INDICES OF VENTILATORY MEASUREMENTS

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Single breath pulmonary function tests of the forced expiratory volume in one second (FEV₁) and forced vital capacity (FVC) type require adjustments for age and height before the extent of their deviation from normal standards can be assessed. Many regression equations have been proposed in the literature. The Committee on Rating of Mental and Physical Impairment (1965) has provided tables of normal values of FEV₁ and FVC for adults by sex, age, and height. These recommended standards were adapted from a study in the United States (Kory, Callahan, Boren, and Syner, 1961). Subsequently, a multiple regression equation was derived from the pooled results of four international studies (including the work of Kory and his co-workers) to predict FEV₁ values in white Caucasian males (Cotes, Rossiter, Higgins, and Gilson, 1966). In epidemiological investigations it is sometimes necessary to estimate the extent of impairment in lung function for groups of persons exposed to certain occupational hazards, in relation to their smoking habits, age, and the presence or absence of respiratory symptoms. An extensive study of the aetiology, prevalence, and progression of respiratory disability among men employed in the steel industry in South Wales was recently conducted (Lowe *et al.*, 1968). Regression equations were published which were derived from observations on 8,106

non-bronchitic subjects for the calculation of expected values of FEV₁, FVC, and FEV₁ % (defined as $FEV_1 \times 100$)

FVC

The study showed that both age and height were significant predictors for estimating FEV₁ and FVC, but that age alone was of importance for FEV₁ %. All the three ventilatory functions decreased with age, and within age groups FEV₁ and FVC increased with height. The within age regression coefficients of FEV₁ and FVC on height were, however, significantly non-parallel, and their slopes decreased appreciably with age. In a later part of this study (Lowe, Campbell, and Khosla, 1970) it was reported that the groups of smokers not only had lower values of FEV₁ at each age group than the non-smokers, but their decline of FEV₁ with age was also steeper.

These results show that the overall multiple regression coefficient of FEV₁ on age in any particular study is likely to be influenced by the smoking habits or the health condition of the group, and the regression coefficient of FEV₁ on height could be affected by the age distribution. It is, therefore, not surprising that the regression relationships reported in the literature differ in their regression coefficients (Table I). There is as yet no uniformly acceptable equation for estimating FEV₁ and Table I shows that some of the estimating equations include even nonlinear and logarithmic functions

*This work was done from the Department of Social and Occupational Medicine.

TABLE I
SOME REGRESSION RELATIONSHIPS OF FEV₁ ON AGE AND HEIGHT REPORTED IN THE LITERATURE

Reference	Series	Prediction from Age and Height (age in years, height in metres)	Nature of Relationship
Cotes <i>et al.</i> (1966)	1. U.S.A. 2. Sweden 3. Berlin 4. U.K.	3.7 HT—0.028 Age—1.59 3.75 HT—0.036 Age—1.09 3.6 HT—0.027 Age—1.65 3.46 HT—0.033 Age—1.12	Regression of FEV ₁ on age and height
Lowe <i>et al.</i> (1968)	5. Port Talbot (U.K.) 6. Ebbw Vale (U.K.)	4.24 HT—0.042 Age—2.037 3.34 HT—0.041 Age—0.667	
Cotes <i>et al.</i> (1966)	7. C.E.C.A. 8. Dutch Foundries	HT ^a (825.57 + 1.05Age - 0.061Age ²) 10 ^a (0.219 - 0.00425 Age) HT ^{a.12} × 10	Regression of FEV ₁ /HT ^a on age and age ^a Based on regression of log (FEV ₁) on log (height), and age

of age and height as independent variables. Further, any ethnic label attached to a standard (Cotes *et al.*, 1966) lacks universal applicability for epidemiological purposes.

An analogy may be drawn with obesity which depends on weight and height, and because the 'normal' or 'ideal' weight tables are mostly based on Caucasians, the authors of a study of coronary heart disease in Hawaii (Bassett *et al.*, 1969) preferred to use an index of obesity (weight/height²). The three indices combining weight (W) and height (H) that have been most commonly used are W/H, W/H², and W/H³ (the ponderal index H/³W is another way of expressing W/H³). It has been shown, however (Khosla and Lowe, 1967), that on theoretical considerations only the index W/H³ is satisfactory and its suitability in different adult populations has been confirmed in a number of other studies (Edwards and Whyte, 1962; Grimley Evans and Prior, 1969; Khosla, 1970).

The following report shows that the three proposed indices of ventilatory function also have a sound theoretical basis and that their validations in other populations would be of interest.

SOURCE OF DATA

The data used are derived from an epidemiological study of the prevalence and aetiology of respiratory disability of men employed in the steel industry. A full description of the methods by which the information was collected is given in an earlier paper (Lowe *et al.*, 1968). Here it is sufficient to mention that ventilatory measurements were recorded on the Garthur Vitalograph; two recordings were made after a practice blow, and the higher of the two readings of FEV₁ and its related FVC (corrected at 37°C saturated with water vapour (BTPS) from

the ambient temperature recorded on the charts) were used for statistical analysis and FEV% was defined as $\frac{\text{FEV}_1}{\text{FVC}} \times 100$.

FVC

As this paper deals with the theoretical aspects of deriving indices of ventilatory functions, all available information on 18,838 persons (10,912 at Port Talbot, and 7,926 at Ebbw Vale) are used, and no attempt is made to derive 'standard' or 'normal' indices from any specific subgroups of persons.

THEORETICAL CONSIDERATIONS

Because FEV₁ is negatively correlated with age (Fig. 1) and within age groups is positively correlated with height (Fig. 2), the index FEV₁ may be expressed as a function of FEV₁, age, and height of the general form:

$$\text{Index FEV}_1 = \frac{\text{FEV}_1 \text{ Age } n_1}{\text{Height } n_2}$$

Similarly,

$$\text{Index FVC} = \frac{\text{FVC Age } n_1}{\text{Height } n_2}$$

and

$$\text{Index FEV\%} = \frac{\text{FEV\% Age } n_1}{\text{Height } n_2}$$

It will be shown that if height is unimportant as it is in the case of FEV%, the power n_2 becomes zero, and the index is automatically reduced to the form:

$$\text{Index FEV\%} = (\text{FEV\% Age } n_1)$$

(It should be noted that values of n_1 , n_2 are estimated separately for each of the three indices.)

where n_1 , n_2 are the powers to which age and height must be raised to satisfy the two following criteria:

FIG. 1.—Trend of FEV₁ and FVC with age (P.T. males 1964).

FIG. 2.—Trend of FEV₁ with height and age (P.T. males 1964).

TABLE II
POWERS ON HEIGHT WITHIN AGE GROUPS FOR INDICES
FEV₁, FVC, AND FEV% IN TWO SURVEYS (PORT TALBOT, EBBW VALE)

No.	Port Talbot Ebbw Vale	Age Group									
		20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69
Function FEV ₁	Port Talbot Ebbw Vale	509 921	799 830	1373 809	1643 888	1817 925	1506 809	1362 872	950 816	617 561	188 12
		2.03 1.65	2.29 1.80	2.22 1.54	2.09 1.63	1.99 1.87	1.99 1.65	2.33 1.42	1.94 1.79	2.66 2.43	2.43 —
FVC	Port Talbot Ebbw Vale	2.25 1.92	2.42 1.89	2.39 1.73	2.39 2.02	2.16 2.08	2.23 1.87	2.42 1.77	2.01 1.96	2.63 2.15	2.61 —
		-0.22 -0.26	(-0.13)* (-0.09)	-0.17 (-0.19)	-0.31 -0.39	-0.17 (-0.22)	-0.24 (-0.22)	(-0.09) (-0.35)	(-0.07) (-0.17)	(0.05) (0.27)	(-0.18) —
FEV%	Port Talbot Ebbw Vale										

* Powers not significantly different from zero are given in parentheses
Powers for the age group 65-69 (Ebbw Vale) are not calculated because of small numbers

1. The index must be highly correlated with FEV₁.
2. It must be independent of both age and height.

The first criterion would ensure that for fixed values of age and height, a higher (or lower) FEV₁ would correspondingly yield a higher (or lower) index. The second criterion essentially adjusts for age and height (in the sense that the index is invariant along the regression plane of FEV₁ on age and height).

It should be noted that the two powers n_1 and n_2 are not arbitrarily chosen but have a theoretical basis. It can be shown that n_1 and n_2 are the multiple regression coefficients of log FEV₁ on log (age) and on log (height). Essentially, therefore, the basic approach for deriving a satisfactory index is founded on the application of multiple regression methods.

RESULTS

Table II gives the powers of height (n_2) within five-yearly age groups in each of the two works for the three indices. The powers are consistently higher at Port Talbot than at Ebbw Vale for the indices FEV₁ and FVC, but within the two works there is no consistent trend in the variation of n_2 with age. The importance of height is negligible in index FEV%; although some of the powers are statistically significant (Table II), the additional information on log (height) reduces the percentage variation in log (FEV%) by less than 1% (Table III). The method of deriving the value of n_2 is also illustrated with an example from a typical age group in Table III.

In the European coal and steel community (CECA) study, it was assumed on theoretical grounds that a relationship exists between FEV₁ and height cubed (Table I, row 7) but this assumption

was found to be unrealistic by Cotes and his co-workers (1966) when applied to their own data. Table I (row 8) also reproduces the results of 'Dutch Foundries' on the relationship between FEV₁ and the power of height. Their reported power $n_2 = 2.12$ for FEV₁ is much closer to the values observed at Port Talbot and Ebbw Vale (Table II).

Table IV gives the powers on age (n_1) and on height (n_2) for each of the three indices in the two works. The powers on age (n_1) are remarkably similar at Port Talbot and Ebbw Vale.

Figure 3 compares the trends of FEV₁ and that of the derived index FEV₁ (as observed at Port Talbot) with age. The mean FEV₁ declines consistently

TABLE III
METHOD OF DERIVING POWERS (TYPICAL AGE GROUP
35-39, EBBW VALE)

Mean S.D.	No. of observations 888 Mean and standard deviation (LOG _e Scale)			
	Height	FEV ₁	FVC	FEV%
	4.2129 0.0358	1.2257 0.2516	1.4994 0.1811	4.3315 0.1629
Correlation Matrix				
	Log Height	Log FEV ₁	Log FVC	
Log FEV ₁	0.2326			
Log FVC	0.3999	0.7633		
Log FEV%	-0.0856	0.6958	0.0671	

Power n_2 is the regression coefficient of Log (Function) on Log (Height)

$$\text{For Index FEV}_1^* = \frac{\text{FEV}_1}{(\text{Height})^{n_2}}; n_2 = \frac{r (\text{S.D. of Log FEV}_1)}{\text{S.D. of Log Height}} = \frac{(0.2326) (0.2516)}{0.0358} = 1.6347$$

*For a fixed age group $n_1 = 0$; the general form of Index FEV₁ = $\frac{\text{FEV}_1 \text{ Age}^{n_1}}{\text{Height}^{n_2}}$ is reduced to the form $\frac{\text{FEV}_1}{\text{Height}^{n_2}}$

TABLE IV
DERIVED INDICES OF VENTILATORY FUNCTIONS IN
TWO WORKS (ALL AGES 18-69)

	Port Talbot	Ebbw Vale
No.	10,912	7,926
Index FEV ₁	FEV ₁ Age ^{0.55}	FEV ₁ Age ^{0.55}
	Height ^{2.23}	Height ^{1.74}
Index FVC	FVC Age ^{0.37}	FVC Age ^{0.33}
	Height ^{2.37}	Height ^{2.06}
Index FEV%	(FEV%) (Age) ^{0.176}	(FEV%) (Age) ^{0.185}

FIG. 3.—Trend of indices with age (P.T. males).

tently with age, and in the youngest age group (20-24 years) its value is about 84% higher than in the oldest age group (60-64 years). The corresponding trend of the index with age is much reduced. The trend (displayed by the index) is quadratic but in the age range 30-55 years its value is almost constant. Figure 3 also shows that the trends of the derived and proposed indices are parallel in the age range 30-55 years.

Figures 4, 5, and 6 highlight the absence of trend with age of the proposed indices of ventilatory functions (FEV₁, FVC, and FEV%). For practical purposes the three indices are invariant in the age range 30-55 years, and the two criteria defined earlier are satisfied by the correlation matrix (Table V). To illustrate, the FEV₁ index is highly correlated with FEV₁ ($r = 0.83$) but it is uncorrelated with height ($r = 0.02$), and although its correlation with age ($r = -0.05$) is statistically significant, in practice the unaccounted information on age

FIG. 4.—Trend of index with age (P.T. males).

FIGS. 5 AND 6.—Trend of indices with age (P.T. males 1964).

amounts to only about 0.25% of the total variation in the index. In comparison, it should be noted that FEV₁ measurements themselves are highly correlated with age (-0.48) and with height (0.42).

CALCULATION OF THE INDICES

The indices for FEV₁ and FVC can be calculated quickly for given values of age and height from tables provided by Comrie (1952), popularly known as 'Barlows tables', and the values of $(age)^{0.2}$ for calculating the FEV% index are provided in the Appendix.

The proposed indices would be of restricted use if a great deal of tedious arithmetic were involved in

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TABLE V

SOME ZERO ORDER INTER-CORRELATIONS OF INDICES, VENTILATORY MEASUREMENTS, AGE, AND HEIGHT, PORT TALBOT, MALES AGED 30-55 YEARS (BASED ON 7,701 OBSERVATIONS)

	FEV ₁	Index FEV ₁	Age	Height
FEV ₁ Index FEV ₁	1	0.83 1	-0.48 -0.05	0.42 0.02

	FVC	Index FVC	Age	Height
FVC Index FVC	1	0.83 1	-0.43 -0.06	0.53 0.08

	FEV %	Index FEV %	Age	Height
FEV % Index FEV %	1	0.96 1	-0.25 0.03	-0.01 -0.07

their calculations. The exact method of calculating them is certainly tedious and costly. However, their approximate values can be calculated quickly from mean values of FEV₁, FVC, FEV%, age, and height. Table VI shows that the results given by the exact and approximate methods are in good agreement.

APPLICATION OF LUNG FUNCTION INDICES

Table VII gives the mean values of age, height, and lung function measurements (FEV₁, FVC, and FEV%) for nine groups of males categorized by smoking habits. Rows 7, 8, and 9 give the values of the proposed indices calculated from minimal

TABLE VI

APPROXIMATE AND EXACT VALUES OF VENTILATORY INDICES, PORT TALBOT, MALES AGED 30-55 YEARS

MEAN BASED ON 7,701 OBSERVATIONS				
Age (yr)	Height (in)	FEV ₁ (litres)	FVC (litres)	FEV %
41-93	67.50	3.48	4.46	77.71
Index	Approximate	Exact	Approximate % Exact	
FEV	4.95	4.87	101.6	
FVC	3.40	3.37	100.9	
FEV %	164.1	163.5	100.4	

Formulae for calculating indices

$$\begin{aligned} \text{Approximate Index} &= \frac{(\text{Mean FEV}_1)(\text{Mean Age})^{0.75}}{(\text{Mean Height})^3} \left(\frac{\sum \text{FEV}_1(\text{Age})^{0.75}}{(\text{Height})^3} \right) / 7701 \\ \text{Exact Index} &= \frac{\sum \text{FEV}_1(\text{Age})^{0.75}}{(\text{Height})^3} / 7701 \\ \text{FVC} &= \frac{\text{Mean FVC}(\text{Mean Age})^{0.75}}{(\text{Mean Height})^3} \left(\frac{\sum \text{FVC}(\text{Age})^{0.75}}{(\text{Height})^3} \right) / 7701 \\ \text{FEV \%} &= \frac{\text{Mean FEV \%}(\text{Mean Age})^{0.75}}{(\sum \text{FEV \%}(\text{Age})^{0.75}) / 7701} \end{aligned}$$

information available from rows 2 to 6. The estimated values of ventilatory measurements (adjusted to age 40 and height 67.5 inches) based on the usual multiple regression approach are given along rows 10, 11, and 12.

To illustrate, the mean FEV₁ of ex-smokers who gave up smoking more than eight years ago (3.38 litres along row 4) is appreciably lower than that of the never smoked group (3.76 litres), but a large part of the difference is probably attributable to their

TABLE VII

MEAN VALUES OF AGE, HEIGHT, VENTILATORY MEASUREMENTS, VENTILATORY INDICES, AND ADJUSTED VALUES OF VENTILATORY MEASUREMENTS BY HISTORY OF SMOKING, PORT TALBOT, MALES, 1964

Row		History of smoking								
		Never Smoked	Ex-Smokers (yr, given up)				Current Smokers (amount smoked)			
			< 2	2-4	5-7	8+	< 15	15-24	25-34	35+
1	No.	1,842	551	527	256	859	2,490	2,747	1,000	390
2	Mean									
3	Age (yr)	38.9	39.7	41.8	42.2	47.3	43.8	43.2	43.3	44.9
4	Height (in)	67.6	67.9	67.7	67.6	67.4	67.3	67.3	67.5	67.3
5	FEV ₁ (litres)	3.76	3.58	3.50	3.55	3.38	3.38	3.31	3.26	3.13
6	FVC (litres)	4.64	4.57	4.50	4.49	4.31	4.35	4.33	4.30	4.16
7	FEV %	80.9	77.9	77.3	78.6	77.9	77.1	75.9	77.5	74.8
8	Indices									
9	FEV ₁	5.13	4.89	4.94	5.05	5.13	4.94	4.80	4.71	4.63
	FVC	3.44	3.38	3.41	3.42	3.44	3.39	3.36	3.32	3.27
	FEV %	168.3	162.9	163.3	166.1	168.4	164.4	160.1	160.1	160.1
10	Adjusted Values (Age = 40; Ht = 67.5)									
11	FEV	3.70	3.52	3.56	3.64	3.72	3.57	3.48	3.41	3.37
12	FVC	4.58	4.49	4.51	4.56	4.62	4.53	4.49	4.44	4.39
	FEV %	80.5	77.8	77.9	79.4	80.3	78.4	77.0	76.5	76.4

* Excludes known pneumoconiotics

mean age differences (row 2; 38.9 and 47.3 years). The FEV₁ index (row 7) accounts for both age and height, and the inference based on it is in excellent agreement with the adjusted values calculated by the sophisticated approach (row 10). Figure 7

FIG. 7.—Index FEV₁ and history of smoking (P.T. males).

gives the histogram of the FEV₁ index and shows the extent of its variation with the history of smoking.

DISCUSSION

The proposed indices on lung function tests are of value in epidemiological investigations as they can be calculated quickly from minimal information. The inferences based on the indices are in excellent agreement with those arrived at by the multiple regression approach. The application of the latter method needs trained personnel, is time consuming, and is largely dependent on the availability of computers.

The alternative approach of comparing age and height specific mean values of lung function measurements has the obvious limitation of small numbers of observations in some of the sub-groups of even a large-sized epidemiological investigation.

The proposed indices are invariant in the age range 30–55 years. In practice, the mean ages of the various subgroups under comparison are unlikely to fall outside these limits in any adult population of working age. The mean ages in the nine subgroups categorized on smoking history (Table VII) ranged from 38.9 to 47.3 years, well within the stated limit.

The method of forming the indices is based on theoretical considerations. But the indices themselves may vary in different populations. Further research is needed to study the universal applicability of the proposed indices in other ethnic groups with a view to standardizing indices of ventilatory function in epidemiological investigations.

SUMMARY

Ventilatory measurements of about 8,000 steel workers at Ebbw Vale and over 10,000 at Port Talbot were recorded as part of the extensive bronchitis survey in the steel industry. Ventilatory functions (FEV₁, FVC, and FEV/FVC%) decrease with age and within age groups increase with height. Height itself decreases with age. Because of these interrelations the usual regression approach is complex. Three simple indices have therefore been derived from the Port Talbot study and have then been applied to the Ebbw Vale study to validate them. Although the two works populations are different, the indices are in good agreement. The calculation of indices requires minimal information on mean age, mean height, and mean values of FEV₁, FVC and FEV% to compare groups which are different by other criteria such as symptomatology grades, smoking habits, occupation, race, and diseased state. Results derived from multiple regression analysis and indices are shown to be very similar for the age range 30–55 years.

The proposed indices are:

1. Index FEV₁ = $\frac{\text{FEV Age}^{\frac{1}{2}}}{\text{Height}^2}$
2. Index FVC = $\frac{\text{FVC Age}^{\frac{1}{2}}}{\text{Height}^2}$
3. Index $\frac{\text{FEV}}{\text{FVC}}\%$ = $\frac{\text{FEV}}{\text{FVC}}\% \text{ Age}^{0.2}$

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APPENDIX TABLE
VALUES OF $(AGE)^{0.75}$ AT SELECTED AGES

Age	$(AGE)^{0.75}$	Age	$(AGE)^{0.75}$	Age	$(AGE)^{0.75}$
30	1.974	40	2.095	50	2.187
31	2.987	41	2.102	51	2.195
32	2.000	42	2.112	52	2.204
33	2.012	43	2.122	53	2.212
34	2.024	44	2.132	54	2.221
35	2.036	45	2.141	55	2.229
36	2.048	46	2.151	56	2.237
37	2.059	47	2.160	57	2.245
38	2.070	48	2.169	58	2.253
39	2.081	49	2.178	59	2.260

Values of the function $(age)^{0.75}$ at intermediate ages can be found by interpolation.