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Evaluation of two techniques for measurement of respiratory resistance by forced oscillation

A study in young subjects with obstructive lung disease

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The measurement of respiratory resistance by forced oscillation requires minimal patient co-operation and should be a useful test in children. Sixty-eight children and adolescents with obstructive lung disease were studied using two different techniques. In patients with severe obstructive lung disease, unexpectedly low values for respiratory resistance were found when the measurement was made at points of peak flow (write-out method). Measurements made at simulated resonant frequency (subtraction method) in these patients were more in keeping with other tests of respiratory function; however, they probably did not reflect true respiratory resistance. The subtraction method of measuring respiratory resistance would seem to be of value in separating the normal from the abnormal, but the absolute values in obstructed subjects are difficult to interpret.

The measurement of respiratory resistance by the technique of forced oscillation was introduced by Brody and DuBois (1956) and subsequently assessed by Brody, DuBois, Nissell, and Engelberg (1956), DuBois, Brody, Lewis, and Burgess (1956), and Brody *et al.* (1964). It has been applied to clinical measurements because it eliminates the need for an oesophageal balloon, and as it requires very little co-operation from the subject it can be used during spontaneous breathing.

The method is based on the theory that the respiratory system has a resonant frequency (DuBois *et al.*, 1956). If a sinusoidal pressure is applied to subjects who suspend their own efforts to breathe, the human respiratory system has a resonant frequency of about 6 cycles per second. At this frequency, compliance and inertial factors are equal and of opposite sign thus cancelling each other. The resultant impedance is purely flow-resistive. Therefore the ratio of applied pressure to flow amplitude can be used to measure the flow resistance of the respiratory system. Grimby *et al.* (1968) found a resonant frequency of 5–7 cycles per second in normal adult patients. However, in some patients with chronic obstructive lung disease no definite resonant frequency was demonstrable at least up to 10 cycles per second. With change in frequency they found that pressure and flow remained out of phase and that these patients, in fact, had frequency dependence of resistance.

Mead (1960) modified the technique and showed that the measurement could be made during spontaneous breathing by superimposing the forced oscillations on the breathing pattern. Two methods have been described to use this principle in the measurement of total respiratory resistance at frequencies other than the resonant frequency. Grimby *et al.* (1968) simulated the conditions of resonant frequency by electrically subtracting from the pressure signal a signal which varied with either volume or volume acceleration, depending on whether the measurement was being made above or below the resonant frequency. They displayed pressure and flow on the x and y axes respectively of an oscilloscope and determined the resistance from the angle of the slope. Goldman *et al.* (1970) described a direct write-out method by which resistance was determined by relating flow at points of zero volume acceleration, i.e., the extremes of flow, to the corresponding pressure change. These points fall midway in each cycle and so occur at points of equal oscillatory volume, which means that the pressure related to the elastic properties (volume change) of the system must be the same at the two points. As the measurement is made between points of zero volume acceleration inertial factors are zero. Commercial equipment using this principle has been developed.

In this laboratory a write-out method based on the theory of Goldman *et al.* (1970) was used to study normal children and adolescents and those with obstructive airways disease. It appeared to give satisfactory results in normal patients; however, a number of patients with significant airways disease and low forced expiratory flow rates had pressure and flow so markedly out of phase that calculated resistance was very low. The subtraction method of Grimby *et al.* (1968) was then used and this gave higher values for some of these patients with obstructive lung disease. Therefore a series of tests were performed on patients with obstructive lung disease to determine the relative merits of these two methods of measuring respiratory resistance.

MATERIALS AND METHODS

The two techniques were performed in 68 patients, most of whom had obstructive airways disease of varying type and severity. The patients comprised 25 with bronchial asthma, 24 with cystic fibrosis, 13 with bronchiectasis, two with suppurative bronchitis, and four with a funnel chest deformity and no known underlying lung disease. Inspiratory resistance was measured in 34 patients by both of these techniques, while expiratory resistance was measured in another 34.

Oscillatory resistance was measured with the patient sitting in a flow displacement total body plethysmograph (Mead, personal communication). He supported his cheeks with his hands and breathed into a mouthpiece. Oscillations at the mouth were produced at 4 to 5 counts/sec by a sine wave generator and amplifier driving a loud speaker system in a box with two 12 inch loud speakers (Acoustic Research Model AR1) arranged mechanically in series. The box and loud speakers were designed to provide a sine wave with as little impedance to breathing as possible and with a pressure variation at the mouth which was as nearly as possible independent of changes in mechanical impedance offered by the patient (Grimby *et al.*, 1968). A length of tubing connecting the box to atmosphere provided high impedance to the oscillations but very little to breathing. To avoid re-breathing the expired air a bias flow of 0·4 l./sec was taken from a side tap and the resulting shift was suppressed electrically. Flow at the mouth was measured with a Fleisch No. 4 pneumotachograph (1 mm H_2O=1·541 l./sec). Mouth pressure was measured from a side tap in the mouthpiece assembly by a Statham pressure gauge (p 23 dB) (Fig. 1).

Forced oscillations were produced at 4–5 cycles/sec. This low level was used to avoid the fall in resistance that has been noted with increasing frequency (Grimby *et al.*, 1968; Hyatt, Zimmerman, Peters, and Sullivan, 1970). A lower frequency was impractical because with a child's respiratory rate of 20–24 breaths/min insufficient oscillations per breath would be available for analysis.

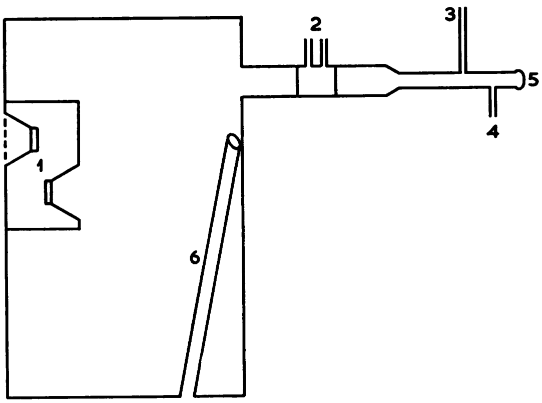

FIG. 1. *Equipment used to produce oscillations:*

1. *2×12 inch loud speakers arranged mechanically in series*
2. *Flow meter*
3. *Bias flow*
4. *Mouth pressure gauge*
5. *Patient*
6. *Tubing from atmosphere to box. This provides a high inertial impedance at high frequencies (oscillations) and low inertial impedance at low frequencies (tidal breathing).*

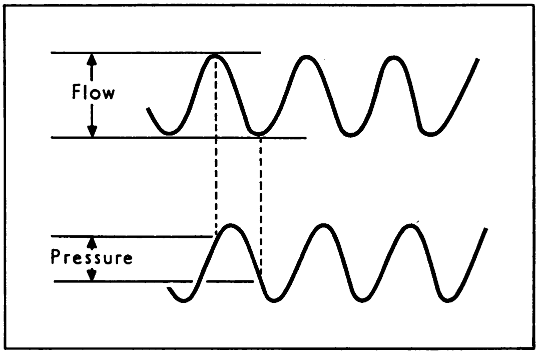

FIG. 2. *Technique for calculating resistance using the write-out method.*

Measurements were made during both inspiration and expiration in this study. Inspiration is more commonly used because of the possibility of dynamic compression and changes in the upper airways during expiration (Ferris, Mead, and Opie, 1964).

For the write-out technique, the actual pressure change between the points of zero volume acceleration was derived from continuous chart recordings of flow and pressure on a Hewlett Packard 8 Channel Recorder. Resistance was then calculated from the tracings (Fig. 2).

In the subtraction techniques, pressure was recorded on the x axis and flow on the y axis of a storage oscilloscope (Tektronix 564 B). When looping was present a signal approximately proportional to volume was subtracted from the pressure signal until a straight line was obtained or looping was minimal. From the angle of the line resistance was calculated (Fig. 3).

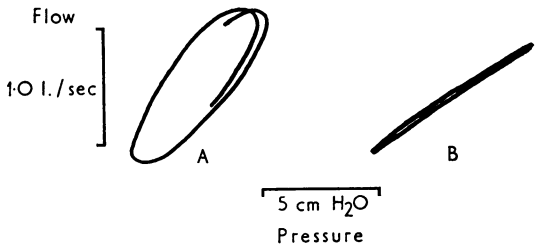

FIG. 3. *(A) Pressure-flow loop obtained using subtraction technique. (B) Looping diminished by subtracting a signal proportional to volume from the pressure signal. Resistance measured from slope of line.*

Lung volumes were measured in the body plethysmograph by a technique based on that described by DuBois *et al.* (1956). Maximum expiratory flow volume curves were obtained by recording expiratory flow and lung volume on the y and x axes respectively of a storage oscilloscope during a forced expiration (Hyatt, Schilder, and Fry, 1958).

RESULTS

Tables I and II show resistance measurements together with details of patient's age, height, diagnosis, residual volume: total lung capacity ratio, and maximal expiratory flow at 50% TLC expressed as a fraction of TLC per second. Zapletal *et al.* (1969) have shown that this method of expressing maximum expiratory flow eliminates variability that may be seen due to difference in lung size in children, and using this lung inflation provides good discrimination. Some patients have a residual volume greater than 50% and these are tabulated with a dash; others have negligible flow rates for part of the vital capacity above residual volume and these are recorded as zero. Normal maximum expiratory flow rate at 50% TLC is greater than 0·41 TLC/sec (Zapletal *et al.*, 1969). Normal RV/TLC ratio is less than 30% (Polgar and Promadaht, 1971).

Conductance (the reciprocal of resistance) has a straight line relationship with the cube of height and the lower limit of normal for the ratio of conductance to height^3 is $0{\cdot}038 \times 10^{-6}$ l./sec/cm H_2O/cm^3 (Wohl, personal communication; Landau and Phelan, unpublished data). However, the value is usually expressed as resistance and the results have been tabulated as such with those readings falling outside the normal range marked with an asterisk.

TABLE I

DETAILS OF PATIENTS

Patient	Age (yr)	Height (cm)	RV/TLC %	Max. Exp. Flow at TLC 50	R_I (write-out)	R_I (slope)
Bronchial asthma						
1	13	158	65	—	5·5	15·4*
2	13	133	64	—	12·2*	2·1
3	8	138	43	0·09	5·2	10·2*
4	7	129	38	0·13	7·1	10·6
5	7	123	39	0·13	5·0	7·1
6	10	139	22	0·14	8·1	12·0*
7	14	154	23	0·16	5·5	10·4*
8	8	135	32	0·22	6·4	7·4
9	12	139	44	0·27	7·0	5·2
10	11	144	23	0·28	4·6	6·8
11	12	146	34	0·40	7·0	9·6*
12	11	159	31	0·40	5·6	5·2
13	10	143	16	0·77	7·8	12·2*
Cystic fibrosis						
14	13	142	42	0·00	5·9	7·9
15	10	128	48	0·00	10·0	9·6
16	21	171	39	0·01	2·9	3·1
17	12	148	36	0·06	6·4	10·7*
18	18	153	45	0·07	3·7	3·0
19	12	136	40	0·10	10·1	10·1
20	14	163	42	0·10	17·0*	6·7
21	15	153	34	0·23	6·1	8·2*
22	14	158	25	0·41	4·4	7·4*
23	11	137	31	0·53	3·6	9·9
Suppurative bronchitis						
24	12	131	67	—	4·1	11·0
25	32	165	37	0·02	6·8*	12·5*
26	10	138	36	0·09	7·1	15·8*
Bronchiectasis						
27	8	128	39	0·18	6·9	11·8
28	18	156	32	0·31	3·5	4·8
29	18	181	22	0·43	3·0	3·2
30	19	166	21	0·48	2·4	3·3
31	19	156	31	0·55	4·3	5·0
32	9	127	21	0·56	8·0	10·1
33	11	159	18	0·82	4·8	4·8
Funnel chest deformity						
34	10	139	28	0·56	5·2	5·1

RV/TLC ratio expressed as percentage, max. exp. flow at 50% TLC expressed as TLC/sec
R_I (write-out) = total respiratory resistance measured by write-out method during inspiration
R_I (slope) = total respiratory resistance measured from slope by subtraction method during inspiration
Resistance expressed as cm $H_2O/(l./sec)$
Levels of resistance greater than normal predicted for height marked with an asterisk
Patients are graded in order of increasing flow rates for each disease.

Figures 4 and 5 show the relationship between resistance measured by each technique. The line of identity is shown.

Children with mild obstructive lung disease had similar values for total resistance measured by each of these techniques. Patients with very

TABLE II
DETAILS OF PATIENTS

Patient	Age (yr)	Height (cm)	RV/TLC %	Max. Exp. Flow at TLC 50	R_E (write-out)	R_E (slope)
Bronchial asthma						
1	13	148	49	0·03	7·9	17·2*
2	16	153	26	0·05	11·0*	12·0*
3	11	136	46	0·07	15·2*	18·2*
4	13	145	40	0·08	10·8*	10·4*
5	15	137	37	0·09	5·1	9·0
6	15	144	38	0·15	5·5	7·6
7	11	126	31	0·25	10·2	10·4
8	10	126	28	0·30	7·5	10·1
9	18	169	20	0·30	8·2*	8·9*
10	11	138	28	0·37	5·4	7·8
11	11	158	14	0·40	7·0*	6·9*
12	13	153	16	0·50	7·3	7·6*
Cystic fibrosis						
13	10	144	73	—	4·8	7·8*
14	17	160	72	—	11·3*	17·6*
15	10	123	44	0·00	8·2	12·3
16	11	134	43	0·03	8·0	18·1*
17	11	149	41	0·03	9·6*	7·8
18	12	134	36	0·03	12·7*	19·7*
19	13	132	43	0·03	9·3	7·4
20	13	162	34	0·08	5·3	7·6*
21	16	149	31	0·11	5·3	7·7
22	13	132	39	0·40	8·7	15·6*
23	11	128	29	0·40	8·0	7·4
24	12	148	29	0·43	10·5*	15·4*
25	11	170	25	0·53	3·2	2·5
26	13	166	28	0·57	4·0	8·4*
Bronchiectasis						
27	13	144	26	0·21	6·6	12·9*
28	23	161	31	0·30	4·5	6·8*
29	17	162	28	0·42	6·4*	6·6*
30	19	155	23	0·50	4·3	5·2
31	34	162	30	0·50	4·0	4·0
Funnel chest deformity						
32	10	141	34	0·18	5·6	5·7
33	12	151	38	0·19	3·0	3·2
34	18	161	33	0·49	2·7	2·1

RV/TLC ratio expressed as percentage, max. exp. flow at 50% TLC expressed as TLC/sec
R_E (write-out) = total respiratory resistance measured by write-out method during expiration
R_E (slope) = total respiratory resistance measured from slope by subtraction method during expiration
Resistance expressed as cm H_2O/(l./sec)
Levels of resistance greater than normal predicted for height marked with an asterisk
Patients are grouped in order of increasing flow rates for each disease.

severe obstructive airways disease tended to have relatively high levels of resistance by both techniques, although the subtraction method gave higher readings than the write-out method. However, 15 children with moderately severe airways obstruction causing reduction in forced expiratory flow rates and hyperinflation had a normal resistance measurement using the write-out technique but an elevated resistance by the subtraction technique. There were four (two with cystic fibrosis and two with asthma) with normal maximum expiratory flow rates who had an abnormal resistance by subtraction and normal resistance by write-out.

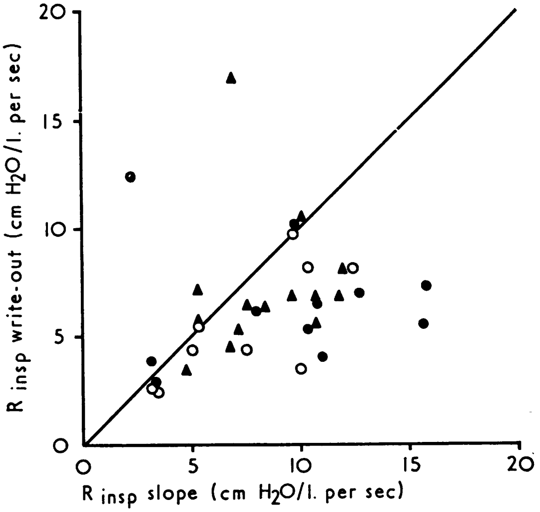

FIG. 4. *Inspiratory resistance. Value measured by write-out method on ordinate, that from slope by subtraction method on abscissa. Line of identity shown. Maximum expiratory flow rates at 50% TLC in TLC/sec are shown with the following symbols:* ●<0·10; ▲0·11–0·40; ○>0·41.

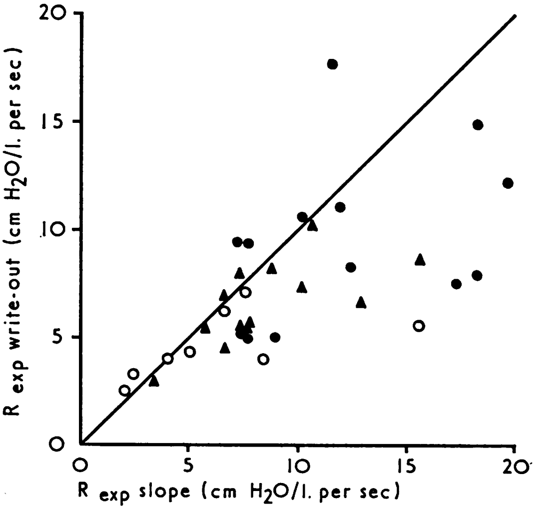

FIG. 5. *Expiratory resistance. Value measured by write-out method on ordinate, that from slope by subtraction method on abscissa. Line of identity shown. Maximum expiratory flow rates at 50% TLC in TLC/sec are shown with the following symbols:* ●<0·10; ▲0·11–0·40; ○>0·41.

DISCUSSION

It is very desirable to have a simple and repeatable method of measuring non-elastic resistance in children. Many methods are impractical as they are difficult in younger children. Children dislike swallowing an oesophageal balloon which is necessary for the measurement of pulmonary non-elastic resistance and some children find the panting technique for measuring airways resistance in the body plethysmograph difficult to perform. Forced oscillations have been used to measure total non-elastic respiratory resistance in adults (Hyatt *et al.*, 1970 ; Fisher, DuBois, and Hyde, 1968 ; Frank, Mead and Whittenberger, 1971) and are considered to give satisfactory results. Hyatt *et al.* (1970) recorded a lower level of total non-elastic respiratory resistance compared with pulmonary resistance when they made these two measurements in the same patients with obstructive lung disease. In view of the simplicity of the procedure it appears to be ideal for use in children.

Initially, the write-out method as described by Goldman *et al.* (1970) was used. With this technique pressure changes due to compliance or inertial factors are theoretically eliminated by measuring pressure change related to flow between points of zero volume acceleration and constant volume. However, in patients with obstructive lung disease in this study pressure and flow were so markedly out of phase that an unusually low pressure change was measured and consequently a very low resistance calculated. This phase difference is probably due to time constant inequality so that points of zero flow at the mouth do not actually represent points of zero flow in the various component pathways of the lungs with varying time constants (DuBois, 1969 ; Alpers and Guyatt, 1967 ; Peslin, 1968 ; Jaeger and Bouhuys, 1969). This could also explain the lower levels of respiratory resistance recorded by Hyatt *et al.* (1970) using this method.

The subtraction technique gave a higher level for respiratory resistance in the obstructed patients. However, this measure of effective resistance is probably still not the true resistance. In diseased lung the theory that at resonant frequency impedance is equal to flow resistance due to cancellation of compliance and inertial factors must be an oversimplification of the underlying functional abnormality. Resonant frequency is very rarely found in patients with severe obstructive lung disease, consequently the resistance measured is probably equal to true resistance plus 'in-phase' reactance (that is, factors relating to compliance and inertia) even after subtraction of some of the pressure signal to reduce looping (Fisher *et al.*, 1968).

It could be argued that the write-out method was giving true resistance readings and that these patients had small airways disease. This could cause reduced maximal expiratory flow rates associated with dynamic compression of large airways during a forced vital capacity manoeuvre but normal resistance during tidal breathing. Small airways in adolescents and adults contribute less than 20% to the total airways resistance (Macklem and Mead, 1967 ; Hogg *et al.*, 1970). This suggestion is unlikely to explain many of the discrepancies as these were children with severe cystic fibrosis and bronchiectasis with marked hyperinflation and therefore more likely to have significant large airways disease or extensive small airways involvement, both of which should have been reflected by an elevated total non-elastic respiratory resistance.

Consequently there are a number of problems with both of these techniques of measuring respiratory resistance by forced oscillation. Both gave satisfactory results which correlated well with each other in normal patients and in those with mild airways obstruction. In patients with severe obstructive lung disease the write-out method appeared to give low results, probably due to time constant inequality leading to marked phase difference between pressure and flow waves recorded. On the other hand, the subtraction technique probably gave too high a reading of resistance in these patients by including changes due in compliance and inertial factors as well as purely flow-resistive factors. Any measurement of pressure at the mouth used in the estimation of resistance has limitations in patients with airways obstruction as units with shorter time constants would contribute more to the pressure recorded (Mead, 1961).

The main value of this test is to separate the abnormals from the normals, and the subtraction method provided a better means of accomplishing this as a number of patients with very low expiratory flow rates had a normal resistance by the write-out method but abnormal on the subtraction method. However, the absolute level of resistance was very difficult to interpret because of the complicated events contributing to the result. Further investigation is warranted to define the relative merits and significance of the results obtained with various methods of measuring total non-elastic respiratory resistance by the oscillatory technique as this is a most useful method to use in children and adolescents.

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