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Determinants of Forced Expiratory Volume in 1 Second (FEV₁), Forced Vital Capacity (FVC), and FEV₁/FVC in Chronic Spinal Cord Injury

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Abstract

Objective—To assess factors that influence pulmonary function, because respiratory system dysfunction is common in chronic spinal cord injury (SCI).

Design—Cross-sectional cohort study.

Setting—Veterans Affairs Boston SCI service and the community.

Participants—Between 1994 and 2003, 339 white men with chronic SCI completed a respiratory questionnaire and underwent spirometry.

Interventions—Not applicable.

Main Outcome Measures—Forced expiratory volume in 1 second (FEV₁), forced vital capacity (FVC), and FEV₁/FVC.

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Results—Adjusting for SCI level and completeness, FEV₁ (−21.0mL/y; 95% confidence interval [CI], −26.3 to −15.7 mL/y) and FVC (−17.2mL/y; 95% CI, −23.7 to −10.8mL/y) declined with age. Lifetime cigarette use was also associated with a decrease in FEV₁ (−3.8mL/pack-year; 95% CI, −6.5 to −1.1mL/pack-year), and persistent wheeze and elevated body mass index were associated with a lower FEV₁/FVC. A greater maximal inspiratory pressure (MIP) was associated with a greater FEV₁ and FVC. FEV₁ significantly decreased with injury duration (−6.1mL/y; 95% CI, −11.7 to −0.6mL/y), with the greatest decrement in the most neurologically impaired. The most neurologically impaired also had a greater FEV₁/FVC, and their FEV₁ and FVC were less affected by age and smoking.

Conclusions—Smoking, persistent wheeze, obesity, and MIP, in addition to SCI level and completeness, were significant determinants of pulmonary function. In SCI, FEV₁, FVC, and FEV₁/FVC may be less sensitive to factors associated with change in airway size and not reliably detect the severity of airflow obstruction.

Keywords

Pulmonary disease; chronic obstruction; Pulmonary function tests; Quadriplegia; Rehabilitation; Spinal cord injuries

RESPIRATORY DYSFUNCTION IS among the most common causes of morbidity and mortality in chronic spinal cord injury (SCI).¹⁻³ Early assessments of pulmonary function in SCI included relatively few subjects and focused mainly on the relation between level and completeness of injury and reduction in pulmonary function.⁴⁻⁷ Because the degree of muscle paralysis in SCI is determined by the extent of neurologic damage, the higher the neurologic level and more complete the injury, the greater is the likelihood of respiratory muscle dysfunction.^{8,9} More recently, investigators have begun to address factors in addition to SCI level in larger cross-sectional cohorts. In particular, the contributions of duration of injury, respiratory symptoms, and smoking have been assessed.⁹⁻¹² However, the results for cigarette smoking have varied, and the contributions of other factors such as respiratory muscle strength and coexisting medical conditions to pulmonary function in SCI have not been considered in previous studies.⁴⁻¹³

In this article, we present the results of a cross-sectional assessment of forced expiratory volume in 1 second (FEV₁), forced vital capacity (FVC), and FEV₁/FVC in a large cohort of participants with SCI. We adjusted for SCI level and completeness of injury, and we examined the effects of age, pack-years of smoking, duration of injury, and respiratory symptoms (eg, wheeze). We also assessed the contributions of other factors that may influence pulmonary function but have not previously been assessed in SCI. These factors include respiratory muscle strength, body mass index (BMI), coexisting medical conditions, and previous chest injury or operations.

METHODS

Patient Population

Between October 1994 and June 2003, 484 participants free from acute illness were recruited from the SCI Service of the Veterans Affairs (VA) hospital in West Roxbury, MA, and by advertisement from the community. A recruitment criterion of being 1 or more years post-SCI was selected to ensure that we tested subjects who had survived acute injury and related complications. Participants requiring mechanical ventilation or having a tracheostomy were not tested. The recruitment was from a pool of 1807 potential participants that included 1194 who were treated previously by SCI Service at Veterans Affairs Boston Healthcare System, 546 participants from the National Spinal Cord Injury Association from New England and New

York, and 67 participants who had responded to advertising. There were 271 participants who could not be contacted because of outdated addresses, 43 who declined testing because they lived too far from the VA medical center, 232 who were not interested, 73 who had other neuromuscular diseases or did not have SCI, and 279 who were deceased, resulting in 909 potential participants.

Of the 484 participants tested, we excluded from the analysis participants with a history of polio, multiple sclerosis, stroke ($n = 26$), or lung resection ($n = 4$) and those without a detectable SCI level ($n = 8$) or with incomplete testing ($n = 3$). Because pulmonary function varies based on race and sex, 27 women and 32 nonwhite men were excluded because there were too few such participants to conduct a separate analysis. At least 1 acceptable value for both FEV₁ and FVC were obtained in 98.5% of the remaining participants. The final dataset for analysis ($n = 339$; 307 with traumatic and 32 nontraumatic SCI; 270 veterans, 69 nonveterans) excluded participants using bronchodilators ($n = 24$), those with missing values for maximal inspiratory pressure (MIP) ($n = 14$), and those with other variables ($n = 11$), as well as 1 participant whose reported lifetime cigarette consumption was considered an outlier. One person tested at 0.9 years after injury was retained in the cohort because there was no a priori basis for excluding him. The approval for this study was obtained from the institutional review boards of our institutions, and informed consent was obtained from each participant.

Neurologic Examination, Stature, and Weight

Motor level and completeness of injury was based on American Spinal Injury Association (ASIA) guidelines.¹⁴ Either a trained physician (CGT in 311 cases) or a trained research assistant (in 25 cases) determined the motor level and completeness of injury by examination. Level of injury was determined from medical record review in 3 participants who did not undergo examination. Participants were grouped a priori into 1 of 9 motor injury level and severity groups. Motor complete SCI included high cervical (C4-5), low cervical (C6-8), high thoracic (T1-6), low thoracic (T7-12), and lower levels of motor complete SCI. Participants with motor incomplete SCI were categorized as ASIA grade C (the majority of key muscles below the neurologic level grade $< 3/5$) or ASIA grade D (most muscles grade $\geq 3/5$) and were divided further into cervical grade C, other ASIA grade C, cervical grade D, and other ASIA grade D. Participants ($n = 52$) with motor complete SCI but who had evidence of some preservation of neurologic function below the neurologic level (> 2 neurologic levels) were grouped with ASIA grade C participants. Participants were weighed, and supine length was measured.¹⁵ In people who declined length measurement or who had severe joint contractures that precluded accurate assessment ($n = 65$ [19%]), stature was self-reported. In 26 (8%), weight was not measured and stated weight was used. BMI was divided into normal (BMI $< 25\text{kg}/\text{m}^2$), overweight (BMI ≥ 25 to $< 30\text{kg}/\text{m}^2$), and obese (BMI $\geq 30\text{kg}/\text{m}^2$).

Health Questionnaire

A respiratory health questionnaire (the American Thoracic Society 1978 Adult Questionnaire)¹⁶ with supplemental questions was used. Chronic cough was defined as cough on most days for 3 consecutive months of the year, and chronic phlegm was defined similarly. Persistent wheeze was defined as wheeze reported on most days or nights, or with a cold and occasionally apart from colds. Participants were asked if they had ever had any chest injuries or operations and to indicate what type.

Pulmonary Function Tests

Spirometry was based on American Thoracic Society standards¹⁷ modified for use in SCI, as described previously.^{18,19} Participants with SCI are more likely than the able-bodied to have short expiratory efforts and to exhibit excessive back extrapolation¹⁹ (the volume exhaled before the development of maximal expiratory flow at the start of a forced expiratory

maneuver). Therefore, to study these subjects, we accepted excessive back extrapolation and efforts lasting less than 6 seconds if the effort appeared maximal, there was an acceptable flow-volume loop, and there was at least a 0.5-second plateau at residual volume. We have demonstrated that the FEV₁ and FVC values derived from such efforts are highly reproducible and that the degree of excessive back extrapolation is small.^{18,19} Testing was performed using a 10-L water-seal spirometer in 97.9% of participants, and a water-seal portable spirometer^a was used in 2.1% of participants. Of the 339 participants, 314 (92.6%) had at least 3 acceptable expiratory efforts with the 2 best values of FEV₁ and FVC each within 200mL, 23 (6.8%) were able to produce at least 2 acceptable values of FEV₁ and FVC, and 2 (0.6%) participants were able to perform only 1 acceptable effort. In our study, we used the highest values of FEV₁ and FVC from the expiratory efforts. MIP and maximum expiratory pressure (MEP) were reported as the maximum of 3 values, but MEP was not assessed in our analysis because it was measured in fewer participants (n = 230).²⁰ Lung volumes were measured by helium dilution. Predicted values for FEV₁ and FVC were calculated using the Hankinson equations for white men,²¹ and the Crapo equations were used for predicted total lung capacity (TLC).²²

Statistical Analysis

Generalized linear models^{b,c} were used to assess determinants of FEV₁, FVC, and FEV₁/FVC. After adjusting for age, stature, and motor level and completeness of injury (in 9 groups), variables significant at the *P* equal to .10 level were assessed in multivariate models. Residual plots were examined for goodness of fit. We also assessed effect modification—that is, whether the effects of age, years since injury, pack-years, BMI, persistent wheeze, and MIP on pulmonary function varied based on neurologic level and completeness of injury. To assess effect-modification, we divided SCI level and severity into 3 groups (tetraplegia ASIA A and C, paraplegia ASIA A and C, all ASIA D) and created interaction terms. Separate regression models were used for each interaction term (effect-modifier) while we adjusted for the remaining variables.

RESULTS

Baseline characteristics are presented with the cohort divided into 3 motor injury level and completeness groups (table 1) because some of the 9 injury level and severity groups had few subjects. The mean age of study participants was 50.7 ± 14.9 years (range, 21.8–87.0y), and they were tested at an average of 17.4 ± 12.8 years postinjury (range, 0.9–54.7y). Of the 120 people with a chest injury or operation, 64 (53%) reported broken ribs and 36 (30%) reported a history of a “punctured” or collapsed lung. Adjusting for age, stature, and neurologic level and completeness of SCI (in 9 groups), predictors of FEV₁ in multivariate models included years postinjury, pack-years (lifetime cigarette smoking), previous chest injury or surgery, physician-diagnosed asthma, persistent wheeze, and MIP (table 2). Because previous studies in the able-bodied suggest that the relation of lung function and age may not be linear,²³ a quadratic term for age was assessed but was not significant. Quadratic and cubic terms for stature were also assessed²¹ but were not significant. Predictors of FVC included years postinjury, previous chest injury or surgery, and MIP but not pack-years (see table 2). For FEV₁/FVC, predictors were pack-years, previous chest injuries or surgery, persistent wheeze, and BMI but not stature (table 3). Current smoking was not a predictor of FEV₁/FVC or FEV₁ after adjusting for pack-years. Because stature was self-reported in 65 participants and weight in 26 participants, we included an indicator variable in the final multivariate models

^aDSII or Survey III; Collins Pulmonary Diagnostics, Ferraris Respiratory, 901 Front St, Louisville, CO 80027.

^bPROC GLM, SAS version 8.2; SAS Institute Inc, 100 SAS Campus Dr, Cary, NC 27513.

^cGLM, version 8.0; StataCorp, 4905 Lakeway Dr, College Station, TX 77845.

adjusting for whether length was measured or stated and, similarly, for whether weight was measured or stated. Results similar to those in tables 2 and 3 were obtained (data not shown).

Factors not significantly contributing to FEV₁, FVC, and FEV₁/FVC included chronic cough, chronic phlegm, respiratory illness in the 8 weeks before testing (usually reported as a mild cold), physician-diagnosed chronic bronchitis or emphysema, heart disease (defined as treatment for heart disease in the 10y before testing), and a history of occupational dust exposure. A history of physician-confirmed pneumonia since injury; a chest illness in the year before testing keeping the patient from work, indoors at home, or in bed; or a history of tracheostomy when first injured also did not significantly predict lung function. BMI was not a significant determinant of FEV₁ and FVC. Physician-diagnosed asthma was a borderline predictor of FEV₁ and was retained in the final model (−148mL; 95% confidence interval [CI], −388 to 92mL).

When assessing effect-modification, the effect of age on FVC (for interaction term, $P = .02$) and FEV₁ was least in the tetraplegia ASIA A and C group compared with other injury severity groups (tables 4, 5). Although other interactions with SCI level and severity were not statistically significant, some distinct and consistent patterns were observed. Specifically, the decrease in FEV₁ and FVC attributable to years since injury was greater for the tetraplegia ASIA A and C group than the other groups (see table 4). There was no significant effect of pack-years on FEV₁ in the tetraplegia ASIA A and C group, but in the other injury groups the FEV₁ decreased significantly. Participants with persistent wheeze in the paraplegia ASIA A and C group had a greater reduction in FEV₁, FVC, and FEV₁/FVC compared with the all D group (tables 4-6). A greater BMI was associated with lower values of FEV₁/FVC, with the greatest reduction in the tetraplegia ASIA A and C group.

Multivariate models (see tables 2, 3) were used to calculate mean FEV₁, FVC, and FEV₁/FVC for all 9 of the SCI level and severity groups (table 7), thereby assessing the effect of injury on pulmonary function adjusting for other factors. Higher levels of complete injury were associated with a lower percentage predicted²¹ FEV₁ and FVC and with a greater FEV₁/FVC. There was a linear trend of decreasing FEV₁/FVC for participants with lower complete SCI ($P < .001$).

DISCUSSION

Although previous investigations on pulmonary function in SCI have assessed factors in addition to SCI level and completeness in large cross-sectional cohorts, to our knowledge the contribution of respiratory muscle strength and coexisting medical conditions has not been considered previously.⁴⁻¹³ The results for cigarette smoking have also varied. Some previous studies^{4-8,13} included relatively few participants, resulting in inadequate power to assess multiple factors. A few studies^{5,7,13} tested participants at the time of rehabilitation, thereby creating a bias toward inclusion of subjects with poor functional status and lower levels of pulmonary function. Technical aspects of performing spirometry and measuring stature in SCI were not considered, and MIP was not measured.^{4-7,13} Cigarette smoking, a major determinant of pulmonary function in the able-bodied, was not assessed adequately.^{4-7,13} Methodology used to assess neurologic level and completeness of injury was also not described in some previous reports.⁴⁻⁸ In our study, after adjustment for age, stature, and level and completeness of injury, significant determinants of FEV₁ and FVC included past chest injury or surgery, MIP, and years since injury. Additional predictors of FEV₁ included pack-years and persistent wheeze. Persistent wheeze, pack-years, a higher BMI, and past chest injury or operation were associated with lower values of FEV₁/FVC. Lifetime smoking was not a predictor of FVC, and stature was not a predictor of FEV₁/FVC.

Previous studies^{8,10,24} have shown that higher and more neurologically complete SCI is associated with lower values of FEV₁ and FVC. Studies^{6,24,25} that included fewer subjects whose smoking history was unknown and who often were from rehabilitation centers reported mean FEV₁ and FVC values of approximately 40% to 50% of those predicted in complete cervical injury. In the current study, adjusted FEV₁ and FVC in high complete motor cervical SCI were 56% and 53% of predicted values, respectively, and in low complete motor cervical SCI were 65% and 64% of predicted values, respectively. The lower values reported in previous cohorts are likely due to selection bias. In cohorts with recruitment criteria similar to ours, FVC values comparable to our cohort were reported. For example, in the Bronx VA cohort, an FVC of 59% ± 17% in nonsmoking tetraplegics was reported, and an FVC of 60% ± 18% was observed in the Los Angeles SCI cohort.^{8,11}

In our study, FEV₁/FVC decreased with SCI level in complete injury. Similarly, in the Los Angeles and Bronx cohorts, FEV₁/FVC was greater in tetraplegia than in paraplegia.¹¹ We expected the trend in FEV₁/FVC to be in the opposite direction, because participants with the greatest impairment have the lowest TLC (see table 1). At lower lung volumes, airway caliber is reduced, and a reduction in both FEV₁ and FEV₁/FVC would be expected. In addition, other studies in cervical SCI have shown a high prevalence of bronchial hyperreactivity,²⁶ a brisk response to bronchodilators,²⁷ and an increase in resting airway smooth muscle tone measured by forced oscillation methods.²⁸ These observations suggest that complete cervical injury would result in a greater reduction in FEV₁/FVC compared with lower SCI levels.

Why, then, was there a lesser effect of respiratory muscle impairment on FEV₁ than on FVC—that is, why did FEV₁/FVC decrease at lower levels of injury? Also, in the tetraplegia ASIA A and C group, why was FVC not related to smoking and why was the effect of smoking on FEV₁ least apparent? Although the differences were small, the reduction in FEV₁/FVC per pack-year smoked in the tetraplegia ASIA A and C group was also slightly less than in the other groups (see table 6). Two mechanisms that would explain the results relate to the physical properties of turbulent flow and to dynamic compression of airways during forced exhalation. When flow is turbulent, the relation between driving pressure and flow is nonlinear. Flow is turbulent in the trachea and larger airways even during tidal breathing. During forced exhalation in the weakest subjects, the lower flows will be less turbulent, and when compared with the stronger subjects, there will be progressively smaller decreases in flow for given decreases in driving pressure. Thus, as respiratory muscle weakness increases, FEV₁ decreases less. FVC is not affected similarly; with weakness, FEV₁/FVC increases. Also, for a decrease in airway diameter such as that due to cigarette smoking, flow will decrease less in the weakest subjects because it is less turbulent, and the effect of smoking on FEV₁ will be less apparent. In the able-bodied, smoking causes a reduction in vital capacity by increasing closing volume. In high-level SCI, closing volume is not reached during voluntary maximal exhalations, even in smokers.²⁴ Thus, in respiratory muscle weakness, the mechanisms that would be expected to cause a decrease in FVC due to smoking do not apply.

During forced exhalation dynamic compression of airways occurs. With less driving pressure, there is less compression of airways and less increase in resistance. In the weakest subjects, resistance increases less than in the stronger subjects, and FEV₁ is reduced less. FVC is not similarly affected. As a result, this is another mechanism by which FEV₁/FVC increases with weakness. Because FEV₁/FVC is greatest in those with the most impaired muscles, an important implication of our data is that in conditions resulting in respiratory muscle weakness, FEV₁/FVC is less sensitive to factors normally associated with its reduction and may not be used in the standard manner to detect airway obstruction.

Studies of the effect of cigarette smoking on FEV₁, FVC, and FEV₁/FVC in SCI have produced variable results. We found that that FEV₁ and FEV₁/FVC significantly decreased with each

pack-year smoked. A similar result was found in the Bronx VA cohort in which smoking resulted in a reduction in FEV₁/FVC in subjects with both tetraplegia and paraplegia. By contrast in the Los Angeles cohort, the percentage predicted FEV₁/FVC was not significantly affected by smoking in either paraplegia or tetraplegia.¹¹ Another analysis⁹ investigated the relation between pack-years and FVC in subgroups of the Los Angeles cohort. There was no effect of pack-years on FVC in past smokers with tetraplegia or paraplegia. In subjects with high tetraplegia who were current smokers, pack-years was associated with a greater FVC, and in those with low tetraplegia and paraplegia who were current smokers, pack-years was associated with a lower FVC. The effect of age on pulmonary function was similar to that observed in the able-bodied but was less in the tetraplegia ASIA A and C injury group.^{29,30} The reduction in FEV₁ and FVC associated with normal aging in the able-bodied is attributable to an age-related increase in closing volume, a reduction in elastic recoil pressure, and flow limitation. As with smoking, the mechanisms that would be expected to cause a decrease in FVC and FEV₁ attributable to aging do not apply in conditions leading to respiratory muscle weakness.

Persistent wheeze was associated with a reduction in FEV₁, FVC, and FEV₁/FVC, with a greater effect in the paraplegia ASIA A and C group (see tables 4, 5, 7). In the able-bodied, wheeze has been associated with lower values of FEV₁, both cross-sectionally³¹ and longitudinally,³² and is a risk factor for developing asthma later in life.³³

Previously, a greater BMI has been associated with the development of bronchial hyperreactivity and asthma.³⁴ The relation between BMI and FEV₁/FVC was not specifically addressed in these studies, but in another study in the able-bodied,³⁵ the FEV₁/FVC increased as BMI increased. In contrast, in our study, overweight and obese participants had significantly lower values of FEV₁/FVC compared with those with normal BMI. In the able-bodied, the effect of obesity on pulmonary function has been attributed to thoracic cage compression.^{36, 37} This effect might be expected to reduce airway caliber due to a reduced TLC. However, when percent TLC was included in the regression models (data not shown), the effect of BMI on FEV₁/FVC was not attenuated. The mechanism whereby BMI results in a reduced FEV₁/FVC in SCI is uncertain. The effect of years since injury on FEV₁ and FVC was greatest in the tetraplegia ASIA A and C group. Also, for the tetraplegia ASIA A and C group the effect of age and years since injury on FEV₁ were of similar magnitude, whereas for the all D group, the effect of age was greater. Years since injury is possibly a surrogate for factors that were not measured directly but influence pulmonary function. Others have reported decrements in pulmonary function associated with greater years since injury.^{9,10} For example, following SCI, lung and chest wall compliance decrease.^{38,39} The chest wall in SCI stiffens as intercostal muscles and ribs develop contractures. The natural history of long-term changes in lung and chest wall compliance in SCI is not known, but it is possible that these might account for a reduction in lung function related to time since injury. MIP also influenced FEV₁ and FVC independent of level and completeness of injury, and therefore, respiratory muscle performance in SCI may not be completely explained by differences in level and severity of injury.

Our study was limited to assessment of white male veteran participants and some nonveteran participants from the community who agreed to be tested. Hence, our results may not be applicable to other SCI populations that do not fit these criteria. Because those with the lowest pulmonary function may be the least likely to survive, our cross-sectional study may be biased by the inclusion of participants who are likely to have better pulmonary function. A longitudinal assessment of pulmonary function in our cohort is underway to address this limitation. Although some studies have found that self-reported stature or weight may be an overestimate,^{15,40} adjustment for whether stature and weight were measured or stated did not influence the results of our study. Excluding participants unable to undergo accurate measurement of stature

or who declined this measurement would have resulted in the differential exclusion of participants with higher and more complete injury levels.

CONCLUSIONS

Our study shows that in SCI, in addition to level and severity of injury, pulmonary function is influenced by previous chest injury or operation, age, time since injury, lifetime smoking, obesity, wheeze, and MIP. The effects of age and lifetime smoking were less apparent in participants with greater degrees of neurologic impairment and muscle weakness. Hence, decrements in FEV₁, FVC, and FEV₁/FVC in tetraplegia, and by extension in others with respiratory muscle weakness, may not reliably detect the severity of airflow obstruction. Our results suggest that interventions such as smoking cessation programs, treatment of wheeze, weight management, and inspiratory muscle training⁴¹ may be evaluated to improve pulmonary function in SCI.

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Table 1
Selected Baseline Characteristics of White Male Participants With SCI

Characteristics	Motor Level and Severity of Injury			Total of Groups (N = 339)
	Tetraplegia ASIA A and C Group (n = 98)	Paraplegia ASIA A and C Group (n = 159)	All D Group (n = 82)	
Age (y)	47.6 ± 13.8	50.6 ± 15.3	54.7 ± 14.5	50.7 ± 14.9
Stature (cm)	178.8 ± 7.5	177.2 ± 7.3	177.2 ± 7.6	177.6 ± 7.4
BMI (kg/m ²)				
Normal (< 25)	53 (54.1)	70 (44.0)	22 (26.8)	145 (42.8)
Overweight (25 to < 30)	29 (29.6)	54 (34.0)	39 (47.6)	122 (36.0)
Obese (≥30)	16 (16.3)	35 (22.0)	21 (25.6)	72 (21.2)
Years postinjury	17.2 ± 12.4	19.0 ± 13.0	14.3 ± 12.5	17.4 ± 12.8
Smoking				
Current smoker	20 (20.4)	32 (20.1)	32 (39.0)	84 (24.8)
Past smoker	44 (44.9)	65 (40.9)	28 (34.2)	137 (40.4)
Never smoker	34 (34.7)	62 (39.0)	22 (26.8)	118 (34.8)
Lifetime pack-years smoked (for ever smokers)	25.1 ± 24.3	28.9 ± 24.4	33.4 ± 22.0	29.0 ± 23.9
Chest injuries/surgeries	25 (25.5)	71 (44.7)	24 (29.3)	120 (35.4)
Physician diagnosed COPD	3 (3.1)	9 (5.7)	6 (7.3)	18 (5.3)
Physician diagnosed asthma	4 (4.1)	13 (8.2)	6 (7.3)	23 (6.8)
Heart disease treatment in last 10y	4 (4.1)	12 (7.6)	15 (18.3)	31 (9.1)
Chronic cough	12 (12.2)	22 (13.8)	18 (22.0)	52 (15.3)
Chronic phlegm	18 (18.4)	25 (15.7)	22 (26.8)	65 (19.2)
Persistent wheeze	6 (6.1)	21 (13.2)	22 (26.8)	49 (14.5)
Occupational dust exposure	40 (40.8)	85 (53.5)	46 (56.1)	171 (50.4)
FEV ₁ (L)	2.5 ± 0.8	3.2 ± 0.8	3.1 ± 0.8	3.0 ± 0.8
FVC (L)	3.1 ± 0.9	4.1 ± 0.9	4.1 ± 1.1	3.8 ± 1.0
FEV ₁ /FVC (%)	81.7 ± 9.9	78.5 ± 8.0	75.0 ± 8.7	78.6 ± 9.1
Percentage predicted FEV ₁	63.0 ± 15.7	84.1 ± 16.4	81.4 ± 16.1	77.3 ± 18.5
Percentage predicted FVC	60.7 ± 15.4	83.2 ± 15.2	83.3 ± 15.2	76.7 ± 18.3
Percentage predicted FEV ₁ /FVC	78.2 ± 2.8	77.6 ± 3.2	76.8 ± 3.0	77.6 ± 3.1
TLC (L) [*]	5.6 ± 1.1	6.2 ± 1.1	6.3 ± 1.2	6.0 ± 1.2
Percentage predicted TLC [*]	78.7 ± 15.2	89.9 ± 13.8	90.4 ± 13.7	86.8 ± 15.0
MIP (cmH ₂ O)	74.2 ± 29.0	96.5 ± 34.0	83.3 ± 31.8	86.8 ± 33.4

NOTE. Values are mean ± standard deviation or n (%).

Abbreviation: COPD, chronic obstructive pulmonary disease.

^{*} Missing in 9 participants.

Table 2
Predictors of FEV₁ and FVC Adjusted for Level and Completeness of SCI*

Covariate	FEV ₁ (N = 339)		FVC (N = 339)	
	β	95% CI	β	95% CI
Age (y)	-21.0	-26.3 to -15.7	-17.2	-23.7 to -10.8
Stature (cm)	25.8	17.6 to 34.1	39.4	29.2 to 49.7
Years postinjury (y)	-6.1	-11.7 to -0.58	-7.4	-14.3 to -0.5
Lifetime pack-years smoked	-3.8	-6.5 to -1.1	†	†
Chest injuries/surgeries	-248	-378 to -117	-228	-390 to -67
Physician diagnosed asthma [†]	-148	-388 to 92	†	†
Persistent wheeze	-256	-436 to -75	-168	-388 to 51
MIP (cmH ₂ O)	5.3	3.2 to 7.4	8.2	5.6 to 10.8

Abbreviation: CI, confidence interval.

* Level and completeness in 9 groups.

[†] Variables not used in the multivariate model for FVC.

Table 3
Predictors of FEV₁/FVC* Adjusted for Level and Completeness of SCI[†]

Covariate	FEV ₁ /FVC % (N = 339)	
	β	95% CI
Age (y)	-0.14	-0.20 to -0.08
Lifetime pack-years smoked	-0.13	-0.16 to -0.09
Chest injuries/operations	-2.6	-4.4 to -0.9
Persistent wheeze	-3.1	-5.5 to -0.7
BMI (kg/m ²)		
Normal (< 25)	Reference	
Overweight (25 to < 30)	-2.6	-4.5 to -0.7
Obese (≥ 30)	-3.0	-5.2 to -0.7

* Not significant at the .05 level.

[†] Level and completeness in 9 groups.

Table 4
Effect Modification* by Level and Severity of SCI on Factors Predicting FEV₁

Covariate	Motor Level and Severity of Injury		
	Tetraplegia ASIA A and C Group β (95% CI)	Paraplegia ASIA A and C Group β (95% CI)	All D Group β (95% CI)
Age (y)	-16.8 (-25.7 to -7.9)	-19.4 (-26.3 to -12.5)	-28.7 (-37.8 to -19.6)
Years postinjury (y)	-12.0 (-21.6 to -2.3)	-5.8 (-13.4 to 1.8)	2.3 (-8.0 to 12.6)
Lifetime pack-years smoked	-0.5 (-5.6 to 4.6)	-4.2 (-8.1 to -0.4)	-5.7 (-10.9 to -0.4)
MIP (cmH ₂ O)	9.1 (5.1 to 13.0)	4.0 (1.1 to 6.8)	5.5 (1.4 to 9.5)
Persistent wheeze	†	-416 (-683 to -150)	-137 (-419 to 144)

* Each factor was divided based on SCI level and severity and included in a regression model adjusting for the main effects of the remaining terms.

† Only 6 cervical motor complete and cervical C group participants reported persistent wheeze.

Table 5

Effect Modification* of Factors Predicting FVC

Covariate	Motor Level and Severity of Injury		
	Tetraplegia ASIA A and C Group β (95% CI)	Paraplegia ASIA A and C Group β (95% CI)	All D Group β (95% CI)
Age (y)	-9.3 (-20.3 to 1.7)	-16.3 (-24.9 to -7.7)	-30.2 (-41.6 to -18.7)
Years postinjury (y)	-13.4 (-25.6 to -1.2)	-4.4 (-14.1 to 5.3)	-1.3 (-14.2 to 11.6)
MIP (cmH ₂ O)	12.3 (7.3 to 17.2)	6.3 (2.7 to 9.8)	10.2 (5.1 to 15.3)
Persistent wheeze	†	-373 (-707 to -38)	23 (-331 to 377)

* Each factor was divided based on SCI level and severity and included in a regression model adjusting for the main effects of the remaining terms.

† Only 6 cervical motor complete and cervical C group participants reported persistent wheeze.

Table 6
Effect Modification* of Factors Predicting FEV₁/FVC

Covariate	Level and Severity of Injury		
	Tetraplegia ASIA A and C Group β (95% CI)	Paraplegia ASIA A and C Group β (95% CI)	All D Group β (95% CI)
Age (y)	-0.24 (-0.35 to -0.13)	-0.09 (-0.17 to -0.01)	-0.12 (-0.23 to 0.00)
Lifetime pack-years smoked	-0.11 (-0.18 to -0.04)	-0.13 (-0.18 to -0.07)	-0.15 (-0.22 to -0.08)
BMI [†]	-4.8 (-7.8 to -1.8)	-1.5 (-3.9 to 0.9)	-2.9 (-6.7 to 0.9)
Persistent wheeze	*	-4.2 (-7.7 to -0.7)	-2.7 (-6.4 to 1.0)

* Only 6 cervical motor complete and cervical C group participants reported persistent wheeze.

Table 7

Estimated FEV₁, FVC, and FEV₁/FVC for Each Level and Severity of SCI

Level and Severity of Injury	N	FEV ₁ , L (95% CI)	Percentage Predicted* FEV ₁ (95% CI)	FVC, L (95% CI)	Percentage Predicted* FVC (95% CI)	Percentage FEV ₁ /FVC (95% CI)	Predicted* FEV ₁ /FVC (95% CI)
Neurologically motor complete injury							
High cervical (C4-5)	23	2.16 (1.93-2.40)	55 (49-61)	2.67 (2.38-2.96)	53 (47-59)	82.0 (78.8-85.1)	106 (102-110)
Low cervical (C6-8)	34	2.55 (2.35-2.74)	65 (60-70)	3.20 (2.96-3.44)	64 (59-68)	80.2 (77.6-82.8)	103 (100-107)
High thoracic (T1-6)	51	3.12 (2.96-3.28)	80 (76-84)	3.90 (3.71-4.10)	78 (74-81)	79.5 (74-81.6)	102 (100-105)
Low thoracic (T7-12)	50	3.18 (3.03-3.34)	82 (78-86)	4.07 (3.87-4.27)	81 (77-85)	77.0 (74.9-79.1)	99 (97-102)
Other complete	9	3.33 (2.96-3.70)	85 (76-95)	4.47 (4.01-4.92)	89 (80-98)	73.4 (68.4-78.3)	95 (88-101)
Neurologically motor incomplete injury							
Cervical C	41	2.55 (2.37-2.73)	65 (61-70)	3.24 (3.02-3.46)	64 (60-69)	78.3 (75.9-80.7)	101 (98-104)
Other C	49	3.35 (3.19-3.50)	86 (82-90)	4.22 (4.02-4.41)	84 (80-88)	79.1 (76.9-81.2)	102 (99-105)
Cervical D	46	3.03 (2.86-3.19)	78 (73-82)	3.90 (3.69-4.11)	78 (73-82)	77.1 (74.9-79.4)	99 (97-102)
Other D	36	3.40 (3.21-3.59)	87 (82-92)	4.52 (4.29-4.75)	90 (85-94)	76.0 (73.5-78.5)	98 (95-101)

* Percentage predicted values derived based on mean age of 50.7 years and mean height of 177.7cm of participants in the study population.