ABNORMALITIES OF VENTILATORY CAPACITY IN CHILDREN WITH ASTHMA AND BRONCHIECTASIS

BY

L. B. STRANG*

From the Department of Child Health, University of Durham

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It is now generally accepted that patients with pulmonary diseases frequently suffer from an impairment of ventilatory capacity and that much of their disability is connected with this. A number of methods have been devised to measure the ventilatory capacity, which all depend on measuring the maximum volume which can be ventilated in a given time. It can be done directly by persuading the subject to hyperventilate maximally and measuring the volume of gas expired in 15 sec. or some other part of a minute. This is the direct Maximum Breathing Capacity (M.B.C.)† and it can be performed at a pre-determined rate to a metronome, or at a rate of the subject's own choice. The result is expressed in litres per minute.

A different approach to measuring the same function has been to analyse a single fast maximum expiration against time and take that part of the volume expired in the first second or part of a second, as a measurement of ventilatory capacity. This measurement was introduced about 10 years ago (Tiffeneau, Bousser and Drutel, 1949; Gaensler, 1951) and has since then come into general use. It is termed the Forced Expiratory Volume (F.E.V.) and the time interval referred to is indicated in seconds as a suffix (e.g. F.E.V._{1.0}, F.E.V._{0.75}).

Kennedy and his colleagues have used the 0.75 sec. volume (Kennedy, 1953) but the 1.0 sec. volume introduced by Tiffeneau *et al.* (1949) has probably become more generally accepted as a standard measurement (Gandevia and Hugh-Jones, 1957).

The original justification for using a timed fraction of the forced vital capacity (F.V.C.) as an estimate of the ventilatory capacity, depended on the concept that this fraction represented that part of the vital capacity which was actually used during hyperventilation, the 'capacité pulmonaire utilisable à

l'effort' of Tiffeneau *et al.* (1949). Thus, if the duration of expiration and inspiration were equal, the one second F.E.V. would be the tidal volume of the Maximum Breathing Capacity performed at a respiratory rate of 30 per min., and the 0.75 sec. F.E.V. would be the tidal volume at a rate of 40 per min. The relationships are more complex than these concepts imply as the times taken for inspiration and expiration are different and the limit of inspiration varies at different rates of breathing (Bernstein and Kazantzis, 1954). In fact, the correct factor by which the F.E.V._{1.0} should be multiplied for prediction of the M.B.C. is 37.5 (Cara, 1953).

In this study the ventilatory capacity is measured in terms of F.E.V._{1.0} and nothing seems to be gained from the practice of converting these values to an indirect M.B.C., except that normal values for the latter are better known. In children, this does not apply and, therefore, in this study values of F.E.V._{1.0} are given unaltered. The Forced Vital Capacity (F.V.C.) is measured at the same time as the F.E.V._{1.0} and from them a ratio termed the F.E.V. % is derived, i.e. $\frac{\text{F.E.V.}}{\text{F.V.C.}} \times 100$.

Very few studies of ventilatory function have been done in children. Kennedy and his colleagues (Kennedy and Thursby-Pelham, 1956; Kennedy, Thursby-Pelham and Oldham, 1957; Thursby-Pelham and Kennedy, 1958), have studied the ventilatory capacity of normal and asthmatic children using the F.E.V._{0.75}. (These authors, using a different terminology, refer to this as the Expiratory Flow Rate—E.F.R.) Engström, Karlberg and Kraepelin (1956) have studied the static lung volumes of normal children and Helliesen, Cook, Friedlander and Agathon (1958) the static lung volumes and the mechanical properties of the lungs of normal children. Earlier studies such as that of Stewart (1922) were confined to measurement of the vital capacity.

In initiating an investigation of pulmonary

* Now at the Postgraduate Medical School of London, Ducane Road, London, W.12.

† The terminology and abbreviations are those recommended by the Thoracic Society (Gandevia and Hugh-Jones, 1957).

function it seemed of importance to find tests which would evoke the cooperation of children and which would measure functions which were, in fact, altered in the chronic pulmonary diseases of childhood. The Forced Expiratory Volume in one second (F.E.V._{1.0}) had the advantage that it could be measured very simply in a way which is interesting for children.

In a previous investigation (Strang, 1959) 418 healthy schoolchildren were studied and normal standards for F.E.V._{1.0}, F.V.C. and F.E.V.% obtained. The F.E.V._{1.0} was best correlated with standing height, and a regression on the cube of the height with intervals of two standard deviations, derived from this study, provides normal standards for all comparisons in this paper. These are applicable equally to boys and girls.

The present investigation is intended to determine the circumstances in which the Ventilatory Capacity, in terms of the F.E.V._{1.0}, is lowered, its discrimination as a clinical test and the ways in which the measurement can be used in the management and investigation of bronchitis in childhood.

Clinical Material and Methods

Serial readings of F.E.V._{1.0} were made on 59 children with chronic pulmonary diseases. Two groups were examined: 20 with asthma and 39 with bronchiectasis.

Asthma. Twenty children had the syndrome of recurrent dyspnoea, wheezing and cough which is usually termed asthma. All of them had a persistent eosinophilia in the peripheral blood, and none of them had evidence of bronchiectasis. Three of these patients produced purulent sputum from which *H. influenzae* was cultured and eight of the others had mucoid sputum intermittently. This group of patients were examined repeatedly (237 examinations) during the period from July, 1958 to February, 1959 and 14 of them were seen at two-weekly intervals during this period, with the exception of 26 planned examinations which were missed due to holidays, illness and other minor events.

At the beginning of the study general clinical data relating to each child were recorded, including the height, weight and age. At each subsequent visit the following information was also recorded, the clinical signs being classified into four arbitrary grades as follows—(0) Cough absent, no chest signs; (1) Cough present, no chest signs; (2) Cough present, scattered rhonchi audible in some parts of the lungs; (3) Cough present and rhonchi audible in all parts of the lungs. In the group of patients examined at two weekly intervals, the number of attacks of wheezing in the previous 14 days, the number of days since the last attack and the presence or absence of dyspnoea on exertion, were also recorded.

The clinical data were entered on specially prepared forms which provided space for the recording of each of the factors. At each visit the clinical assessment was recorded before the ventilatory measurement was made

and usually the clinical and ventilatory observations were made by two different people working in different rooms.

Bronchiectasis. Thirty-nine patients with the clinical picture of chronic pulmonary infection and expectoration of purulent sputum, were examined. All of these patients had persistent abnormal segmental shadows on plain radiographs of the chest and in 35 the presence of bronchiectasis had been confirmed by bronchography. None of them had eosinophilia. Serial observations were made (209 examinations) but these were less frequent than in the group with asthma as a less marked variation from time was expected.

The following clinical information was recorded for each patient.

- (a) The height and weight and age.
- (b) The clinical severity in three general grades as follows: (1) No obvious disability other than cough and sputum. (2) Cough and sputum; and in addition, general health interrupted by one or more febrile spells or other episodes of illness each year. (3) Cough and sputum with either dyspnoea or frequent febrile episodes or considerable loss of schooling, so that the child cannot live a normal life at any time.
- (c) A note was made of the diffuseness of râles or rhonchi on auscultation of the chest and divided into the following categories of diffuseness. (1) Signs, unilateral and localized. (2) Signs, bilateral and localized (usually basal). (3) Signs disseminated in all parts of the lungs.

A radiological assessment of the extent of the condition was made by examining plain films and bronchograms and making an estimate of the numbers of bronchopulmonary segments containing an abnormal shadow or deformed bronchus. Thirty-two patients had bronchograms which were considered adequate for this count but as the numbers counted on the plain film and on the bronchogram did not always correspond, the larger value in each case was taken as indicating the radiological extent.

The allocation of patients into grades of diffuseness and severity was done by two observers working together with the clinical records of the patients. Some of the ventilatory data had been collected at this time but it was not before them when the assessment was made. The radiological assessment was made with a radiologist who had no knowledge of the ventilatory results.

Testing Procedure. The child was taught how to make maximum fast expirations into a spirometer with a light aluminium bell similar to that described by Bernstein, D'Silva and Mendel (1952), which recorded on a drum revolving at 2 cm. per second. One cm. vertical movement of the bell was equivalent to a volume of 200 ml. so that the recording pen described a time—volume graph of the forced expiration similar to that shown in Fig. 1. After a number of practice attempts, three recordings were made from which mean values of the F.E.V._{1.0} and the F.V.C. were calculated. These volumes were corrected to 37° C. and the F.E.V.%, i.e. $\frac{\text{F.E.V.}}{\text{F.V.C.}} \times 100$

calculated. In the previous study of normals, 95% of repeated readings of F.E.V.₁₋₀ were within 3·8% of the individual's mean value.

Each child was examined clinically at the same time as the ventilatory measurements were made. All the children were receiving medical treatment of some kind. The group of 14 children with asthma, who were seen fortnightly, were taking part in a controlled drug trial and each of them was having choline theophyllinate in high dosage during three months of the observation period.

Results

Normal Pattern. Fig. 1 is typical of tracings which were obtained from normal children. The full height of the tracing represents the Forced Vital Capacity (F.V.C.) and the distance between the onset of expiration and the one second point represents the Forced Expiratory Volume in one second (F.E.V.₁₋₀). In normal children the absolute values of F.E.V.₁₋₀ and F.V.C. depend on the child's size, but the shape of the curve is constant. This is conveniently expressed as the ratio, $\frac{\text{F.E.V.}_{1-0}}{\text{F.V.C.}} \times 100$ or F.E.V.%. In a study of normal children (Strang, 1959) the mean F.E.V.% was 85% (S.D. 5·8) in boys and 89% (S.D. 5·4) in girls.

Fig. 1.—Spirometer tracing of maximum forced expiration. Normal child: standing height—53 in.

Abnormal Patterns. The types of abnormal tracing obtained were similar to those described by Thomson and Hugh-Jones (1958) in adult patients. In Fig. 2, three abnormal tracings have been superimposed on that of a normal child, all of the children

Fig. 2.—Superimposed spirometer tracings of a normal child and three children with chronic pulmonary disease, all 53 in. in height.

being of the same height and, therefore, comparable. A was from a normal child, B from a child with diffuse pulmonary fibrosis due to pulmonary haemosiderosis and C and D from children with asthma. The shape of the curve B was similar to the normal, the F.E.V.₁₋₀ and F.V.C. being reduced in proportion. This fact is expressed in a normal F.E.V.%. B was of the pattern expected in a restrictive lesion of the lungs or chest wall in which the extent of movement was limited but not its rate. The abnormal shape of curve C was due to a lesion which restricted the rate of movement of the chest, but its total volume only slightly. This was the pattern expected due to bronchial obstruction or diminished elastic recoil of the lungs. The F.E.V.₁₋₀ was reduced to a much greater degree than the F.V.C. and the F.E.V.% was much lower than normal. Curve D was a similar pattern but more severe. In this case, the F.V.C. and F.E.V.₁₋₀ were both diminished but this was more marked for the F.E.V.₁₋₀ than for the F.V.C.

In each case the F.E.V.₁₋₀ was a measurement of ventilatory capacity and the F.E.V.% gave an indication of the cause of the ventilatory impairment.

Results in Children with Asthma. In order to allow comparison between variable clinical factors and the pooled F.E.V.₁₋₀ results, the latter were converted to a percentage of the mean normal value for the child's height. The pooled results in this group showed a significant discrimination between each of the grades of physical signs (Fig. 3); between the presence and absence of dyspnoea on exertion (Fig. 4) and between whether or not there had been an attack of wheezing in the previous 14 days (Fig. 5); there was no difference between one and more than one attack in this period (Fig. 5) and the number of days since the attack was not apparently

FIG. 3. Asthma. Pooled results of F.E.V. as per cent of normal compared with physical signs on auscultation (20 patients, 237 readings). Black circles indicate means, vertical lines indicate two standard deviations about the means; rectangles indicate two standard errors of the means; numbers refer to number of observations in each group. Where the rectangles do not overlap there is a significant difference between the means.

FIG. 4. Asthma. Pooled results of F.E.V. as per cent of normal compared with presence or absence of dyspnoea on exertion at that time. (14 patients, 185 readings.) Symbols and significance as in Fig. 3.

FIG. 5. Asthma. Pooled results of F.E.V. as per cent of normal compared with number of attacks of wheezing in previous 14 days. (14 patients, 185 readings.) Symbols and significance as in Fig. 3.

significant (0-3 days since attack—mean F.E.V. 59%, (n=78): >3 days since attack—mean F.E.V. 65%, (n=47): S.E. of difference between means=5.5).

There was a marked difference between readings of F.E.V._{1.0} at different times on the same child, the coefficient of variation about the individual means

FIG. 6. Asthma. Serial records of F.E.V. in three children.

being 27%. The actual usefulness of the measurement was most evident in serial recordings in individuals such as shown for three children in Fig. 6. The top record is from a child who was in the normal range of ventilatory capacity most of the time but had a short-lived episode of abnormality. The middle record is of a child who was occasionally within the normal range, in this respect, but more frequently below normal. The lowest record is of a

FIG. 7. Asthma. Serial readings of F.E.V. in nine children compared with normal limits, for height. Each child represented as a vertical line and different readings of F.E.V. by short horizontal lines.

FIG. 8. Asthma. Serial readings of F.E.V. in 11 children compared with normal intervals for height. Each child represented as vertical line and different readings of F.E.V. by short transverse lines. Thick vertical lines represent children with purulent sputum.

child who had a persistently and severely impaired ventilatory capacity throughout the observation period.

The serial records of the 20 children are summarized in Figs. 7 and 8 and compared with the normal limits for height. Nine of these patients were never within the normal during the period of observation (Fig. 8), and particularly severe ventilatory defects were present in the three asthmatic children who also had purulent sputum.

The differences in ventilatory capacity between different children were evidently marked but not readily correlated with clinical data. The mean of the F.E.V.s recorded for each child was compared with the child's height and weight and with the persistence or otherwise of cough. These were the only reasonably permanent clinical characteristics which could be defined in this group.

The mean height was 97.8% (S.D. 7.95) of normal.* The mean weight was 83% (S.D. 13.8) of normal and there was no significant correlation between weight (per cent normal) and F.E.V. (per cent normal) ($r=0.184$; $n=20$). Nine patients had cough on each occasion they were seen and, in 11, cough was absent on one or more occasions, and between these groups the difference in F.E.V._{1.0} was significant. (Cough persistent mean F.E.V._{1.0} (per cent normal) = 49.7. Cough not persistent mean F.E.V._{1.0} (per cent normal) = 70.08; $t=2.35$; $p>0.05$.)

Relationship of F.E.V._{1.0} and F.V.C. (F.E.V.%) in Asthma. Usually a reduction of F.E.V._{1.0} below normal was proportionately greater than the associated reduction of F.V.C. and this produced tracings similar to C and D in Fig. 2, in which the F.E.V.% was reduced. These changes were regarded as largely due to bronchial obstruction. In Fig. 9 the relationships of F.E.V._{1.0} and F.V.C. in these patients is presented. The diagonal line represents the relationship which would exist if the form of the spirometer tracings were normal and in purely restrictive lesions the results could be expected to fall about such a line. The quadratic regression line indicates the trend of the actual data and can be taken to show the changes likely to occur in a severely affected child during treatment or spontaneous improvement. In the low ranges, the F.E.V._{1.0} increases less markedly than the F.V.C.; they then increase at equal rates and the normal range of F.V.C. is reached before that of the F.E.V._{1.0}. Finally the F.E.V._{1.0} increases with relatively small change in F.V.C., reaching first the normal range

* The normal heights and weights were taken as the mean heights and weights for age from the charts prepared by Dr. P. E. Polani for the National Spastics Society.

FIG. 9. Asthma. Relationship of F.E.V. as per cent of normal and F.V.C. as per cent of normal (20 patients, 237 readings). Diagonal interrupted line is relationship of F.E.V. and F.V.C. in spirometer tracings of normal shape. Horizontal and vertical interrupted lines show lower limits of normal for F.E.V. and F.V.C. Continuous line is quadratic regression fitted to data. ($F.E.V. = 57.11 - 1.08 \times F.V.C. + 0.0138 \times F.V.C.^2$: F.E.V. and F.V.C. as per cent of normal for height.)

for $F.E.V_{1.0}$ and finally the normal $F.E.V./F.V.C.$ ratio.

Results in Patients with Bronchiectasis. The variation in $F.E.V_{1.0}$ at different times in individual patients was less than in children with asthma, the coefficient of variation about the individual means being 12%. Many children had abnormally low $F.E.V.$ s on serial recordings as compared with the normal for height (Fig. 10).

In order to allow comparison with clinical factors, the $F.E.V_{1.0}$ was expressed as a percentage of the normal for height. Clearly definable clinical variations, from time to time during the observation period, were not very obvious in these patients, so that a comparison of variations in chest signs and similar factors with the pooled data was not relevant. For this reason, comparisons were confined to clinical differences between patients and the mean $F.E.V_{1.0}$ of each.

The mean height of the group was 97% (S.D. 4.7) of normal. The mean weight was 85.6% (S.D. 10.9) of normal, but there was no significant correlation between $F.E.V_{1.0}$ (per cent normal) and weight (per cent normal) ($r = 0.069$, $n = 39$). The results in the three grades of general severity were not significantly different (Table 1). The diffuseness of physical signs showed no difference between the

TABLE 1
BRONCHIECTASIS. COMPARISON OF F.E.V. (PER CENT OF NORMAL) WITH GRADE OF GENERAL CLINICAL SEVERITY

Grade of Severity	No. of Patients	Mean F.E.V. (% normal)	t	p
1	11	72.3	0.288	> 0.05
2	21	70.5		
3	6	63.2		

TABLE 2
BRONCHIECTASIS. COMPARISON OF F.E.V. (PER CENT OF NORMAL) WITH DEGREE OF DIFFUSENESS OF SIGNS ON AUSCULTATION

Degree of Diffuseness	No. of Patients	Mean F.E.V. (% normal)	t	p
1	13	74.3	8.25	< 0.05
2	14	73.1		
3	12	57.5

FIG. 10. Bronchiectasis. Serial readings of F.E.V. in 39 children compared with normal limits for height. Each child represented as vertical line and different readings of F.E.V. by short horizontal lines.

first two categories but there was a significantly lower mean in the third category (Table 2). The numbers of affected segments in the radiological

assessment ranged from two to 13 but the correlation with F.E.V.₁₋₀ was not significant ($r=0.24$, $n=32$).

F.E.V./F.V.C. Relationship (F.E.V.%) in Bronchiectasis. The relationship of F.E.V.₁₋₀ and F.V.C. in these patients was not so obvious as in children with asthma (Fig. 11). In general the trend was similar, reduction of F.E.V.₁₋₀ being proportionately greater than the reduction of F.V.C. The degree of this change was less marked, and in some cases the F.E.V.₁₋₀ and F.V.C. were reduced in equal proportions.

FIG. 11. Bronchiectasis. Relationship of F.E.V. as per cent of normal and F.V.C. as per cent of normal in 39 patients with bronchiectasis (209 readings). Lower limits of normal for F.E.V. and F.V.C., and diagonal indicating normal F.E.V./F.V.C. ratio, as in Fig. 9.

Discussion

Asthma. The severe ventilatory abnormalities in the children with asthma are reasonably closely related to clinical observations, but in the individual case it would be impossible to predict the degree of ventilatory impairment from clinical data, and in particular, serious impairment may be present in the absence of physical signs on auscultation. The usefulness of measuring the F.E.V.₁₋₀ is most obvious in the serial records of individual children and the most striking fact about most of these is the relatively continuous nature of the abnormality. Only rarely is it intermittent and the symptoms of overt wheezing arise more often as exacerbations of a chronic condition than from a previously normal ventilatory state.

A number of consequences appear to follow from the concept of asthma as a continuous sub-acute

condition. Treatment with anti-spasmodics or other agents might be expected to achieve optimum results when given continuously three or four times daily over long periods. The results of treatment of this kind would need to be assessed in terms of ventilatory capacity as a degree of impairment will persist after the disappearance of clinical signs. The aim will be to bring the F.E.V.₁₋₀ and F.V.C. into the normal limits and during such a development the relationship of F.E.V.₁₋₀ and F.V.C. might be expected to follow a trend similar to the regression in Fig. 9. Thomson and Hugh-Jones (1958) have described a similar relationship in adult asthmatics and have pointed out that the normal F.E.V.₁₋₀ for a particular patient has not been reached until the normal F.E.V./F.V.C. ratio (F.E.V.%) exists. This is important as the patient is likely to enter the normal range of F.E.V.₁₋₀ well before achieving his own particular normal value. Treatment cannot be regarded as wholly successful until a normal F.E.V.% has been achieved.

The persistence of an impaired ventilatory capacity in children over long periods may have a bearing on the natural history of the condition. It cannot be concluded that all of the patients who remained outside the normal limits of ventilatory capacity had permanent pulmonary damage; different treatment, in particular, inhalations of isoprenaline, might have improved some of them. Nevertheless, the possibility exists that a prolonged ventilatory abnormality, which is presumably associated with bronchial obstruction, may contribute to permanent pulmonary damage particularly if additional agents capable of damaging the lung are added to it. In this connexion it may be important that persistent cough was associated with lower values of F.E.V.₁₋₀ than when cough was intermittent, and that the three children with persistent cough and purulent sputum were very seriously affected.

Bronchiectasis. The frequency of ventilatory impairment in children with bronchiectasis was greater than expected. These abnormalities are probably due to factors causing increased stiffness of the lungs such as fibrosis and oedema, and also to bronchial obstruction, the latter being more important. Different tests would be necessary to elucidate these factors further.

Whatever the exact cause of the mechanical disorders of ventilation, they are likely to be due to a diffuse process rather than to localized bronchiectasis. The clinical counterpart of ventilatory impairment is not very obvious except in the case of diffuse signs on auscultation. Morbid anatomical

studies including those of Allison, Gordon and Zinnemann (1943) and Whitwell (1952) have shown that the disease may be extremely diffuse and may involve areas which appear normal on bronchography. It has also been known for a long time that patients frequently have persistent cough and sputum following the apparently complete resection of bronchiectatic areas. There is obviously a need for a study which includes pre-operative and post-operative ventilatory measurements, but it seems likely that many children with bronchiectasis may have a diffuse bronchial damage or bronchitis, and in so far as measurement of F.E.V.₁₋₀ and F.E.V. % may show this, it should enable detection of children unlikely to benefit from surgical resection.

Field (1949), in a study of bronchiectasis in children, claimed that 33% of children had attacks of wheezing similar to asthma. This observation has not been confirmed in this centre and this may be due to differences in material or in terminology. The presence of impaired ventilatory capacity, due in part to bronchial obstruction, could lead to wheezing in certain circumstances, so that the present finding narrows the difference between our observations and those of Field (1949) to one of degree. Measurement of F.E.V.₁₋₀ should place the phenomenon on a quantitative basis, thus allowing exact comparisons.

Summary

Measurements of ventilatory capacity, in terms of the F.E.V.₁₋₀ reveal persistent abnormalities in children with asthma and bronchiectasis. They appear to provide an objective means of assessing an important aspect of these conditions which cannot be accurately assessed on clinical examination.

Measurements of this kind seem readily applicable to assessing the natural course of these diseases and the effects of treatment.

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