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Estimates of restrictive ventilatory defect in the mining industry. Considerations for epidemiological investigations: a cross-sectional study

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ABSTRACT

Objectives: (1) To assess the impact of American Thoracic Society and European Respiratory Society (ATS/ERS) 'acceptability' and 'usability' criteria for spirometry on the estimates of restrictive ventilatory defect in a population of taconite miners. (2) To compare estimates of restrictive ventilatory defect with three different pulmonary function tests (spirometry, alveolar volume (VA) and diffusing capacity ($D_{L,CO}$)). (3) To assess the role of population characteristics on these estimates.

Design: Cross-sectional study.

Setting: Current and former workers in six current taconite mining operations of northeastern Minnesota were surveyed.

Participants: We attempted to enrol 3313 participants. Of these, 1353 responded while 1188 current and former workers fully participated in the survey and 1084 performed complete pulmonary function testing and were assessed.

Primary and secondary outcome measures: We applied ATS/ERS acceptability criteria for all tests and categorised participants into groups according to whether they fully met, partially met or did not meet acceptability criteria for spirometry. Obstruction and restriction were defined utilising the lower limit of normal for all tests. When using VA, restriction was identified after excluding obstruction.

Results: Only 519 (47.9%) tests fully met ATS/ERS spirometry acceptability criteria. Within this group, 5% had obstruction and 6%, restriction on spirometry. In contrast, among all participants (N=1084), 16.8% had obstruction, while 4.5% had restriction. VA showed similar results in all groups after obstruction was excluded. Impaired gas transfer (reduced $D_{L,CO}$) was identified in less than 50% of restriction identified by either spirometry or VA. Body mass index (BMI) was significantly related to spirometric restriction in all groups.

Conclusions: Population estimates of restriction using spirometry or VA varied by spirometric acceptability criteria. Other factors identified as important considerations in the estimation of restrictive ventilatory defect included increased BMI and gas transfer impairment in a relatively smaller proportion of

ARTICLE SUMMARY

Article focus
- Few studies have evaluated the impact of age, smoking and obesity on population estimates for restrictive disease within working populations.
- The hypothesis is that there is a difference in lung function between groups excluded by current spirometry guidelines and those that strictly meet all the acceptability criteria.

Key messages
- Spirometry plays a key role in respiratory health screening in occupational settings especially those with risk of lung disease.
- Estimates of restrictive ventilatory defect (RVD) vary by interpretation of acceptability criteria in population data.
- Future efforts to understand qualitative and quantitative exposure–disease relationships in miners require attention to these criteria to determine more representative lung disease estimates.

Strengths and limitations of this study
- This study combined results from three tests of pulmonary function in determining prevalence of RVD.
- Pulmonary function tests carried out in this study were used to estimate lung restriction in the absence of the ideal testing method, body plethysmography.

those with spirometric restriction. These insights are important when interpreting population-based physiological data in occupational settings.

INTRODUCTION

The determination of population estimates for restrictive ventilatory defect (RVD) within populations exposed to mining dusts typically relies upon the use of chest X-ray (CXR) and spirometry. Restrictive lung disease (RLD)

refers to a decrease in total volume of the lungs due to impaired expansion from decreased lung elasticity. It is diagnosed using body plethysmography. It is a subset of what is actually measured, RVD which includes other causes of impaired expansion like decreased chest wall expansion and pulmonary vascular disease. In this paper, we measure RVD as an estimate for RLD. In the occupational setting, spirometry plays a key role in respiratory health surveillance. It can be performed on-site at low cost and with minimal risk to the employee. It can assist the health professional by determining if an individual worker demonstrates a specific pattern of respiratory impairment and in occupational settings, RVD. It can also help assess the effectiveness of measures implemented to protect the worker population and can help estimate exposure patterns to known hazards within working populations.[1] An understanding of this exposure likelihood aids the interpretation of results from morbidity and mortality studies, particularly in the setting of absent or incomplete industrial hygiene information.

With the use of spirometry, the identification of RVD is complicated by several factors including low sensitivity/low positive-predictive value (PPV), variation in individual performance and the impact of confounding factors, particularly obesity and the effects of cigarette smoking. Few studies have evaluated the impact of these factors on population estimates for restrictive disease within working populations.

In clinic settings lung obstruction can be identified with high reliability and validity using the American Thoracic Society and European Respiratory Society (ATS/ERS) recommendations for spirometry.[2–6] Assessing the presence of restriction can be more difficult with spirometry showing a higher negative than PPV in the identification of lung restriction (PPV<60%).[7–10] Ideally, it is suggested that after conducting spirometry, the presence of lung restriction should be further defined with the use of lung volume testing.[8 9] Given the problems of cost and access to lung volume testing, it has also been suggested that spirometry alone may be used to identify restriction without greatly compromising diagnostic accuracy.[7 8 11] Other methods for assessing lung function may be helpful. These include the measurement of diffusing capacity ($D_{L,CO}$), and the measurement of alveolar volume (VA), which is carried out as a part of the $D_{L,CO}$ test. VA, in the absence of obstruction, is more closely related to total lung capacity (TLC).[6 12–14] Although these tests are often used to enhance diagnostic accuracy in clinical practice, they are not routinely available in most clinical or occupational settings.[3]

Individual spirometry measurement is effort-dependent and quality of test performance is variable. Some of this variability can be related to underlying morbidity, which may affect an individual's ability to adhere to ATS/ERS criteria for acceptability. In epidemiological settings, these criteria may provide important insights into the impact of data quality on study results. For example, spirometry interpretation using 'acceptable' or 'usable' quality criteria can differentially exclude people with poor lung function from the assessment.[5] Similar to the lack of data on spirometry quality and its impact on medical decisions,[15] an in-depth look at spirometry use in mining populations has not been undertaken with these considerations in mind.

There were three primary objectives in this study. The first was to assess the impact of ATS/ERS 'acceptability' and 'usability' criteria on estimates of RVD in a population of taconite miners. The second was to compare estimates of RVD with three different pulmonary function tests (PFTs; spirometry, VA and (DL, CO)). The third was to assess the role of population characteristics on these estimates.

METHODS
In 2010, a survey of current and former workers in the taconite mining industry of Minnesota was conducted as an attempt to quantify the types and severity of non-malignant lung disease associated with exposure to dusts from mining operations. The survey included workers from all six current mining operations who were exposed after the 1950s (when workplace dust levels were likely higher than current levels) up to the present. A sample size of 1200 workers was selected to provide sufficient power to explore associations between lung function and exposures of interest and to determine the prevalence of lung pattern abnormality in the overall population of workers.[16]

With the help of union and company officials, we searched employment records to identify current and former miners in seven different Minnesota counties for recruitment to the study. The lists included workers who were employed at any time between 1989 and the present, regardless of when they started work. Individuals were contacted by mail or telephone and invited to participate. We obtained informed consent in accordance with a protocol approved by the University of Minnesota Human Subjects Research Committee.

Participants completed self-administered health and work questionnaires, underwent CXRs and PFTs which included spirometry and $D_{L,CO}$ (with VA), in that order. Testing was performed at a community clinic in a location close to the miners' homes. Estimation of the prevalence of obstruction and RVD in this population of miners was made using current ATS/ERS criteria for all test methods.[2–6] These criteria for spirometry testing included both criteria for acceptable blows, and criteria for manoeuvre repeatability.

Standard approaches to measurement used
The use of lower limits of normal (LLN) from reference equations has been shown to have a better combination of sensitivity, specificity and predictive values (positive and negative) as well as enhanced concordance and discordance when compared with the use of traditional

cut-off points of 70% and 80% (for forced expiratory volume/forced vital capacity (FEV_1/FVC) ratio, FEV_1 and FVC percentage predicted).[6] [17–20] Using the fifth centile LLN adjusts for age-related decline in lung function so that only 5% of individuals in each age reference group is labelled as 'abnormal.' In contrast, using 70% or 80% absolute cut-offs potentially results in an increased proportion of false positives in older participants.[21]

A 10.2 L, dry rolling seal, volume displacement spirometer (Sensormedics 1022, Occupational Marketing Inc, Houston, Texas, USA) was used to conduct spirometry while an Ultima PF system (Medical Graphics Corporation, St Paul, Minnesota, USA) was used to conduct $D_{L,CO}$ measurements. The latter uses single-breath helium dilution for the measurement of VA. The ambient temperature was recorded automatically and barometric pressure was entered manually at the beginning of each test session. Screening spirometry was performed by technicians trained in a 2-day NIOSH-certified spirometry course. These technicians were also trained to perform $D_{L,CO}$ testing. Precautions were taken to avoid errors. These included carrying out regular quality checks of equipment and monitoring the procedural performance of technicians. Testing followed ATS/ERS recommendations[4] [5] except that here, five spirometry efforts were performed as a minimum.

Different categories based on meeting ATS/ERS guidelines on acceptability and repeatability of spirometric manoeuvres was assessed (table 1). Measurement of $D_{L,CO}$ and VA were performed according to published guidelines.[12] [22] $D_{L,CO}$ results met criteria if a participant had a minimum of three valid tests without exceeding five attempts. A valid test required a participant to hold their breath for 8–12 s with an Inspiratory Vital Capacity of ≥85% of Slow Vital Capacity. Repeatability criteria require that the best two $D_{L,CO}$ results must be within 10% of each other. For data analysis, the average of the best two results was used.

Several standard reference equations for FEV_1, FVC and FEV_1/FVC have been developed for the general US population[23–27] and for the US blue collar workers.[28] [29] The reference equations of Hankinson et al[23] were used for the estimation of respective LLNs of the spirometric indices. In addition to being recommended by ATS/ERS as the best standard for US population assessment,[4] [17] Hankinson et al stratified their analysis by gender and age, covering a broad age range (8–80 years) and showed good agreement with previous reference equations. It has also been shown that these reference equations for spirometry may be applied to individuals older than 80 with low risk of misclassification.[30]

The current recommendations for interpretation in PFT were used.[3] [5] [6] [17] A participant was identified as having 'airflow/lung/spirometric obstruction' if the FEV_1/FVC ratio was <LLN and 'spirometric restriction' if their FEV_1/FVC ratio was normal (≥LLN) but their FVC value was <LLN. A 'mixed pattern' was identified when both FEV_1/FVC ratio and FVC values were <LLN. A 'mixed pattern' may be seen in individuals with obstruction plus either superimposed restriction or air trapping, either of which can lead to a reduction in FVC. 'All spirometric restriction' referred to estimates of spirometric restriction plus mixed pattern impairment identified in the population. Borderline obstruction, which may represent either a very mild obstruction or a normal physiological variant, sometimes called 'dysanapsis,' was identified by a low FEV_1/FVC ratio plus an FEV_1≥LLN.[3] [5] [6] [17] [31]

Reference equations from Stocks and Quanjer[32] were used for determining the LLN for VA as recommended by ATS/ERS. These were corrected for the anatomic dead space volume (VD) difference between VA and TLC.[22] [33] [34] For VD, when the body mass index BMI was <30, the formula: VD (mL)=2.2×(weight in kg) was used,[34] while when BMI was ≥30 the formula: VD (mL) =24×(height in cm)^2/4545 was used.[22] Reference values for $D_{L,CO}$ from Crapo et al were utilised as

Table 1 Different categories based on meeting ATS/ERS guidelines on acceptability and repeatability of spirometric evaluations

Participant manoeuvre	Category	Frequency	Percentage
One acceptable manoeuvre only	1	33	3
Two acceptable, repeatable manoeuvres only	2	45	4.2
Two acceptable, not repeatable	3	27	2.5
Two highest acceptable not repeatable*	4	41	3.8
No plateau end-point reached	5	384	35.4
No acceptable manoeuvre	6	7	0.6
Not repeatable (3 acceptable manoeuvres)†	7	28	2.6
Meets ATS criteria	8	519	47.9
Total		1084	100

'No plateau end-point reached' referred to the inability to achieve end-of-test volume (EOTV), an important end-of-test (EOT) criterion. In this case, the volume–time plateau was not obtained.
*Attained three acceptable manoeuvres but, as per criteria, the two highest values were not repeatable. The lower two were repeatable and their values were used.
†Attained three acceptable manoeuvres but, as per criteria, none were repeatable.
ATS/ERS, American Thoracic Society and European Respiratory Society.

recommended by ATS/ERS,[6][22][35] with an adjustment for haemoglobin.[6][22][36]

Other definitions used

We used the term 'VA restriction' when the FEV_1/FVC ratios were normal ($\geq$LLN) and the VA was reduced, independently of FVC. This was carried out because previous studies have shown that, in the presence of lung obstruction, lung volume measured by single-breath helium dilution underestimates TLC measured by body plethysmography (VL, pleth).[6][13][14] These obstructive scenarios include cysts, non-communicating bullae/airspaces and pneumothorax and are not incorporated in the single-breath helium estimate of lung volume (VA).[6][13] However, when obstruction is excluded, lung volume estimation by single-breath helium dilution approximates VL, pleth.[12–14][37] For $D_{L,CO}$ estimations, the term 'low $D_{L,CO}$ without obstruction' was used when $D_{L,CO}$ was reduced (<LLN) but the FEV_1/FVC ratio was normal ($\geq$LLN).

Participants were categorised into four non-exclusive groups (table 2) defined by the extent to which ATS/ERS criteria for spirometric performance were met. Group 1 ('Total group') includes all tested participants. Group 3 ('Met criteria') comprises participants who met all criteria for acceptability and repeatability.[5] Group 2 ('Exclusions') includes those who failed any of the criteria (groups 2 and 3 were mutually exclusive). Group 4 ('Usable') uses relaxed acceptability criteria and can be thought of as allowing 'usable' tests as described by ATS/ERS and included all participants from group 3 and some from group 2. These 'usable' tests were (1) tests with quality control grades of $\geq$'B' (at least two acceptable manoeuvres with FEV_1 values repeatable within 101–150 mL)[17] and (2) tests that did not meet end-of-test (EOT) criteria (no plateau end-point reached). The assigned FVC values in this group (no plateau end-point reached) were likely close to true FVC values that would have been attained if plateau had been reached. The EOT criteria for acceptability are related to being unable to continue further exhalation and having a volume–time curve showing no change in volume (<0.025 L) for $\geq$1 s and an expiratory time $\geq$6 s.[5][38]

Although the other tests (VA and DL,CO) have unique criteria for acceptability which we adhered to, we formed groups on the basis of spirometry testing only. We were most interested in spirometric classification because it is the test most available in occupational settings. $D_{L,CO}$ testing as well as spirometry are effort dependent, while $D_{L,CO}$ (and VA) has the drawback of performing inconsistently in the presence of lung obstruction.

Description of the different groups was carried out and the only two mutually exclusive groups (groups 2 and 3) were compared using t test and χ^2 analysis. Crude prevalence estimates of obstruction and restriction by spirometry were determined. Exact (Clopper-Pearson) 95% CIs

Table 2 Demographic characteristics of four test groups

Parameters	Group 1 (total group) (n=1084)	Group 2 (exclusions) (n=565)	Group 3 (met criteria) (n=519)	Group 4 (usable) (n=989)
BMI*	31.4 (5.4)†	31.2 (5.2)†	31.6 (5.6)†	31.4 (5.4)†
<18.5	0.2	0.2	0.2	0.2
18.5–25	8.0	7.6	8.6	8.2
25–29.9	37.6	39.6	35.5	37.5
30–34.9	32.6	31.3	33.4	32.4
35–39.9	13.7	14.0	13.9	14.0
≥40	7.9	7.3	8.4	7.7
Age	59.7 (10.8)†	62.2 (9.9)†	57.0 (11.1)†	59.2 (10.7)†
<50	16.5	9.6	22.9	17.3
50–64	49.2	46.9	51.2	50.1
65–79	31.4	40.5	22.9	29.9
>79	2.9	3.0	3.1	2.7
Smoking				
Never	38.0	27.5	48.4	37.8
Current	12.0	14.9	9.2	12.5
Former	50.0	57.6	42.4	49.7
Gender				
Female	9.3	4.4	14.6	9.9
Male	90.7	95.6	85.4	90.1

All values were percentage distributions of each parameter within the population groups.
Group 1—all workers surveyed without consideration for exclusion based on ATS/ERS test criteria for spirometry.
Group 2—all workers who did not meet all ATS/ERS criteria for spirometric assessment.
Group 3—workers who met all ATS/ERS criteria for spirometric assessment.
Group 4—All workers with spirometry quality ≥"B" (see Methods section) and repeatable tests not meeting end-of-test (EOT) criteria.
*BMI—weight in kilograms/height in metres squared (kg/m^2).
†These represented the mean and SDs (in parenthesis) for these groups.
ATS/ERS, American Thoracic Society and European Respiratory Society; BMI, body mass index.

were derived for the all estimates of lung function impairment. This method has the advantage of calculating conservative CI estimates when assessing binomial proportions. Prevalence estimates of RVD determined by combining tests were presented to show increased likelihood of restriction determination (table 3).[6] The combination of these three tests also represented the lower bound for RVD prevalence estimates. When estimates were based on any of the three tests being abnormal ("Or"), this represented the upper bound for RVD estimates.

To explore the impact of obesity on the apparent prevalence of restriction in this population, we performed a multivariate analysis to determine the association of BMI with FVC. For this analysis, FVC was converted to a percentile value for each participant based on normal reference equations.[23] This centile is the FVC of each participant, standardised to the NHANES III population-based distribution of normal lung function. This is different from percentage predicted which is a ratio of the FVC to the median predicted value for each participant (race, age, height and gender adjusted). This association was determined with a generalised linear model both unadjusted and adjusted for age and gender in all the described groups.

RESULTS

We attempted to enrol 3313 potential participants. A total of 1353 participants responded and provided consent and questionnaire information and of these, 1188 current and former workers fully participated in the survey. Of the 1188 workers, 1084 performed complete pulmonary function testing. Their data comprised the data set analysed for this assessment.

The participants lived in seven different counties in northeastern Minnesota and ranged in age from 36 to 89 years with a mean age of 59.7 years (SD=10.8 years). Most participants were men (90.7%), with current smokers comprising 12%, never-smokers, 38% and former smokers, 50% of the population tested. Of the 1084 participants assessed, 519 (47.9%) fully met ATS/ERS criteria of three acceptable and two repeatable manoeuvres for spirometry.[5] The others had criteria for exclusion as shown in table 1. Of the tests that were potentially excluded, the majority were due to failure to meet EOT criteria by reaching an adequate plateau.[5] This latter category comprised 68% of potentially excluded tests.

Table 2 shows the demographics of all groups. While BMI was distributed similarly among all groups, group 3 was younger, had a higher proportion of women and a higher proportion of individuals who had never smoked.

Table 3 Prevalence estimates of lung function patterns in different groups

N	Group 1 (total group) 1084 Per cent	95% CI	Group 2 (exclusions) 565 Per cent	95% CI	Group 3 (met criteria) 519 Per cent	95% CI	Group 4 (usable) 989 Per cent	95% CI
Spirometric obstruction*	16.8	14.6 to 19.2	27.6	24.0 to 31.5	5.0	3.3 to 7.3	17.6	15.3 to 20.1
Spirometric restriction*	4.5	3.4 to 5.9	3.2	1.9 to 5.0	6.0	4.1 to 8.4	3.9	2.8 to 5.4
Mixed disease*	2.9	2.0 to 4.0	4.6	3.0 to 6.7	1.0	0.3 to 2.2	2.9	2.0 to 4.2
All spirometric restriction*	7.4	5.8 to 9.1	7.8	5.7 to 10.3	6.9	4.9 to 9.5	6.9	5.4 to 8.6
VA restriction*	5.9	4.6 to 7.5	5.0	3.3 to 7.1	6.9	4.9 to 9.5	5.7	4.3 to 7.3
Low $D_{L,CO}$ without obstruction*	9.0	7.4 to 10.9	8.3	6.2 to 10.9	9.8	7.4 to 12.7	9.2	7.5 to 11.2
Spirometry & VA†	2.6	1.7 to 3.7	1.8	0.9 to 3.2	3.5	2.1 to 5.4	2.4	1.6 to 3.6
Spirometry & $D_{L,CO}$‡	1.3	0.7 to 2.2	0.7	0.2 to 1.8	1.9	0.9 to 3.5	1.2	0.6 to 2.1
VA & $D_{L,CO}$ §	2.3	1.5 to 3.4	1.4	0.6 to 2.8	3.3	1.9 to 5.2	2.3	1.5 to 3.5
Spirometry & VA & $D_{L,CO}$¶	1.1	0.5 to 1.9	0.5	0.1 to 1.5	1.7	0.8 to 3.3	1.0	0.5 to 1.9
Spirometry or VA**	7.8	6.3 to 9.6	6.4	4.5 to 8.7	9.4	7.1 to 12.3	7.2	5.7 to 9.0
Spirometry or $D_{L,CO}$††	12.3	10.4 to 14.4	10.8	8.4 to 13.7	13.9	11.0 to 17.2	11.9	10.0 to 14.1
VA or $D_{L,CO}$‡‡	12.6	10.7 to 14.8	11.9	9.3 to 14.8	13.5	10.7 to 16.7	12.5	10.5 to 14.8
Spirometry or VA or $D_{L,CO}$§§	14.4	12.6 to 16.6	13.1	10.4 to 16.2	15.8	12.8 to 19.2	13.9	11.8 to 16.2

Per cent—prevalence of lung function patterns in each population group in percentage.
95% CI—Clopper-Pearson (exact) 95% confidence limits of prevalence estimates.
Group definitions are as described in the Methods section.
*Definitions described in the Methods section.
†After excluding spirometric obstruction, both FVC and VA were <LLN.
‡This is the proportion of spirometric restriction that also had a reduced (<LLN) $D_{L,CO}$.
§This is the proportion of VA restriction that also had a reduced (<LLN) $D_{L,CO}$.
¶After excluding spirometric obstruction, FVC, VA and $D_{L,CO}$ were <LLN.
**After exclusion of spirometric obstruction, either FVC or VA were <LLN.
††After exclusion of spirometric obstruction, either FVC or $D_{L,CO}$ were <LLN.
‡‡After exclusion of spirometric obstruction, either VA or $D_{L,CO}$ were <LLN.
§§After exclusion of spirometric obstruction, either FVC or VA or $D_{L,CO}$ were <LLN.
$D_{L,CO}$, diffusing capacity; FVC, forced vital capacity; LLN, ; VA, alveolar volume.

Comparison of groups 2 and 3 ('Exclusions' vs 'Met criteria') showed a significantly higher mean testing age in group 2, a higher proportion of men, a higher mean FEV_1 and a significantly higher proportion of ever smokers (current and former). All p value estimates were <0.0001 and mean BMI was not significantly different between the two groups.

Table 3 presents the lung abnormality estimates for obstruction and RVD by spirometry, restriction by VA restriction and mixed disease by spirometry for all groups. It also presents estimates of abnormal lung function characterised by a $D_{L,CO} < LLN^6$ (low $D_{L,CO}$ without obstruction) after patients with obstruction on spirometry were excluded. Estimation of the prevalence of restriction using VA ranged from 5% to 6.9% across the different groups. Estimation of RVD using spirometry had a wider range across the four groups ranging from 3.2% to 6%. When participants with a mixed pattern were included, the range of estimates of RVD (FVC<LLN) across these four groups were less (6.9–7.8%). Spirometric obstruction varied the most, ranging from 5% to 27.6% depending on adherence to ATS/ERS guidelines. Prevalence estimates of RVD using a combination of available tests ranged from 0.5% in group 2 using the '&' classification and all the tests to 9.4% in group 3 using the 'Or' classification for all the tests (after excluding obstruction).

BMI was ≥30 in 54.2% of study participants. In table 4, BMI was significantly associated with FVC percentiles in all four groups when unadjusted or adjusted for age and gender (p<0.0001). BMI was observed to account for 8.8–9.2% of variation in percentile values when unadjusted. When adjusted for age and gender, this range increased to 9.3–10.6% with the highest value seen in group 3. The association in adjusted as well as unadjusted models demonstrated a trend of decreasing FVC percentile with increased BMI.

Table 4 Linear regression of forced vital capacity (centiles*) by body mass indices (BMIs)

Test criteria groups	Estimate	R^2 (%)
Group 1† (total group)	−0.018	9.1
Group 2‡ (exclusions)	−0.019	9.2
Group 3§ (met criteria)	−0.017	9.0
Group 4¶ (usable)	−0.017	8.8

All crude and multivariate linear regression models had significant p values at <0.0001.
Multivariate models involved adjusting for age and gender.
Groups are as described in the Methods Section.
*centiles of spirometry performance are expressed as the FVC of each participant, standardised to the NHANES III population-based distribution of normal lung function. This is different from percentage predicted which is the ratio of the FVC to the median predicted value for each participant (race, age, height and gender adjusted).
†Adjusted estimate: −0.018; R^2 (%): 9.5.
‡Adjusted estimate: −0.019; R^2 (%): 9.5.
§Adjusted estimate: −0.016; R^2 (%): 10.6.
¶Adjusted estimate: −0.017; R^2 (%): 9.3.
FVC, forced vital capacity.

DISCUSSION

The use of pulmonary function testing to estimate the prevalence of RVD in a dust-exposed population of workers has uncertainties about it. These uncertainties relate to individual performance on testing, testing errors, group characteristics of the participants tested and representativeness of the group tested. The focus of this investigation was to highlight the potential range of estimates of lung impairment depending on how spirometry acceptability criteria were applied and by the different PFTs used while considering population characteristics.

The overall response rate in this study was 40.8%. We would expect similar factors to affect variability in estimates of RVD despite the degree of study participation. Estimates could vary upwards or downwards depending on the degree of underlying illness within the study participants.

The application of spirometry acceptability criteria to test results was an important factor in assessing abnormality. Acceptability criteria for spirometry impacted the prevalence estimates for RVD, especially lung obstruction and, consequently, mixed disease. Our assessment showed a high prevalence of obstructive patterns in those not meeting acceptability criteria, compared with those fully meeting criteria (27.6% vs 5%). Identifying lung obstruction in this mining population is relevant because of the recognised role of heavy dust exposure in causing lung obstruction (non-pneumoconiotic effect).

A key criterion for the recommended exclusion of spirometric manoeuvres ('acceptable' vs 'usable') was not meeting EOT criteria. Among the participants, 35.4% (68% of potentially excluded tests) did not meet EOT criteria for acceptability. Current ATS/ERS guidelines recommend not using manoeuvres or not meeting all acceptability criteria except where they may still contain useful information ('usable' manoeuvres).[5] This recommendation referred to assessments for morbidity important for clinical care of patients. In this epidemiological assessment, most test curves not meeting EOT criteria were repeatable and represented the participants' best performance. Even though EOT criteria were not met, these results were included in groups 1, 2 and 4. Group 3 excludes these results. We regarded them as a necessary inclusion for epidemiological assessment (group 4), meeting the 'usability' criteria. Including these tests (not meeting EOT criteria) increased test success from 47.9% to 83.3%. The diagnosis of 'true restriction' (RLD) is usually based on demonstrating a reduced TLC measured by body plethysmography (VL, pleth). This is considered the gold-standard for the diagnosis of RLD.[3 6 8 17 39] This test is not widely available in occupational or clinical settings, is costly and not portable.[3] Though some studies have shown VL,pleth to be comparable to lung volume measured by single-breath helium dilution (VA), current guidelines point out that VA underestimates TLC in the setting of moderate-to-severe obstructive disease.[6 9 12–14] This is a

key limitation of using VA as an approximate for TLC. For these reasons, use of VA (and $D_{L,CO}$) in this study was limited to participants without obstruction (FEV_1/FVC≥LLN). In the same subpopulation in all four groups (after excluding obstruction), VA restriction proportion was consistently higher than spirometric restriction proportion. This is thought to reflect the higher PPV of VA than spirometry in detecting restriction.

With our inclusion of tests not meeting EOT criteria, VA restriction could have included some participants with obstruction. The addition of $D_{L,CO}$ to spirometry increases the accuracy of functional lung disease determination.[6] It further characterises restriction identified by spirometry by providing a quantitative measure of gas transfer in the lungs.[32] In this study, the prevalence of 'low $D_{L,CO}$ without obstruction' was higher than 'VA restriction' in all groups. While $D_{L,CO}$ may be a sensitive indicator of early interstitial lung disease, it is not a measure of lung volume. It is rather, a product of $D_{L,CO}$/VA ratio and VA. $D_{L,CO}$ can also be abnormal in conditions unrelated to dust exposure such as pulmonary vascular abnormality (eg, pulmonary hypertension), or early emphysema not detected by spirometry.[6 24 33 40] It may also be falsely reduced by maldistribution of inspired gas when measuring VA in obstructive disorders.[22] A systematic error in measurement using VA and $D_{L,CO}$ was also possible since they are measured using similar technique (single-breath gas dilution) and on the same manoeuvre.

Although smoking does not result in RVD, the high prevalence of current and former smokers in this cohort could result in a greater estimate of mixed disease. Including the mixed category increases the estimate of RVD and is important for assessing restriction on that basis. Groups 2 and 3 represent the most disparate estimates for RVD, likely due to the higher prevalence (group 2) versus the lower prevalence (group 3) of mixed disease. The group 2 participants were shown to be significantly older than group 3, had significantly higher male proportions and higher amounts of current/former smoking.

The variation in estimates of abnormality across groups and the uniqueness of the potentially excluded group (group 2) highlights the problems of accurately estimating abnormality prevalence in the total group of workers. If only assessments that strictly met all ATS/ERS acceptability criteria were used, many older and potentially sicker participants' tests would not be utilised, resulting in a biased estimate of the prevalence of RVD. Overall, the prevalence estimates determined using group 4 reflected a reasonable compromise in the application of ATS/ERS acceptability criteria. This assumes that the differences in obstruction prevalences observed between groups 3 and 4 represent the sicker, older miners, as suggested by the differences in mean age, BMI and current smoking proportions. Group 4 contained tests not meeting EOT criteria but were still usable in determining prevalence estimates. Exclusion

of the potentially sicker population is avoided (group 3), while still excluding tests of poor quality, which group 1 would include. The minor differences in abnormality estimates between groups 1 and 4 may be accentuated in populations with a higher burden of underlying disease.

The prevalence of RVD determined with either spirometry or VA in combination ('&') with isolated reduction in $D_{L,CO}$ represented RVD likely caused by interstitial lung disease (see footnotes in table 3 for test combinations). The results showed that RVD with impaired gas transfer ($D_{L,CO}$ <LLN) represented less than 50% of estimated lung restriction by either spirometry or VA or both, together. This suggests that more than 50% of estimated restriction (by spirometry or VA) may be from extrapulmonary causes not affecting gas transfer in the lungs (eg, obesity). The effect of using multiple tests, including VA and $D_{L,CO}$, should enhance the estimates of RVD.[8 12]

The effect of obesity on the apparent prevalence of RVD in an occupational group with dust exposure has obvious implications in studying such populations. Obesity can result in chest wall restriction that can affect the estimation the prevalence of RVD. In this study, 10% of the variation in FVC was accounted for by BMI. This is not surprising given the high percentage of overweight participants across all acceptability groups.

The estimate of restriction with spirometry was closest to the VA estimate of restriction in group 3. In this group, restriction estimates from the combination of Spirometry, VA and $D_{L,CO}$ likely represented the best estimate of true lung restriction. It comprises the least amount of obstruction, while theoretically better approximating TLC. This insight, along with the ease of administration suggests that spirometry is a reasonable approach for the identification of lung restriction in this setting, particularly when taking chest wall issues, like obesity, into account. Since spirometry is commonly used in assessing lung health in occupational settings, it is important to characterise estimates of varying conditions in cross-sectional studies. The further understanding of its performance in longitudinal settings will also enhance its use.

CONCLUSIONS

Factors identified as important in the estimation of RVD in this group of miners included BMI, gas transfer impairment and spirometric acceptability criteria. High BMI was identified in a large proportion of the group and was strongly correlated with spirometry-identified RVD. Gas transfer impairment, in combination with spirometry, was likely helpful in more accurately identifying intrinsic RVD. Estimates for RVD also varied by spirometric acceptability criteria with more representative results occurring in those classified as 'usable'. These findings will be useful in future efforts to understand qualitative and quantitative exposure-disease relationships in these miners.

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