PULMONARY FUNCTION UNIT

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The pulmonary function laboratory forms an important part of any major medical centre. Pulmonary function tests have resulted in greater understanding of the normal and abnormal working of the lungs. There are many tests available and the physiology of the lung has been well studied. The intimate contact of the lungs with the atmosphere has made such studies possible and relatively simple. The tests have provided a scientific basis for physiological interpretation of pulmonary diseases and their more rational treatment.[1-5] The tests performed should be regarded as complementary to the clinical and radiological assessment.

APPLICATION OF PULMONARY FUNCTION TESTS

Diagnosis

The main medical application of pulmonary function tests is diagnostic, but the tests help in the management of cases and in the evaluation of therapy. Tests help particularly in the accurate diagnosis of obstructive airways disease (e.g. asthma or emphysema), restrictive lung disease (e.g. pulmonary fibrosis), diffusion defects and ventilation-perfusion abnormalities (e.g. diffuse interstitial pulmonary infiltration) and pulmonary vascular obstruction (e.g. pulmonary emboli). The tests can usually help distinguish cardiac from pulmonary disability but the close inter-relationship of the cardiovascular and respiratory systems result in abnormalities of both, whichever one is primarily at fault.

A large number of cases referred for tests suffer from breathlessness or cyanosis. Vascular shunts from the right side of the circulation to the left can be demonstrated if the arterial oxygen saturation does not increase to almost 100% on breathing pure oxygen, a procedure which eliminates cyanosis owing to diffusion defects or uneven intrapulmonary distribution of inspired air. No case should be diagnosed as psychogenic dyspnoea or hyperventilation syndrome unless all tests are negative.

Primary polycythaemia can be differentiated from the secondary type by the normality of the arterial oxygen saturation and the absence of abnormality in other pulmonary function tests.

Evaluation of Therapy

Pulmonary function tests help to evaluate therapy objectively. For example, in acute conditions such as asthmatic attacks, the effects of aerosols can be compared by measuring changes in distribution of inspired air or in timed vital capacity. In chronic conditions such as diffuse interstitial pulmonary infiltration, the tests help to differentiate the specific effect of steroid therapy on improvement in exercise tolerance from the symptomatic benefit due to euphoria, increased appetite and general well-being.

Aid to Surgery

Preparatory to surgery of any sort in patients with chronic pulmonary disease and particularly before cardio-thoracic surgery, measurement of lung function and assessment of respiratory reserve can be made. If the reserve is low, tracheotomy at the end of the operation must be considered. The thoracic surgeon can be aided in deciding on the advisability and extent of resection of diseased lung. Bronchospirometry, a technique by which the 2 lungs are tested separately and the contribution of each to total oxygen uptake is measured, has its main application here.

Epidemiology and Medico-legal Considerations

In epidemiologic surveys, simple rapid screening tests have been used on large populations to assess the influence of environmental factors on the incidence of disease, for example chronic bronchitis. Miners and non-miners have been compared to determine whether chronic bronchitis is an occupational hazard of the miner. In industries where workers suffer from a high incidence of chest disease, pulmonary function tests at regular intervals may detect the onset of abnormality early and result in advice to the individual to leave his hazardous occupation. The tests have also been applied to assess disability objectively for medico-legal purposes, including injuries to the chest, industrial exposure and workmen's compensation.

The Pulmonary Function Unit of the Johannesburg Hospital has provided a routine service involving all the applications of lung-function tests discussed above. More than 1,500 subjects have been investigated by the Unit. In addition to the routine diagnostic service, research has been carried out into a number of aspects of pulmonary physiology and pathology. A brief account of these studies is given below.

REVIEW OF PUBLISHED WORK

(a) *Investigation of Lung Function at Altitude of* 6,000 *Feet*

As Johannesburg is one of the few major cities in the world at median altitude (approximately 6,000 feet), and as knowledge of the range of normal values is essential for the interpretation of biological tests, it was necessary to establish our own normal values for various aspects of pulmonary function.

In 44 males and 50 females ranging in age from 16 to 75 years, measurements were made of the subdivisions of lung volume, maximal breathing capacity (maximum voluntary ventilation), ventilation at rest and during standardized exercise, arterial oxygen saturation and a mixing index (an index of intrapulmonary distribution of inspired air). This study showed that values for the subdivisions of lung volume of subjects acclimatized at 6,000 feet above sea level do not differ significantly from subjects at sea level. In contrast, maximal breathing capacity and both resting and exercise ventilation are significantly higher, while the resting arterial oxygen saturation is significantly lower. Formulae were derived for predicting various subdivisions of lung volume from age and body characteristics (Table I).[6]

TABLE I. PREDICTION FORMULAE FOR SUBDIVISIONS OF LUNG VOLUME, MAXIMAL BREATHING CAPACITY, AND RESTING VENTILATION

Value to be predicted	*R**	*r*†	*Age* (*A*)	*Height* (*H*)	*Weight* (*W*)	*Surface area* (*S*)	*Constant in the equation*	*Coefficient of variation* %
			Male subjects					
Vital capacity (litres)	0·866	0·855	−0·031(A)	+0·064(H)			−5·335	11
Residual volume (litres)	0·647	0·636	+0·017(A)	+0·027(H)			−3·447	19
Total lung capacity (litres)	0·774	0·769	−0·015(A)	+0·094(H)			−9·167	10
Functional residual capacity (litres)		0·572		+0·081(H)		−1·792(S)	−7·11	17
Residual volume/total lung capacity × 100		0·779	+0·343(A)				+16·7	15
Functional residual capacity/total lung capacity × 100		0·558	+0·187(A)			−14·9(S)	+75·9	11
Maximal breathing capacity (l./min.)	0·870	0·864	−1·873(A)			+78·2(S)	+72·7	14
Resting ventilation (l./min.)	0·675	0·518	+0·037(A)		+2·363(W)		+4·378	12
			Female subjects					
Vital capacity (litres)	0·756	0·744	−0·018(A)	+0·052(H)			−4·36	13
Residual volume (litres)	0·586	0·548	+0·009(A)	+0·032(H)			−3·90	24
Total lung capacity (litres)	0·727	0·716	−0·008(A)	+0·079(H)			−7·49	11
Functional residual capacity (litres)	0·636	0·610		+0·053(H)	−0·017(W)		−4·74	17
Residual volume/total lung capacity × 100	0·629	0·605	+0·265(A)				+21·7	18
Functional residual capacity/total lung capacity × 100	0·633	0·548	+0·146(A)		−0·428(W)		+75·9	13
Maximal breathing capacity (l./min.)	0·806	0·751	−0·965(A)			+67·18(S)	+26·3	15
Resting ventilation (l./min.)	0·562	0·548	−0·02(A)		+0·94(W)		+3·67	18

* Multiple correlation coefficient between measurement and the four body characteristics.
† Correlation coefficient between measurement and the one or two variables retained in the final formula.

(b) *Development of Techniques*

The mixing index used in the altitude study had been devised earlier and it was shown theoretically, with experiments on a model lung and on trained subjects, that indices of intrapulmonary mixing (calculated from closed circuit studies) are likely to be more accurate in describing this aspect of pulmonary function, if cognizance is taken of pulmonary dead space in their calculation.[7-9] A formula for predicting dead space was derived.[10] Mixing indices corrected for dead space were shown to distinguish better between normal and emphysematous subjects than did indices not so corrected. (Fig. 1.)

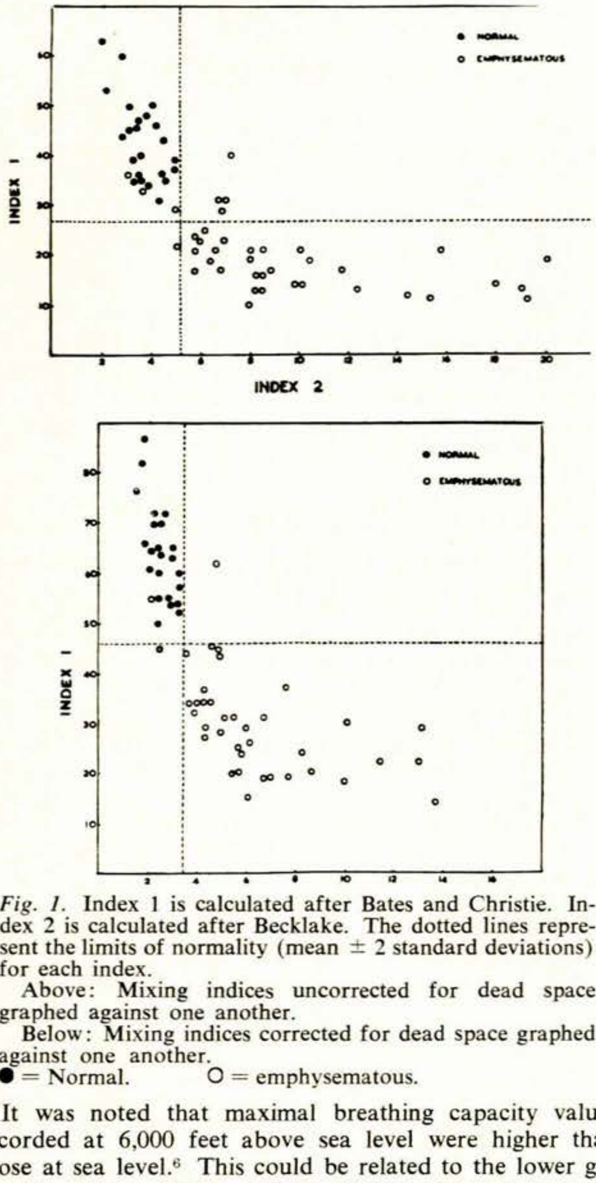

Fig. 1. Index 1 is calculated after Bates and Christie. Index 2 is calculated after Becklake. The dotted lines represent the limits of normality (mean ± 2 standard deviations) for each index.

Above: Mixing indices uncorrected for dead space graphed against one another.

Below: Mixing indices corrected for dead space graphed against one another.

● = Normal. O = emphysematous.

It was noted that maximal breathing capacity values recorded at 6,000 feet above sea level were higher than those at sea level.[6] This could be related to the lower gas density at this altitude, which might be expected to cause reductions in both the internal work of breathing and in the pressure flow characteristics of the instruments used. An investigation of the resistance characteristics of 2 standard methods and our gasometer method of estimating maximal breathing capacity was undertaken.[11] This showed that the gasometer apparatus had low resistance to air flow and was accurate. The influence of increased instrumental resistance on maximal breathing capacity measurements was assessed in 16 normal subjects and in 16 patients with chronic chest disease. Small resistance added to both inspiration and expiration caused a negligible reduction in these values, but larger resistances reduced them significantly especially in some of the patients (Fig. 2).

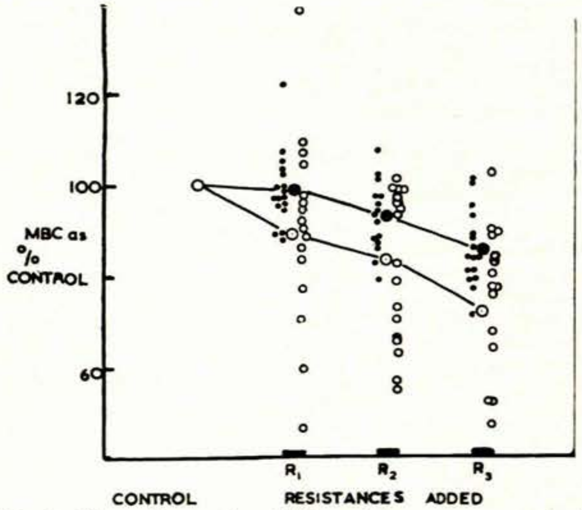

Fig. 2. The effect of added resistance on maximal breathing capacity (MBC) values in 16 normal subjects (closed circles) and in 16 patients (open circles). All values are expressed as a percentage of the MBC measured on the gasometer apparatus without added resistance, hence control values are all 100%. Two lines drawn through the mean values for MBC with each resistance indicate the extent of the decrease of MBC in the normal and abnormal subjects respectively.

An essential feature of the gasometer apparatus is the valve-box which was designed to have low resistance to air flow and a small dead space.[12] It was shown to compare favourably with other respiratory values (Fig. 3) and is currently used in our laboratory for measuring ventilation during exercise. It had been modified from an earlier

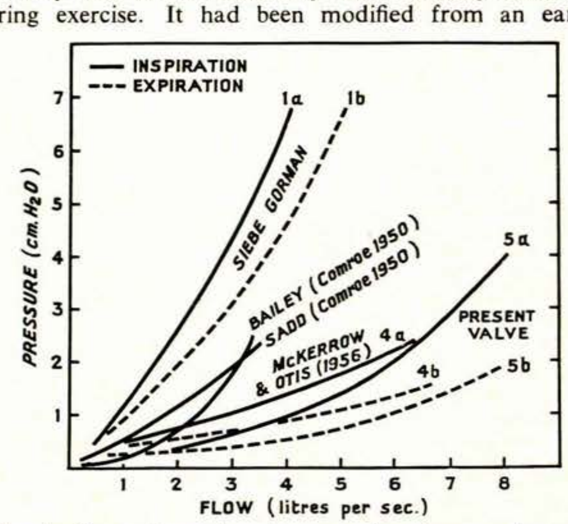

Fig. 3. Comparison of resistances of various respiratory valves measured in inspiration and expiration. The 'present valve' is now used as a routine in our laboratory.

designed valve-box face-mask unit.[13]

Another apparatus was designed for use in the assessment of the work of breathing;[14] it allowed the instantaneous measurement of gas volumes. It consists of a large metal box into which the subject breathes, the volume of each breath being obtained from the pressure change in the box. It has a linear response and negligible phase lag up to the highest frequencies tested (80 breaths/minute). (Fig. 4.)

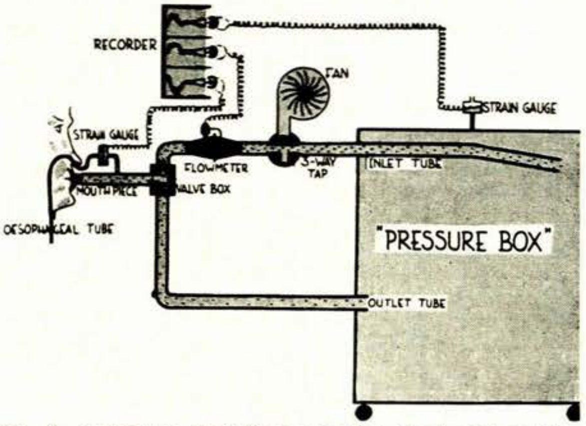

Fig. 4. Apparatus used for measuring work of breathing.

(c) *Dyspnoea and Work of Breathing*

The symptom of dyspnoea can usually be related to the work of breathing. To ventilate the lungs, the respiratory muscles do 'work' which can be measured. The work depends on the volume ventilated, the force to stretch the elastic lung to accommodate the inspired air (compliance), and the force to draw air into the lung (non-elactic resistance). In cardio-pulmonary diseases at least one of these 3 factors is excessive, and the resultant increased respiratory work causes fatigue of the respiratory muscles. This muscular fatigue is possibly related to the symptom of dyspnoea. It was shown that dyspnoea in mitral stenosis was related to hyperventilation during standardized exercise.[15] Conversely, in cases of mitral stenosis without dyspnoea, but with cardiac catheter evidence of severe mitral valve obstruction, we have found marked tachycardia without hyperventilation.

The oxygen consumed by the respiratory muscles (the oxygen cost of breathing) and the work of breathing were compared in 14 normal subjects (mean weight 73 kg.) and 12 obese but otherwise normal subjects (mean weight 112 kg.).[16] It was found that obese individuals have an increased work of breathing, and for similar increments in ventilation in the range 10 - 30 l./min., the oxygen cost of increased ventilation in the obese subjects was markedly higher than that observed in the normal subjects. The higher incidence of dyspnoea and respiratory failure in obese subjects may be related to these observations.

(d) *Evaluation of Therapy*

A number of studies have been performed which demonstrate the value of pulmonary function tests in the objective assessment of therapeutic procedures. A case of diffuse interstitial fibrosis of the lungs was treated with adrenal steroids and followed for more than 3 years with serial tests which showed maintained improvement.[17] Fifteen emphysematous subjects were tested before and after one of two forms of physiotherapy: either a course of breathing exercises or such a course augmented by electrical stimulation of chest and abdominal muscles during expiration. It was concluded that no evidence of the efficacy of these procedures had been obtained, and that the benefit claimed by some subjects was more likely to be the result of psychic than physical factors.[18] Similarly, in 11 cases of emphysema, symptomatic improvement after pneumoperitoneum was claimed by 9, but this could not be correlated with improvement in tests of lung function.[19]

Twenty-one cases of bronchiectasis were studied before and after surgical treatment.[20] It was noted that bronchiectasis of any degree of severity may result in marked impairment of lung function. Consequently, both pre- and postoperative studies are necessary to determine the functional effects of the operation. Studies performed in the immediate postoperative period will not reflect the eventual functional state of the lung. In the months following resection of bronchiectatic segments, two progressive changes were observed, namely, increasing inflation and progressive improvement of maximal breathing capacity. Where excision of segments was limited to the diseased areas, the adverse effects on lung function were small. Considerable hyperinflation of the remaining lung was usual, but there was no evidence that this impaired lung function (Table II).

(e) *Exposure to Nitrous Fumes*

Seven patients who had recovered from an episode of acute pulmonary oedema following an industrial accident with exposure to nitrous fumes were studied serially for up to 5 years. The pattern of physiological disturbance was reduction in maximal breathing capacity and increase in expiratory non-elastic resistance values. The proposed explanation was that the patient had bronchial and bronchiolar narrowing owing to bronchiolitis obliterans following exposure to nitrous fumes.[21]

(f) *Effects of Smoking*

Ten healthy young adult males who had never smoked were compared clinically and by the application of pulmonary function and exercise tolerance tests with a similar group who had regularly smoked cigarettes.[22] They were matched for age, physical characteristics and fitness. Although 6 of the smokers had cough and sputum, these symptoms were absent in the non-smokers. By statistical techniques, physiological indices for smokers and non-smokers were obtained (Fig. 5), using the following variables: vital capacity, ratio of residual volume to total lung capacity, compliance, non-elastic resistance and arterial oxygen saturation and heart rate during exercise. It was concluded that smoking alters pulmonary function in the direction of chronic obstructive lung disease within the first fifteen years after commencing the habit, and adversely affects the cardiovascular system.

(g) *Radiology in Emphysema*

The diagnosis of emphysema is still a problem. There is as yet no definition of the disease which is fully acceptable to clinicians, radiologists, physiologists and pathologists, but we have used the definition recommended at the Aspen Symposium in 1958.[23] The reliability of certain radiological signs of emphysema was investigated by studying the radio-

TABLE II. SUMMARY OF PRE-OPERATIVE AND POSTOPERATIVE LUNG FUNCTION TESTS IN 21 CASES OF BRONCHIECTASIS

Case	*Months post-operatively*	*Vital capacity*		*Residual volume*		*Functional residual capacity*		*Maximal breathing capacity*			*Resting ventilation*	*Exercise ventilation*	*Lung clearance index*	*Arterial oxygen per cent of change on effort*
		l.	*Per cent predicted*	*l.*	*Per cent predicted*	*l.*	*Per cent predicted*	*l./per min.* (1)*	*l./per min.* (2)	*Per cent predicted* (2)	*l./min.*	*l./min.*		
	Normal limits†													
	M		92–108		76–124		79–121			92–108	8–13	22–42	<3·43	<5
	F		90–110		76–124		84–116			90–110	6–12	23–42	<3·45	<5
3A	Pre-operatively	3·53	88	4·37	214	5·23	152	—	68	64	12·6	47·2	5·9	−2
	5	3·53	88	3·40	167	4·59	145	—	80	77	11·0	—	3·0	−7
3B	Pre-operatively	3·80	93	—	—	—	—	26	—	—	—	—	—	—
	7	3·23	79	2·17	125	3·40	102	46	—	—	—	—	3·7	—
	18	2·45	60	2·92	169	4·10	123	70	—	—	—	—	3·7	—
4A	Pre-operatively	2·68	54	3·35	188	4·41	123	28	—	—	—	—	—	−3·5
	1	2·07	42	2·30	129	3·37	94	37	—	—	—	—	4·5	−5
	53	4·13	83	2·62	147	4·25	118	102	106	65	12·6	39·8	3·2	−10
4B	Pre-operatively	2·90	66	1·89	111	2·99	91	—	98	68	11·7	36·2	3·8	−6
	3	3·03	69	1·91	112	2·76	84	—	107	75	9·0	32·7	3·7	−7
4C	Pre-operatively	2·16	68	1·94	150	2·48	102	—	61	59	12·8	41·1	8·0	+3
	5	2·52	80	1·77	137	2·60	107	—	86	83	11·6	38·1	3·4	−1
4D	Pre-operatively	4·24	72	2·18	96	3·89	90	—	108	61	9·1	32·6	2·9	−10
	5	3·95	67	2·47	107	4·40	101	—	123	69	14·0	31·3	2·4	−11
4E	Pre-operatively	3·09	99	1·87	136	2·72	107	—	87	88	5·6	48·6	3·9	−3
	2	2·42	78	1·80	131	2·61	103	—	88	89	9·2	45·2	4·9	−3
5A	Pre-operatively	3·03	65	3·07	186	4·52	134	86	—	—	15·7	42·3	—	—
	9	2·27	49	2·93	178	3·98	118	74	87	48	12·9	40·5	—	—
5B	Pre-operatively	4·52	87	3·14	175	5·06	129	80	—	—	—	—	2·8	—
	6	3·56	68	3·73	206	5·34	136	90	—	—	—	—	3·7	—
5C	Pre-operatively	2·89	77	1·98	130	3·20	103	28	—	—	—	—	2·9	−3·5
	1	1·90	49	1·92	126	2·59	83	31	—	—	—	—	3·3	−3·5
5D	Pre-operatively	2·68	66	2·32	145	3·34	106	55	—	—	—	—	9·0	—
	7	2·26	55	2·25	139	3·42	109	46	—	—	—	—	6·0	—
5E	Pre-operatively	3·73	105	2·19	164	3·99	143	—	88	81	5·5	39·1	4·3	−5
	6	3·09	87	1·62	124	3·30	118	—	79	73	7·5	39·2	2·7	−8
5F	Pre-operatively	2·54	66	1·70	109	2·60	82	—	102	93	9·4	42·8	5·9	−10
	3	2·43	62	1·29	84	2·21	70	—	80	73	10·0	38·3	4·0	−10
	12	2·63	68	1·54	99	3·05	96	—	84	76	10·0	42·2	4·9	−9
6A	Pre-operatively	1·85	54	2·08	181	2·72	102	35	—	—	—	—	5·5	—
	2	1·65	48	1·69	147	2·37	89	33	—	—	—	—	7·5	—
	3‡	—	—	—	—	—	—	—	—	—	—	—	—	—
	7	1·61	47	1·10	96	1·69	68	26	31	31	—	—	7·9	−6
	50	1·51	43	1·38	108	2·08	76	—	36	36	—	—	4·7	−8
6B	Pre-operatively	2·45	70	1·99	156	3·03	110	47	—	—	—	—	2·5	—
	4	2·05	59	1·46	114	2·35	86	48	—	—	—	—	2·9	—
	11	2·12	61	1·92	150	2·93	107	45	—	—	—	—	3·5	—
6C	Pre-operatively	2·61	76	1·59	136	2·24	83	52	—	—	—	—	2·8	—
	2	2·40	71	1·86	159	2·38	88	60	—	—	—	—	2·3	—
	5‡	—	—	—	—	—	—	—	—	—	—	—	—	—
	10	2·01	59	1·81	154	2·39	89	61	—	—	—	—	3·1	—
	16	2·24	66	2·00	171	2·66	99	53	84	83	—	—	—	−1
	60	2·48	75	1·67	137	2·62	98	—	71	70	6·48	36·1	2·8	−1
6D	Pre-operatively	4·83	108	2·20	103	3·70	109	—	118	85	10·9	37·7	3·0	−6
	11	4·28	96	2·49	117	4·28	126	—	102	75	11·2	33·6	2·4	−6
	21	4·43	99	2·33	110	4·48	132	—	110	79	7·4	34·3	2·2	−7
7A	Pre-operatively	2·50	67	2·18	140	3·00	101	37	—	—	—	—	—	—
	4	1·74	47	1·93	125	2·81	95	48	—	—	—	—	—	—
8A	Pre-operatively	3·14	74	2·65	139	3·86	97	—	71	57	8·8	46·1	3·32	−5
	4	2·50	59	2·97	155	4·29	108	—	56	44	9·7	45·4	3·13	−12
	6‡	—	—	—	—	—	—	—	—	—	—	—	—	—
	8	2·53	60	2·68	140	3·99	100	—	78	63	9·8	38·0	2·98	−18
	12	2·82	67	2·24	117	3·67	91	—	66	53	9·4	37·4	2·88	−10
10A	Pre-operatively	2·82	77	2·00	152	3·34	121	53	—	—	—	—	6·22	—
	3	1·65	45	1·47	111	2·00	72	34	—	—	11·7	43·9	3·43	—
	6	2·76	75	1·32	100	2·29	83	69	—	—	9·9	27·4	3·34	−5
	8‡	—	—	—	—	—	—	—	—	—	—	—	—	—
	12	2·57	70	1·43	108	2·27	82	—	90	76	12·0	28·2	3·0	−7
	48	2·99	83	1·24	91	2·35	86	—	105	91	8·7	26·2	2·2	−15
10B	Pre-operatively	3·14	78	2·15	123	3·18	104	62	—	—	11·6	—	4·21	—
	9	2·82	70	1·25	72	2·32	76	51	—	—	11·8	33·7	5·44	−10
	10‡	—	—	—	—	—	—	—	—	—	—	—	—	—
	17	2·30	57	1·78	102	2·59	95	—	50	42	9·1	36·9	3·83	−11
	50	2·86	72	1·87	106	3·23	108	—	52	43	10·2	32·0	2·76	−13

The number of the patient reveals the number of segments of lung finally resected.
* MBC(1) represents test carried out with relatively high resistance circuit. Values are of comparative value only.
† Normal limits based on study of 94 normal subjects (14).
‡ Second operation.

graphs of 93 cases who had been seen in the Pulmonary Function Unit.[24] These included 26 cases of emphysema and 10 normal subjects. Twenty-five of the emphysema cases were correctly diagnosed from the radiographs alone using 4 major signs: diaphragmatic movement in full expiration and full inspiration, loss of lung vascular markings with generalized increase in lung translucency, prominence of the pulmonary artery segment and hilar vessels, and abnormalities of cardiac contour. If generalized adventitious lung markings were visible, emphysema was unlikely to be present.

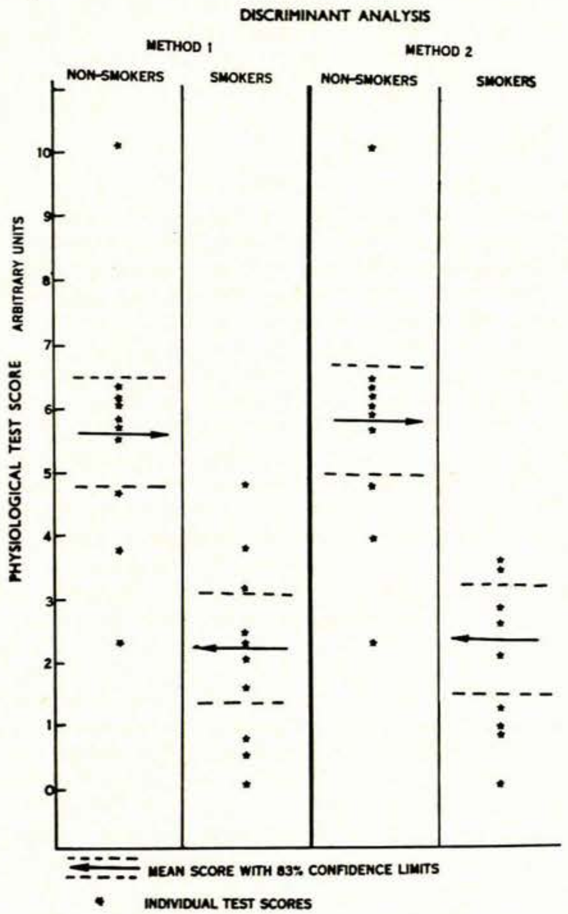

Fig. 5. Physiologic test scores were calculated for each subject, using two different techniques of discriminant analysis: pivotal condensation (method 1) and point biserial correlation (method 2). The units of the two methods were adjusted to a common scale, and the individual and mean scores with 83% confidence limits are shown. The difference between the means of smokers and non-smokers is significant at the 99% level.

(h) *Respiratory Failure*

The Pulmonary Function Unit studied cases of respiratory failure and helped formulate criteria and methods of diagnosis and management.[25-27] Emphasis was placed on the many different causes of the condition and on the fact that simple bedside observations recorded serially helped in deciding what measures of treatment to adopt. The observations include the mental state, the respiratory rate, the pulse rate, the blood pressure, the degree of cyanosis and the rectal temperature. The pathophysiologic basis of the condition was also analysed and discussed. The Unit's work on respiratory failure was instrumental in the establishment of a well-equipped modern Respiratory Resuscitation Unit whose early experiences have been reported.[28]

SUMMARY

Pulmonary function tests are of value in diagnosis, in the objective evaluation of therapy, in assessing patients for cardiothoracic and general surgery, in epidemiology, and in the measurement of disability for medico-legal purposes.

Publications from the Pulmonary Function Unit are reviewed. They include the establishment of normal values for lung function at the altitude of Johannesburg (approximately 6,000 feet); modified techniques for measuring maximal breathing capacity and work of breathing; the assessment of dyspnoea in cardiac disease; the oxygen cost of breathing in obesity; studies to evaluate steroid therapy, physiotherapy in emphysema and surgery for bronchiectasis; the long-term effects of nitrous fumes and smoking; the radiology of emphysema; and the diagnosis and management of respiratory failure.

The Pulmonary Unit acknowledges the cooperation received from the Departments of Radiology and Thoracic Surgery, the orthopaedic surgeons attached to the Hope Training Home, the Pneumoconiosis Research Unit, the Chamber of Mines Hospital and the Statistical Division of the Chamber of Mines Research Laboratory. Appreciation is expressed to those who referred cases for investigation. Miss J. Phillips and Mrs. W. Hogg are thanked for their assistance with testing patients, and Mr. Shevitz and staff for the illustrations.

ADDENDUM

The correct prediction formula for functional residual capacity in females is:

$$FRC = +0{\cdot}053\ (H) - 0{\cdot}017\ (W) - 4{\cdot}74$$

and not

$$FRC = +0{\cdot}53\ (H) - 0{\cdot}017\ (W) - 4{\cdot}74$$

as previously published.[6]

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