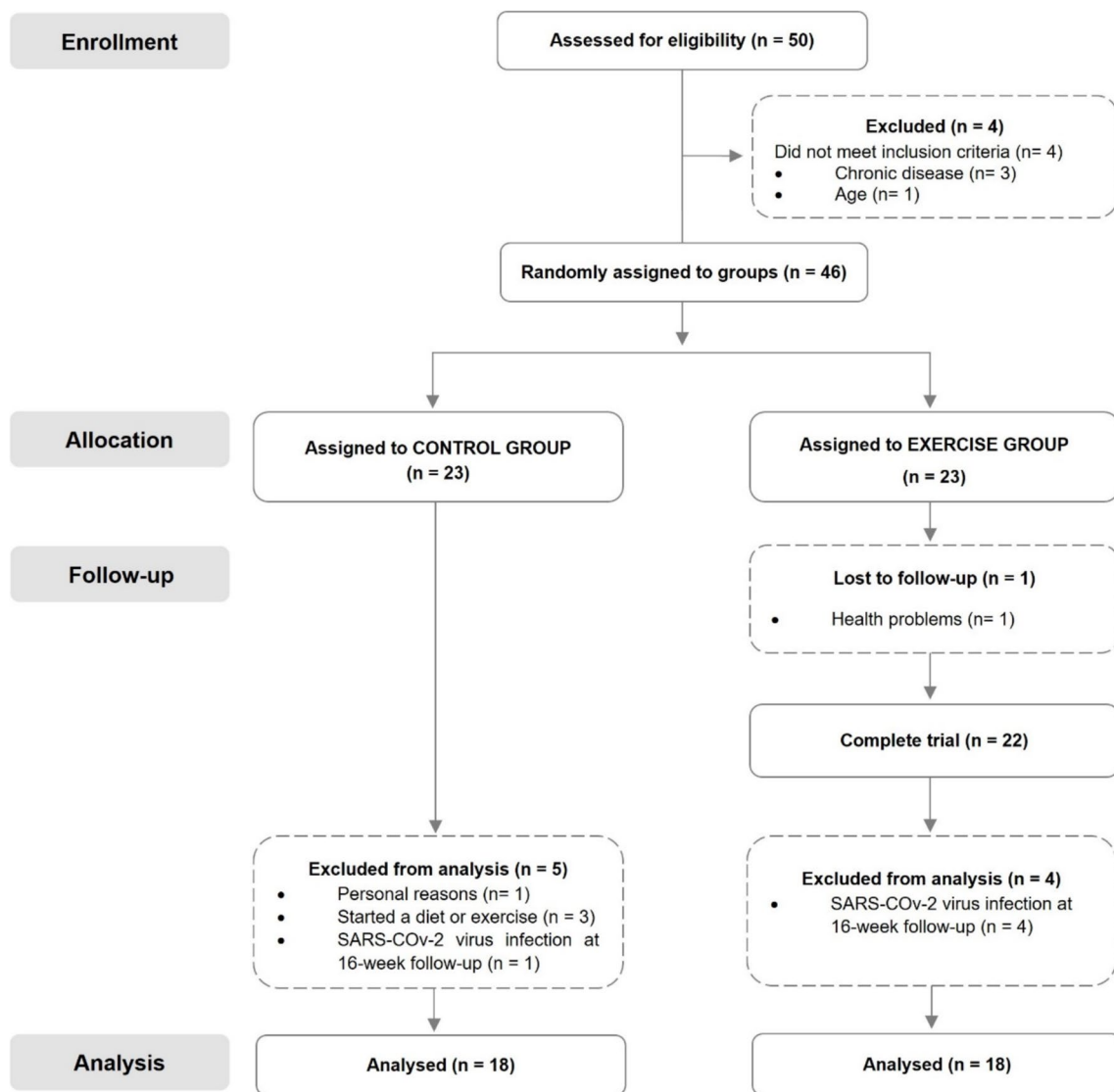


Fig. 1 Flowchart of participant enrolment, randomization and allocation, and analysis

participation. Participants were instructed to maintain their dietary patterns and PA levels (outside the intervention).

The intervention was a 16-week, 3 times per week (~75 min/session), fully supervised, combined resistance and aerobic training. Combined training consisted of a 10-min warm-up, 60-min resistance followed by aerobic exercise, and 5-min active recovery. Resistance training consisted of eight exercises (involving the use of body weight and free weights), which took approximately 30 min to complete. Each exercise with external load was performed using 1–2 sets of 6–15 reps at 45–90% 1-repetition maximum (1RM) and 5–8 rate of perceived exertion (RPE) on the Borg CR-10 Scale, following a gradual progression in intensity through the weeks. The aerobic training also took 30 min to complete and involved different forms of aerobic exercise, including brisk walking, running, stepping, and circuit training. The

intensity was set at 60–95% of their maximum heart rate and 5–8 RPE on the Borg-10 scale, following a gradual progression through the weeks. The training sessions were supervised by two sport sciences professionals. The control group did not receive any intervention.

Assessment of lung function

Lung function was assessed using a portable flow spirometer (Spiropalm 6MWT, Cosmed, Italy), in accordance with recommendations of the American Thoracic Society and European Respiratory Society statements (ATS/ERS 2022; Miller et al. 2005). The maximal inspiratory and expiratory maneuver was performed to obtain the following spirometric parameters: FVC, FEV₁, FEV₁/FVC % ratio, and FEF_{25–75}. Both the flow-volume and volume-time curves

were monitored during the test by an expert. Likewise, after each test, the curves were visually inspected and assessed for reliability and acceptability. Participants were instructed to perform at least 3 and up to 8 spirometric maneuvers per test to obtain acceptable and reproducible values. Acceptability criteria included curves without any artifacts (i.e., cough during the first second of exhalation, glottis closure, early termination, obstructed mouthpiece, or leak), having a good start with extrapolated volume $< 0.5\%$ of FVC or 0.15 L, and exhalation of ≥ 6 s or a plateau in the volume-time curve (Miller et al. 2005). The best two measurements had to fulfill the reproducibility criteria, i.e., the difference between the two largest values of FVC and FEV₁ had to be within 0.150 L of each other (Miller et al. 2005). Predicted values for each spirometric parameter were calculated based on age, stature, ethnicity, and sex through previous equations developed by the Global Lung Function Initiative (GLI) (Quanjer et al. 2012). The Cosmed Omnia Cardiopulmonary Diagnostic software (Cosmed, Italy, version 1.6.5) was used for analysis. Smoking status was self-reported as “smoker” and “non-smoker” at each spirometry examination. The assessments occurred in the morning in controlled conditions and were performed by an experienced clinical physiologist blinded to the protocol. The lung function was assessed in three time points: baseline (M1), after 8 weeks (M2), and 16 weeks follow-up (M3).

Statistical analysis

LGCM was used to analyze the interindividual and intraindividual variations in lung function across the 16-week intervention. This analysis simultaneously estimates intraindividual (intercept and slope growth parameters) and interindividual (differences between subjects) growth trajectories (Byrne 2016; Ribeiro et al. 2022). Intercept and slope are two inferred latent variables (Byrne 2016). The intercept parameter represents a participant’s value/score on the outcome variable at baseline (corresponding to M1 in the model) (Byrne 2016). The slope expresses the participant’s rate of change over the time period of interest. The significance of variance for intercept and slope expresses the interindividual variability at M1, and the existence of interindividual lung function differences between the observed moments, respectively (Byrne 2016). Moreover, the covariance between intercept and slope reveals a relationship between M1 and the level of growth for M2 and M3. Regarding interpretation, a negative value indicates that (high) initial values promoted low growth, whereas a positive value indicates that (high) initial values promoted high growth between the observed moments (Byrne 2016; Ribeiro et al. 2022). A dummy variable (smoking status) was considered in the models as a predictor of growth to create the following groups: (i) “non-smoker” group and (ii) “current

smoker” group. The normalized chi-square/degrees of freedom (χ^2/df) were used to verify the model’s adequacy and was interpreted as: $5 < \chi^2/df$ (poor adjustment); $2 < \chi^2/df \leq 5$ (reasonable adjustment); $1 < \chi^2/df \leq 2$ (good adjustment); and χ^2/df approximately 1 (very good adjustment) (Byrne 2016; Wheaton 1987). In addition, a multigroup analysis was carried out to determine how important smoking status was to the model (Byrne 2016). Thus, two models were generated: (a) model with smoking status effect and (b) model without smoking status effect. The differences between the models were analysed via $\Delta\chi^2$, $P > 0.05$. Statistical analysis was performed on IBM SPSS AMOS (version 20.0).

Results

Descriptive statistics

Thirty-six participants successfully completed the study with 18 participants in each group. Descriptive statistics for the considered variables are listed in Table 1. Smoking status did not change over the intervention in either group. In general, the control group participants tended to decrease their lung function parameters from M1 to M3, whereas the exercise group increased.

LGCM results for the control group

The results of goodness-of-fit statistics in the control group for all the models with smoking status effect can be found in Table 2. The model without the smoking effect is better than the model with the smoking effect. The analysis of the proposed models revealed a reasonable adjustment for FEF_{25–75%} and an excellent adjustment for the other variables under analysis.

The variance of intercept and slope growth parameters was significant for all variables analyzed, suggesting a heterogeneous growth rate of lung function and, accordingly, an interindividual and intraindividual variation from M1 to M2 and M3. The intercept variance at M1 revealed significant values for FVC% ($\beta = 0.98$, $P < 0.05$), FEV₁% ($\beta = 0.97$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = 0.96$, $P < 0.05$), and FEF_{25–75%} ($\beta = 0.94$, $P < 0.05$), suggesting interindividual variability on the lung function in M1. Moreover, the standardized indirect effects between smoking status and dependent variables through intercept and slope showed the following effects: FVC% (M1 = -0.27 ; M2 = -0.33 ; M3 = -0.36), FEV₁% (M1 = -0.42 ; M2 = -0.42 ; M3 = -0.36), FEV₁/FVC% ratio (M1 = -0.39 , M2 = -0.44 , M3 = -0.30), and FEF_{25–75%} (M1 = -0.28 , M2 = -0.32 , M3 = -0.30) (all $P < 0.05$). A non-linear tendency to increase FVC% (24%) and FEV₁% (23%) was observed from M1 to M2. In contrast, from M1 to M2, FEV₁/FVC% ratio and FEF_{25–75%} decreased

Table 1 Descriptive statistics for the considered variables

Variable	M1		M2		M3	
	Control group	Exercise group	Control group	Exercise group	Control group	Exercise group
<i>Smoking status</i>						
Current smoker, n (%)	7 (38.9)	9 (50.0)	7 (38.9)	9 (50.0)	7 (38.9)	9 (50.0)
Non-smoker, n (%)	11 (61.1)	9 (50.0)	11 (61.1)	9 (50.0)	11 (61.1)	9 (50.0)
<i>Lung function</i>						
FVC (%pred.)	106.56 ± 12.59	101.67 ± 10.07	106.56 ± 15.50	104.11 ± 9.47	105.94 ± 16.06	103.33 ± 9.19
FEV ₁ (% pred.)	109.44 ± 14.00	101.50 ± 13.13	110.22 ± 17.61	104.61 ± 13.34	108.33 ± 16.97	103.56 ± 13.12
FEV ₁ /FVC ratio (%pred.)	102.28 ± 5.49	99.39 ± 5.65	102.89 ± 5.29	99.72 ± 7.54	101.78 ± 5.01	99.67 ± 8.50
FEF ₂₅₋₇₅ (% pred.)	119.94 ± 27.20	101.83 ± 29.97	121.44 ± 30.54	108.94 ± 35.75	116.61 ± 27.47	106.50 ± 31.62

Data expressed as unadjusted mean ± SD

FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s; FEF₂₅₋₇₅ forced expiratory flow between 25 and 75% of FVC; %, predicted percentage

Table 2 Multigroup analysis across models analysed—control group

Models	$\Delta\chi^2$	df	<i>P</i>
FVC%	2.58	2	0.273
FEV ₁ %	3.40	2	0.183
FEV ₁ /FVC% ratio	4.96	2	0.082
FEF ₂₅₋₇₅ %	2.16	2	0.231

FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s; FEF₂₅₋₇₅ forced expiratory flow between 25 and 75% of FVC; %, predicted percentage; df, degrees of freedom; χ^2 , chi-square; *P*, significance value

by 6% and 12%, respectively (Fig. 2). However, these trajectories were not significant.

To better understand the levels of variability between control group participants' lung function in M1 and between moments (M2 and M3), smoking status was included in the model as a predictor of growth. Smoking status revealed a significant effect on lung function growth with significant paths to intercept and slope for all models (Fig. 2). The control group participants who are smokers revealed lower initial values (M1) of FVC% ($\beta = -0.28$, $P < 0.05$), FEV₁% ($\beta = -0.42$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = -0.40$, $P < 0.05$), and FEF₂₅₋₇₅% ($\beta = -0.36$, $P < 0.05$) than non-smokers. Also, the control group participants who are smokers had lower growth in FVC% ($\beta = -0.44$, $P < 0.05$), FEV₁% ($\beta = -0.41$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = -0.98$, $P < 0.05$), and FEF₂₅₋₇₅% ($\beta = -0.52$, $P < 0.05$) than non-smokers from M1 to M3.

LGCM results for the exercise group

The results of goodness-of-fit statistics in the exercise group for all the models with the smoking status effect can be found in Table 3. Also, for this group, the model without the smoking effect was better than the model with the smoking

effect. The analysis of the proposed models revealed a reasonable adjustment for FEV₁%, and an excellent adjustment for the other variables.

The variance of intercept and slope growth parameters was statistically significant for all variables under analysis in the exercise group, suggesting a heterogeneous growth rate of lung function and, accordingly, an interindividual and intraindividual variation from M1 to M2 and M3. The intercept variance at M1 revealed significant values for FVC% ($\beta = 0.93$, $P < 0.05$), FEV₁% ($\beta = 0.96$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = 0.91$, $P < 0.05$), and FEF₂₅₋₇₅% ($\beta = 0.92$, $P < 0.05$), suggesting interindividual variability on the lung function in M1. The standardized indirect effects between smoking status and dependent variables through intercept and slope showed the following significant effects: FVC% (M1 = 0.57, M2 = 0.62, M3 = 0.64), FEV₁% (M1 = 0.47, M2 = 0.50, M3 = 0.49), FEV₁/FVC% ratio (M1 = -0.03, M2 = 0.06, M3 = 0.13), and FEF₂₅₋₇₅% (M1 = 0.23, M2 = 0.22, M3 = 0.22) (all $P < 0.05$). A non-linear increase was observed for all variables; from M1 to M2, FVC% increase in the exercise group participants by 56%; FEV₁% increased by 36%; FEV₁/FVC% ratio increased by 44%, and FEF₂₅₋₇₅% increased by 66% (Fig. 3).

When smoking status was included in the model as a predictor of growth, we observed a significant effect on lung function growth with significant paths to intercept and slope for all models (Fig. 3). The non-smoking participants of the exercise group revealed higher initial values (M1) of FVC% ($\beta = 0.65$, $P < 0.05$), FEV₁% ($\beta = 0.48$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = 0.06$, $P < 0.05$), and FEF₂₅₋₇₅% ($\beta = 0.24$, $P < 0.05$) than smoker participants. Also, the non-smoking participants that presented higher initial values, revealed a higher increase in FVC% ($\beta = 0.22$, $P < 0.05$), FEV₁% ($\beta = 0.08$, $P < 0.05$), FEV₁/FVC% ratio ($\beta = 0.19$, $P < 0.05$), and FEF₂₅₋₇₅% ($\beta = 0.06$, $P < 0.05$) than smoker participants from M1 to M3.

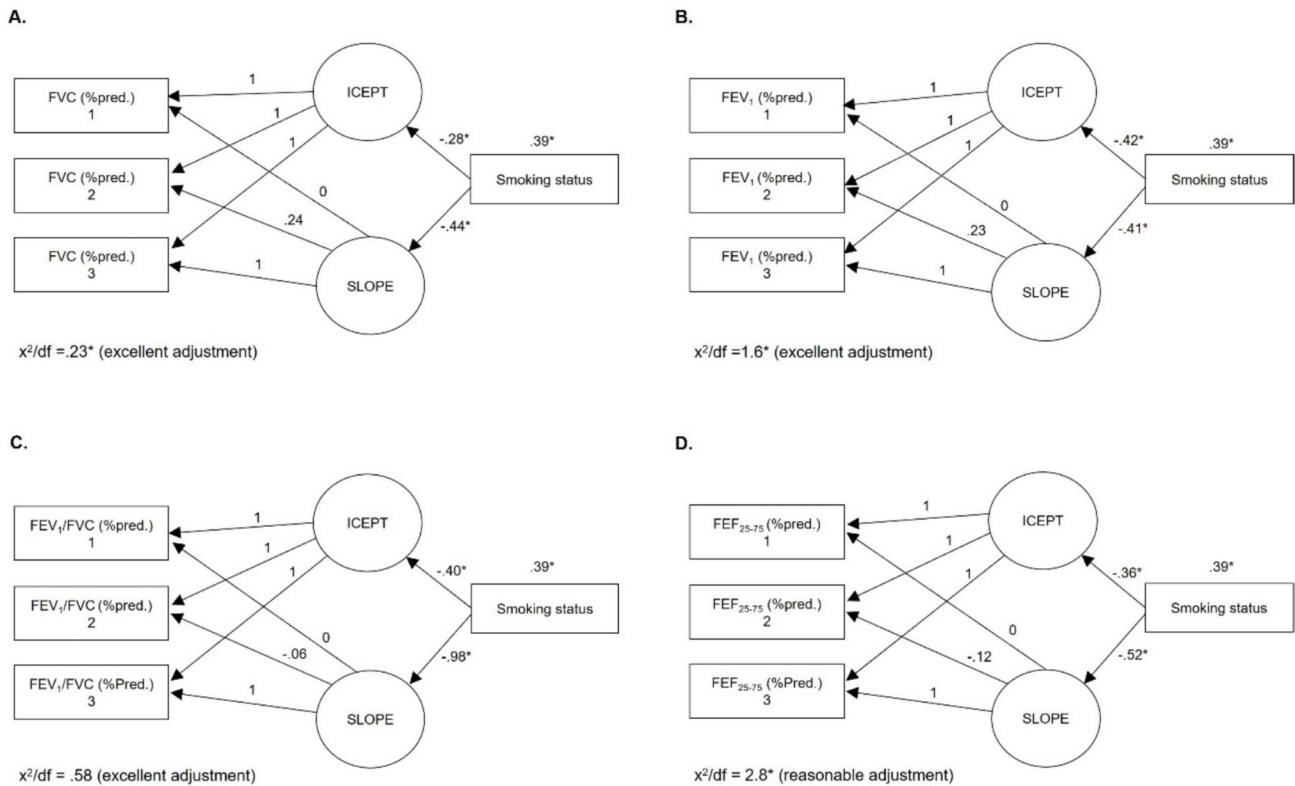


Fig. 2 Latent growth curve models for the considered variables in the control group. **A** FVC (%Pred.), **B** FEV₁ (%pred.), **C** FEV₁/FVC ratio (%pred.), and **D** FEF₂₅₋₇₅ (%pred.). Abbreviations: FVC, forced

vital capacity; FEV₁, forced expiratory volume in 1 s; FEF₂₅₋₇₅ forced expiratory flow between 25 and 75% of FVC. **P* < 0.05

Table 3 Multigroup analysis across models analysed—exercise group

Models	$\Delta\chi^2$	df	<i>P</i>
FVC%	0.323	2	0.433
FEV ₁ %	5.05	2	0.08
FEV ₁ /FVC% ratio	0.501	2	0.778
FEF ₂₅₋₇₅ %	1.09	2	0.581

FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s; FEF₂₅₋₇₅, forced expiratory flow between 25 and 75% of FVC; %, predicted percentage; df, degrees of freedom; χ^2 , chi-square; *P*, significance value

Discussion

The present study attempted to evaluate the longitudinal changes in lung function of middle-aged workers over a 16-week combined training program. Our results revealed a significant increase in spirometric indices by the experimental group over the combined training. In addition, when we considered smoking status in the model as a predictor of growth, we observed that non-smoking exercise group participants revealed higher initial values and a higher increase from M1 to M3 in all spirometric

parameters in comparison with their smoker counterparts. Our multigroup analysis supports these results, demonstrating that the model without smoking effect is better than the model with smoking effect.

Our findings are in line with previous studies demonstrating the beneficial effects of an exercise program on the lung function of adults. A quasi-experimental study (Tartibian et al. 2023) observed that a 6-week home-based combined exercise was effective in improving FVC, FEV₁, FEV₁/FVC ratio, and FEF₂₅₋₇₅ compared to the control group. According to the authors, it is plausible that the exercise protocol strengthened the endurance of respiratory muscles, particularly the diaphragm, and averted respiratory muscle fatigue (Tartibian et al. 2023). The results from Silva-Reis et al. (2022) were partially in agreement since observed that a 12-week combined training increased FVC% and peak expiratory flow but not FEV₁% and FEV₁/FVC% in obese patients. Also, Nikniaz et al. (2021) verified that a 4-week aerobic program was effective in increasing FEV₁ and FVC but not FEV₁/FVC ratio among sedentary adults. However, these studies included only non-smokers (Silva-Reis et al. 2022; Tartibian et al. 2023) or smokers (Nikniaz et al. 2021), which did not allow them to verify if the response to the exercise program differs according to the smoking status.

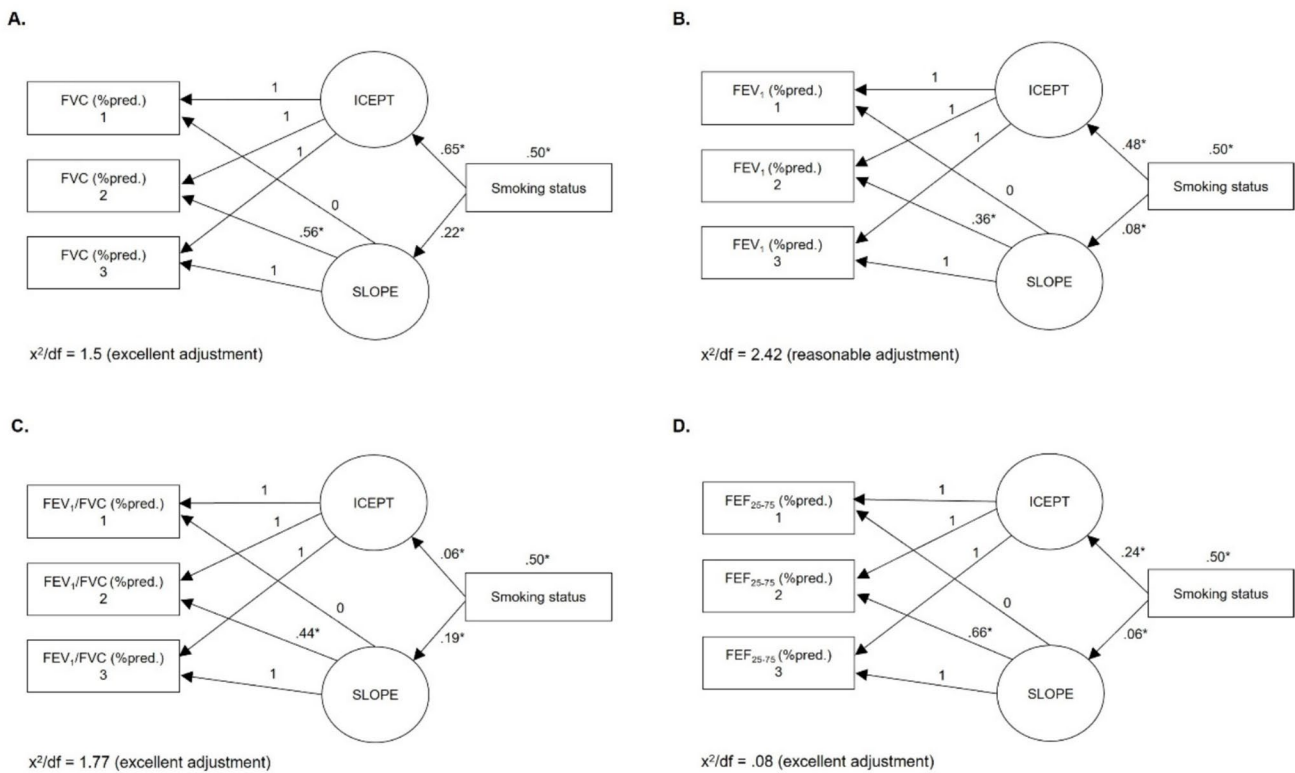


Fig. 3 Latent growth curve models for the considered variables in the exercise group. **A** FVC (%Pred.), **B** FEV₁ (%pred.), **C** FEV₁/FVC ratio (%pred.), and **D** FEF₂₅₋₇₅ (%pred.). Abbreviations: FVC, forced

vital capacity; FEV₁, forced expiratory volume in 1 s; FEF₂₅₋₇₅ forced expiratory flow between 25 and 75% of FVC. * $P < 0.05$

In the present study, the non-smokers of the exercise group revealed higher initial levels of lung function compared to smokers. This initial finding was expected since smoking accelerates the age-related lung function decline, which may lead to air-flow obstruction (FEV₁/FVC < 0.7) and consequent diagnosis of COPD (Oelsner et al. 2020). Cigarette smoke contains many harmful substances that can cause a series of pulmonary and systemic immunological changes (Oelsner et al. 2020). It accelerates lung function decline through various mechanisms including increased inflammation (Shiels et al. 2014), mucous hypersecretion (Vestbo et al. 1996), emphysema (Oelsner et al. 2018), epigenetic alterations and airway hyper-responsiveness (Wang et al. 2015).

The non-smokers of the exercise group also revealed a higher growth over intervention in all spirometric indices compared to smokers. We did not find any clinical trial that has compared the lung function changes over an exercise intervention between smokers and non-smokers, however, our results seem to be consistent with observational results obtained by Hashizume et al. (1999) who found that smokers teenagers obtain less benefits from training than non-smokers. Cheng et al. (2003) also observed that being physically active and not being a recent smoker

was associated with better lung function in both healthy men and women. Other studies found that positive associations between moderate-to-vigorous PA and FEV₁ and FVC were more evident in current or ex-smokers compared to non-smokers, suggesting a higher benefit of PA for subjects being at higher risk for chronic lung diseases (Benadjaoud et al. 2019; Luzak et al. 2017). Nonetheless, although with a lower magnitude of improvement, this increase by the smokers during the combined training program is of important clinical relevance since these subjects are at a higher risk for chronic lung diseases (Postma et al. 2015) and are more predisposed to acute lung injury and pulmonary infection (Lugg et al. 2022). Another previous population-based study also suggested that PA reduces lung function decline and the risk of COPD among active smokers (Garcia-Aymerich et al. 2007). The mechanisms responsible for exercise-related benefits on lung function are not well established, however, previous studies hypothesized that this link can be mediated by lowering systemic inflammation (Garcia-Aymerich et al. 2007; Nikniaz et al. 2021). According to an earlier review (Gleeson et al. 2011), the potential anti-inflammatory effects of exercise are mediated by the reduction in adipokine release and the induction of an anti-inflammatory environment.

Regarding the control group, it was observed a non-linear tendency to increase FVC% and FEV₁% and to decrease FEV₁/FVC% ratio and FEF_{25–75}% from M1 to M2. Further, we observed that the smokers of the control group revealed a lower growth in all the spirometric parameters, compared to non-smokers over the 16 weeks. This decrease in FEV₁/FVC% ratio could be potentially explained by a lower FEV₁ value relative to FVC, even within normal ranges (Stanojevic et al. 2022). In clinical practice, an FEV₁/FVC ratio below the LLN (i.e., 5th percentile) of a normal population or an FEV₁/FVC of <0.7 (Stanojevic et al. 2022), could reflect an obstructive ventilatory impairment. In addition, FEF_{25–75}% usually does not add clinical decision-making beyond the information contributed by FVC, FEV₁, and FEV₁/FVC ratio (Stanojevic et al. 2022), however, a reduction in this parameter over time may indicate the impairment of medium-sized and small airways (Hoesterey et al. 2019). The attenuated slope in the spirometric indices was expected for the control group that maintained their sedentary lifestyle. Sedentary time and low PA levels were inversely associated with FEV₁ and FVC in midlife and early old age (Benadjaoud et al. 2019; Dogra et al. 2018). Dogra et al. (2018) suggested that sitting for prolonged periods causes physiological changes that accelerate the age-associated decline in lung function, increasing the risk of developing respiratory diseases. Benadjaoud et al. (2019) found that this association seems to be more evident among smokers compared to non-smokers which is, in part, congruent with our findings. Sedentary time has been positively associated with systemic inflammation and macrophage infiltration (Vandercappellen et al. 2022), which is also connected to respiratory diseases (Shiels et al. 2014). Therefore, inflammation may also mediate the relationship between sedentary time and lung function (Dogra et al. 2018).

This study has some limitations that warrant discussion. First, smoking status was classified by self-report, which could represent reporting bias. Second, we did not consider participants' body weight, body mass index, or sex in our analysis. Third, given the nature of our experimental data, we consider that a larger sample size and more repeated measurements would provide more robust conclusions; yet our sample size and the number of time points are equivalent to previous studies that used LGCM (Martinho et al. 2024; Ribeiro et al. 2022). Moreover, the strict exclusion criteria may limit the generalizability of the findings to the broader middle-aged population. Future studies should make additional efforts to include more participants and more time assessment points, to confirm the changes in lung function in response to an exercise program. Further, studies should consider the smoking status effect and other relevant factors (i.e., body weight and sex) in the model. Further analysis exploring the mechanisms by which exercise can influence lung function would facilitate the development of new

strategies and therapeutic approaches for preventing lung function deterioration and its related complications.

Conclusions

A 16-week combined exercise program seems to be effective in improving lung function in middle-aged workers. Of relevance, smoking status revealed a significant effect on spirometric indices growth. In the exercise group, the non-smoking participants had a higher increase in spirometric indices, compared to those who are smokers. In the control group, a lower growth in spirometric indices over the 16 weeks was observed; also in this group, non-smokers presented higher spirometric values than smokers.

Practical applications

Our findings can provide valuable references for exercise prescription in this population. Professionals of sports sciences who are informed about variations in adults' lung function during an exercise program are better prepared to delineate the intensity and volume of an exercise program that mitigates the age-associated decline in lung function both in smokers and non-smokers. Future clinical and even therapeutic decisions based on exercise may benefit from the results derived from this study.

Acknowledgements The authors are grateful to all the participants for their time and effort. They would like to thank the Research Unit for Sport and Physical Activity (CIDAF, <https://doi.org/10.54499/UIDP/04213/2020>) for their support. Fernanda M. Silva was a grant holder from the Portuguese Foundation for Science and Technology (<https://doi.org/10.54499/2020.08759.BD>). The funder had no role in the development and preparation of the manuscript.

Author contributions PD-M, AMT, JPF and FMS conceptualized and designed the research. FMS and PDM conducted the research. DM analyzed the data. FMS drafted the manuscript. DM, PD-M, JPF, and AT critically reviewed the results and provided input during critical revisions. The corresponding author attests that all listed authors meet authorship criteria. All authors read and approved the final version.

Data availability The datasets used/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors declare that they have no competing interests.

References

- American Thoracic Society/European Respiratory Society (2022) ATS/ERS statement on respiratory muscle testing. *Am J Respir Crit Care Med* 166:518–624

- Benadjaoud MA, Menai M, van Hees VT et al (2019) The association between accelerometer-assessed physical activity and respiratory function in older adults differs between smokers and non-smokers. *Sci Rep* 9:10270. <https://doi.org/10.1038/s41598-019-46771-y>
- Bui D, Lodge CJ, Burgess JA et al (2018) Childhood predictors of lung function trajectories and future COPD risk: a prospective cohort study from the first to the sixth decade of life. *Lancet Respir Med* 6:535–544. [https://doi.org/10.1016/S2213-2600\(18\)30100-0](https://doi.org/10.1016/S2213-2600(18)30100-0)
- Buist AS, McBurnie MA, Vollmer WM et al (2007) International variation in the prevalence of COPD (the BOLD Study): a population-based prevalence study. *Lancet* 370:741–750. [https://doi.org/10.1016/S0140-6736\(07\)61377-4](https://doi.org/10.1016/S0140-6736(07)61377-4)
- Byrne BM (2016) Structural equation modeling with AMOS: basic concepts, applications, and programming. Routledge, New York
- Cheng YJ, Macera CA, Addy CL et al (2003) Effects of physical activity on exercise tests and respiratory function. *Br J Sports Med* 37:521–528. <https://doi.org/10.1136/bjism.37.6.521>
- Dogra S, Good J, Buman MP et al (2018) Movement behaviours are associated with lung function in middle-aged and older adults: a cross-sectional analysis of the Canadian longitudinal study on aging. *BMC Public Health* 18:818. <https://doi.org/10.1186/s12889-018-5739-4>
- Ferreira JP, Duarte-Mendes P, Teixeira AM, Silva FM (2022) Effects of combined training on metabolic profile, lung function, stress and quality of life in sedentary adults: a study protocol for a randomized controlled trial. *PLoS ONE* 17:e0263455. <https://doi.org/10.1371/journal.pone.0263455>
- Garcia-Aymerich J, Lange P, Benet M, Schnohr P, Antó JM (2007) Regular physical activity modifies smoking-related lung function decline and reduces risk of chronic obstructive pulmonary disease: a population-based cohort study. *Am J Respir Crit Care Med* 175:458–463. <https://doi.org/10.1164/rccm.200607-896OC>
- Gleeson M, Bishop NC, Stensel DJ et al (2011) The anti-inflammatory effects of exercise: mechanisms and implications for the prevention and treatment of disease. *Nat Rev Immunol* 11:607–615. <https://doi.org/10.1038/nri3041>
- Hashizume K, Kusaka Y, Kawahara K (1999) Effects of cigarette smoking on endurance performance levels of 16- to 19-year-old males. *Environ Health Prev Med* 4:75–80. <https://doi.org/10.1007/BF02931998>
- Herle M, Micali N, Abdulkadir M et al (2020) Identifying typical trajectories in longitudinal data: modelling strategies and interpretations. *Eur J Epidemiol* 35:205–222. <https://doi.org/10.1007/s10654-020-00615-6>
- Hoesterey D, Das N, Janssens W et al (2019) Spirometric indices of early airflow impairment in individuals at risk of developing COPD: spirometry beyond FEV₁/FVC. *Respir Med* 156:58–68. <https://doi.org/10.1016/j.rmed.2019.08.004>
- Lucas AR, Kim Y, Lanoye A et al (2023) Longitudinal associations among physical activity and sitting with endocrine symptoms and quality of life in breast cancer survivors: a latent growth curve analysis. *Cancer Med* 12:20094–20105. <https://doi.org/10.1002/cam4.6581>
- Lugg ST, Scott A, Parekh D, Naidu B, Thickett DR (2022) Cigarette smoke exposure and alveolar macrophages: mechanisms for lung disease. *Thorax* 77:94–101. <https://doi.org/10.1136/thoraxjnl-2020-216296>
- Luzak A, Karrasch S, Thorand B et al (2017) Association of physical activity with lung function in lung-healthy German adults: results from the KORA FF4 study. *BMC Pulm Med* 17:215. <https://doi.org/10.1186/s12890-017-0562-8>
- Mannino DM, Aguayo SM, Petty TL, Redd S (2003) Low lung function and incident lung cancer in the United States: data from the first national health and nutrition examination survey follow-up. *Arch Intern Med* 163:1475–1480. <https://doi.org/10.1001/archinte.163.12.1475>
- Martinho DV, Rebelo A, Field A et al (2024) The quantification of physical performance and internal training load in youth male soccer players during preseason. *Int J Sports Physiol Perform* 19:480–486. <https://doi.org/10.1123/ijsp.2023-0312>
- Miller MR, Hankinson J, Brusasco V et al (2005) Standardisation of spirometry. *Eur Respir J* 26:319–338. <https://doi.org/10.1183/09031936.05.00034805>
- Nikniaz L, Ghojzadeh M, Nateghian H et al (2021) The interaction effect of aerobic exercise and vitamin D supplementation on inflammatory factors, anti-inflammatory proteins, and lung function in male smokers: a randomized controlled trial. *BMC Sports Sci Med Rehabil* 13:102. <https://doi.org/10.1186/s13102-021-00333-w>
- O'Donovan G, Hamer M (2018) The association between leisure-time physical activity and lung function in older adults: the English Longitudinal Study of Ageing. *Prev Med* 106:145–149. <https://doi.org/10.1016/j.ypmed.2017.10.030>
- Oelsner EC, Smith BM, Hoffman EA et al (2018) Associations between emphysema-like lung on CT and incident airflow limitation: a general population-based cohort study. *Thorax* 73:486–488. <https://doi.org/10.1136/thoraxjnl-2017-210842>
- Oelsner EC, Balte PP, Bhatt SP et al (2020) Lung function decline in former smokers and low-intensity current smokers: a secondary data analysis of the NHLBI Pooled Cohorts Study. *Lancet Respir Med* 8:34–44. [https://doi.org/10.1016/S2213-2600\(19\)30276-0](https://doi.org/10.1016/S2213-2600(19)30276-0)
- Postma DS, Bush A, van den Berge M (2015) Risk factors and early origins of chronic obstructive pulmonary disease. *The Lancet* 385:899–909. [https://doi.org/10.1016/S0140-6736\(14\)60446-3](https://doi.org/10.1016/S0140-6736(14)60446-3)
- Quanjer PH, Stanojevic S, Cole TJ et al (2012) Multi-ethnic reference values for spirometry for the 3–95 year age range: the global lung function 2012 equations. *Eur Respir J* 40:1324–1343. <https://doi.org/10.1183/09031936.00080312>
- Ribeiro JN, Monteiro D, Gonçalves B et al (2022) Variation in physical performance of futsal players during congested fixtures. *Int J Sports Physiol Perform* 17:367–373. <https://doi.org/10.1123/ijsp.2020-0922>
- Sarycheva T, Capkova N, Pajak A et al (2022) Impaired lung function and mortality in Eastern Europe: results from multi-centre cohort study. *Respir Res* 23:140. <https://doi.org/10.1186/s12931-022-02057-y>
- Shiels MS, Katki HA, Freedman ND et al (2014) Cigarette smoking and variations in systemic immune and inflammation markers. *J Natl Cancer Inst* 106(11):dju294. <https://doi.org/10.1093/jnci/dju294>
- Silva-Reis A, Brandao-Rangel MAR, Moraes-Ferreira R et al (2022) Combined resistance and aerobic training improves lung function and mechanics and fibrotic biomarkers in overweight and obese women. *Front Physiol* 13:946402. <https://doi.org/10.3389/fphys.2022.946402>
- Silvestre OM, Nadruz W Jr, Roca GQ et al (2018) Declining lung function and cardiovascular risk: the ARIC study. *J Am Coll Cardiol* 72:1109–1122. <https://doi.org/10.1016/j.jacc.2018.06.049>
- Stanojevic S, Kaminsky DA, Miller MR et al (2022) ERS/ATS technical standard on interpretive strategies for routine lung function tests. *Eur Respir J* 60:2101499. <https://doi.org/10.1183/13993003.01499-2021>
- Tartibian B, Azadpour N, Eslami R, Khayat SMA (2023) Home-based exercise alters pulmonary function and cellular stress markers in overweight middle-aged men during covid-19 Home quarantine. *BMC Sports Sci Med Rehabil* 15:61. <https://doi.org/10.1186/s13102-023-00673-9>
- Vandercappellen EJ, Koster A, Savelberg HHCM et al (2022) Sedentary behaviour and physical activity are associated with biomarkers of endothelial dysfunction and low-grade inflammation-relevance for (pre)diabetes: the Maastricht Study. *Diabetologia* 65:777–789. <https://doi.org/10.1007/s00125-022-05651-3>

- Vestbo J, Prescott E, Lange P (1996) Association of chronic mucus hypersecretion with FEV₁ decline and chronic obstructive pulmonary disease morbidity. Copenhagen City Heart Study Group. *Am J Respir Crit Care Med* 153:1530–1535. <https://doi.org/10.1164/ajrccm.153.5.8630597>
- Wang G, Wang R, Strulovici-Barel Y et al (2015) Persistence of smoking-induced dysregulation of miRNA expression in the small airway epithelium despite smoking cessation. *PLoS ONE* 10:e0120824
- Wheaton B (1987) Assessment of fit in overidentified models with latent variables. *Sociol Methods Res* 16:118–154. <https://doi.org/10.1177/0049124187016001005>
- Williams B, Mancia G, Spiering W, Agabiti Rosei E, Azizi M, Burnier M, Clement DL, Coca A, de Simone G, Dominiczak A, Kahan T, Mahfoud F, Redon J, Ruilope L, Zanchetti A, Kerins M, Kjeldsen SE, Kreutz R, Laurent S, Lip GYH et al (2018) 2018 ESC/ESH Guidelines for the management of arterial hypertension. *Eur Heart J* 39(33):3021–3104. <https://doi.org/10.1093/eurheartj/ehy339>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.