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Spirometry in the Evaluation of Pulmonary Function

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Spirometry should be more widely used in routine examinations. Equipment should meet the individual physician's or hospital's needs and include either a dependable water-sealed spirometer or an easily calibrated and accurate electronic spirometer. Justifiable concern over the reliability of electronic spirometers has resulted in requests to determine performance standards for these medical devices. Predicted normal standards must apply to the particular spirometer. Recommended tests are those of vital capacity (VC), forced vital capacity (FVC), one-second forced expiratory volume (FEV_1), the ratio of one-second forced expiratory flow (FEF200-1200) and forced midexpiratory flow (FEF25-75 percent). The maximum voluntary ventilation (MVV) test may be useful for evaluation of work disability and detection of extrathoracic obstruction. Additional consideration may be given to measurements of total lung capacity (TLC) to discriminate between restrictive and obstructive impairment and the forced end-expiratory flow (FEF75-85 percent) to detect mild small airway obstruction. At this time, flow-volume curves measurement cannot be justified for routine clinical use.

THE INCREASING PREVALENCE of chronic respiratory disease, particularly chronic bronchitis and emphysema (COPD), is reflected in growing concern regarding its diagnosis and control. The dimensions of the problem of chronic respiratory disease are inexactly known. Estimates of at least 12 million Americans afflicted with some degree of COPD have been offered but the true figure is probably several-fold greater. The dollar costs of COPD are impressive. It ranks behind arteriosclerotic heart disease and arthritis as a cause of early disability payments under the Social Security Administration. The National Center for Health Statistics has tabulated that for 1973 there were 41,042 deaths due to COPD. A steep upward trend in mortality from COPD is reflected in the increase in the death rate attributed to chronic bronchitis, emphysema and asthma from 5.0 per 100,000 population in 1950 to 19.6 in 1973. The exact slope is difficult to measure because of changes in diagnostic terminology. Since 1968, the Health

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ABBREVIATIONS USED IN TEXT

COPD = chronic bronchitis and emphysema
FEF25-75 percent = forced midexpiratory flow
FEF75-85 percent = forced end-expiratory flow
FEF200-1200 = ratio of one-second forced expiratory flow
FEV_1 = one-second forced expiratory volume
FRC = functional residual capacity
FVC = forced vital capacity
MVV = maximum voluntary ventilation
RV = residual volume
TLC = total lung capacity
VC = vital capacity

Resources Administration has combined chronic obstructive lung disease with emphysema, bronchitis and asthma as a cause of death. It is estimated that COPD utilizes approximately 15 percent of both physicians' time and hospital facilities in the United States.

A priority need is detection of COPD by primary physicians at an early stage. This requires reliable yet simple and relatively inexpensive techniques, both to detect early dysfunction and to document the extent of established pulmonary disease. Spirometry is the basic essential for practicing physicians.

Background

The determination of lung volumes began in 1800 with the measurement of residual volume by Davy using a hydrogen gas dilution technique. The practical origin, however, dates from the impressive work of the Reverend John Hutchinson in 1844.[1] He not only designed the first spirometer but also designated the expiratory vital capacity and developed normal standards based upon approximately 2,000 assorted English persons. He recognized the positive correlation with height and the negative relationship with age, excessive weight and pulmonary diseases. Dynamic lung volume measurements were delayed for a century until the valuable studies at Bellevue Hospital by Cournand, Richards and their colleagues in the 1940's.[2] Additional contributions to the measurement of timed vital capacity came from Tiffeneau and Pinelli in 1947[3] and Gaensler in 1951.[4] Tiffeneau and associates in 1949 first advocated the use of the one-second forced expiratory volume/forced vital capacity (FEV_1/FVC) ratio.[5] Leuallen and Fowler contributed the maximum midexpiratory flow test in 1955.[6]

Nomenclature has been troublesome and remains so today. Gandevia and Hugh-Jones in 1957 published widely accepted terminology for pulmonary physiology.[7] The Committee on Pulmonary Physiology of the American College of Chest Physicians in 1963 offered their modification of the terminology of dynamic lung volumes.[8] In 1975, a joint committee of the American College of Chest Physicians and the American Thoracic Society published a broad exposition on pulmonary nomenclature.[9] This latest effort may rescue us from the present welter of abbreviations and terms.

Physiologic Determinants of Spirometry

Forces are necessary to overcome the three opposing pulmonary forces of *inertia* and *compliance* of the lung and chest wall, and *resistance* to air flow and tissue motion. The interaction of these forces generates the measures of pressure, flow and volume. Lung volumes are influenced by degrees of inspiratory and expiratory pressures and by age, height and sex. Body position is also important. For example, changing from the standing to the supine position reduces vital capacity, functional residual capacity and total lung capacity. This is usually explained by an upward shift of the diaphragm, changes in the chest wall dimensions and increase in thoracic blood volume. Diseases that restrict lung volumes encompass a wide collection of pathologic entities including those affecting the chest wall, lung interstitium and pulmonary vasculature, reduction of lung volume by surgical procedures or thoracic space-occupying lesions, and by abdominal distention. All these entities are characterized by a reduced total lung capacity.

Flows are largely dependent upon respiratory muscular effort, force of elastic recoil and the diameter of the airways. The initial forced expiratory effort achieves a peak flow extremely rapidly, normally within the first 100 milliseconds and is dependent upon muscular effort. The flow decreases steadily with decreasing lung volume, is determined by the lung elastic recoil and the patency of the airways, and is largely independent of muscular effort. Pathologic processes which reduce elastic recoil or increase obstruction to air flow impair forced expiratory flows.

TABLE 1.—*Respiratory Health Questionnaire*

1. Do you usually cough or have to clear your throat in the morning or when getting up?
2. Do you usually cough for as many as three months each year?
3. Do you usually bring up any mucus, sputum or phlegm from your chest during the day?
4. Do you usually bring up any mucus, sputum or phlegm for as many as three months each year?
5. Do you have to stop for breath when walking at your own pace on level ground?
6. Do you get short of breath when walking with other people of your own age on level ground?
7. Do you ever wheeze?

Indications for Spirometry

Pulmonary function testing is indicated for all persons in whom there are symptoms and a positive response to a suitable respiratory questionnaire (Table 1).[10] It should be especially indicated for persons with complaint of shortness of breath. In any person, particularly cigarette smokers or asthmatics, spirometry will provide a baseline performance value for comparison with results of future tests. The impact of air pollution on nonsmokers may be detected by such comparison. Specific indications for ventilatory function testing include the following:

- To measure the extent of pulmonary function impairment.
- To help determine the type of impairment, such as restrictive, obstructive or a combination.
- To study possible effectiveness of bronchodilator therapy and the degree of air obstruction reversibility.
- For preoperative evaluation, especially for surgical procedures on the chest or upper abdomen.
- To follow the course of a patient's disease.
- To establish baseline ventilatory function.

Equipment

The traditional spirometer has been the water-sealed apparatus used in previous studies to obtain normal standards for ventilatory function. Minor nuisances are water spillage if moved and the need for maintaining proper water level. Waterless spirometers such as the bellows are less expensive but sacrifice accuracy for portability. With the rapid development of biomedical engineering, electronic spirometers have appeared which offer rapid readings, memory capability, digital displays and computer-assisted readouts. Associated with these devices are problems of accuracy, reliability and applicability of normal standards obtained from water-sealed spirometers.[11,12] The increasing need for screening large numbers of patients and the problem of high labor costs may result in the displacement of nonelectronic spirometers by either electronic ones or nonelectronic ones coupled to electronic accessories, permitting rapid measurement and data processing. Additional studies are needed to assess the suitability of these devices. Of particular concern is the inclusion of tests of questionable value. Physicians should cautiously approach the acquisition of a spirometer or other device for pulmonary function testing by answering some important questions first:

- What tests will be of value in my practice?
- How many tests will be made daily or weekly?
- What normal standards are available?
- What is the requirement for instrument calibration and can it be done in the field?
- Is efficient service available in my area?
- Is the equipment versatile or can it be expanded for other studies?
- What recording system is available for a permanent record?
- What are the initial and the maintenance expenses?

The electronic devices available for ventilatory function testing are valuable for rapid testing of a larger number of subjects with uniform accuracy. Instead of a bellows or water-sealed bell, they use hot wire anemometers, thermistors, thermocouples, pneumotachographs or turbines to detect flow and electronically calculate volumes. They can measure, calculate, display and print out results, some including percentage of predicted normal values in a fraction of the time required by previous apparatus. The capability of providing memory function and calculation of percentage of predicted normal values increases the complexity and cost of the equipment, but does widen the spectrum of testing and reduces manual handling of the data. Before being seduced by the claims of the capacity of greater number of tests, digital displays, rapidity and ease of calculation, physicians should be certain that the qualities of reliability and consistency possessed by the water-sealed and rolling seal spirometers are not being sacrificed. If only a limited number of tests are done, such as up to six per day, a water-sealed or rolling seal spirometer is advisable. Ideally, the addition of electronic data calculation and display increases the usefulness of spirometry. Conver-

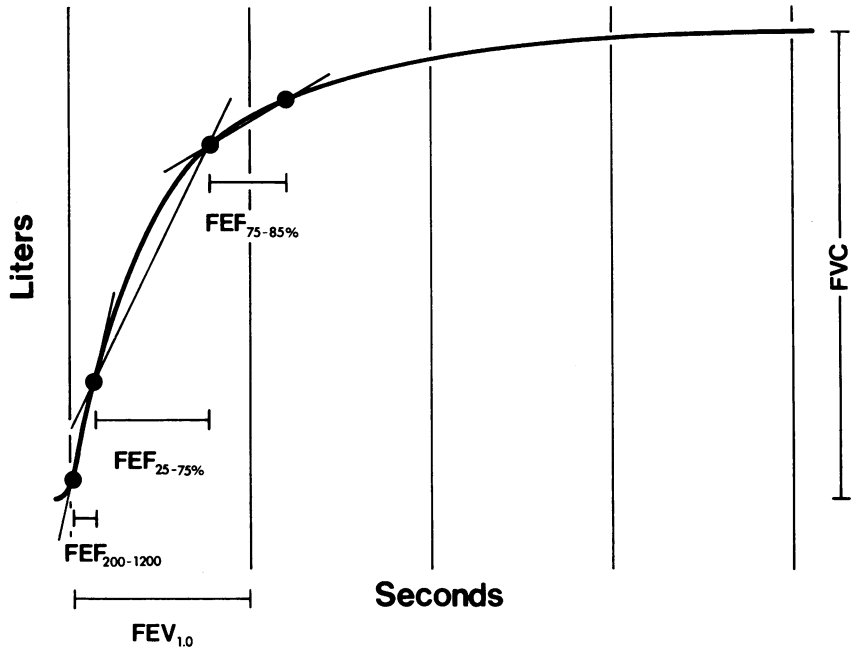


Figure 1.—Components of the forced expiratory vital capacity curve.

sion of the data obtained at ambient conditions of temperature, barometric pressure and water vapor saturation to body conditions is desirable. A final essential ingredient is a capable, trained assistant who is able to get maximal efforts in a humane manner from a patient and to maintain the equipment properly.

Spirometric Tests and Interpretation

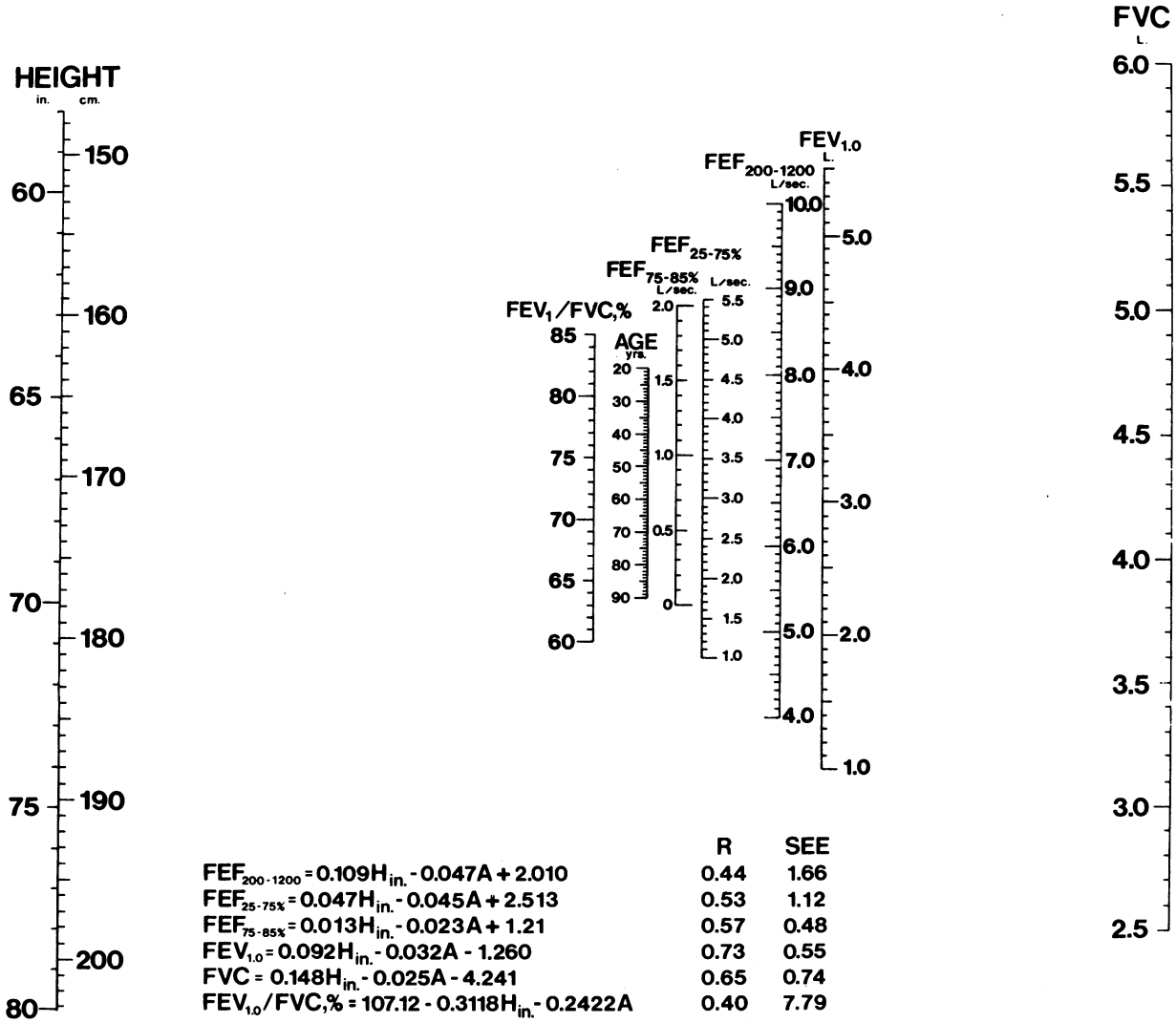
The principal use of spirometry is to record vital capacity (VC) and, more important, to record forced expiratory flow measurements. Both the vital capacity and forced vital capacity (FVC) studies should be done. The VC is the maximum volume of air exhaled from the point of maximum inspiration. The FVC differs only by using a maximally forced expiratory effort. In simpler terms, the VC is slow and the FVC fast. Ordinarily, their findings are similar and any significant discrepancy suggests air trapping. The test for vital capacity is useful primarily as an index of lung restriction but is also an indirect reflection of lung or chest wall compliance. A variety of other spirometric tests may be carried out but some are less useful either because of effort-dependency or lack of reliable normal standards. Included in this category are tests for peak flow and forced expiratory volumes in 0.5, 2 or 3 seconds. Forced expiratory vital capacity is measured against time. The measurements of flow depend indirectly on the resistance to expired air flow. Of special importance is the site of obstruction to air flow. It has been suggested that both by pathological examination and physiological testing, the initial site of involvement in COPD is the small airways less than 2 mm in diameter.[13,14] Because 10 to 15 percent of total airway resistance is provided by the large total cross-sectional area of these small airways, most pulmonary function tests are too insensitive to reflect this relatively small contribution to the total. As the disease process progresses, larger airways become involved. Figure 1 indicates the flow measurements in different portions of the FVC curve. By partitioning the components of the FVC curve, it may be possible to locate the primary areas of dysfunction.

The FEV_1 as seen in Figure 1 occupies approximately the first 75 to 80 percent of the FVC in normal adults. With increasing airway obstruction, the FEV_1 forms a decreasing percentage of the FVC. The FEV_1 appears to be relatively less sensitive in detecting small airway disease than the forced midexpiratory and end-expiratory flows. Controversy exists as to the measurement of zero time. The basic choice is whether to place it at the intersection of the FVC curve and the exhaled 200 ml volume line[15] or to extrapolate the steepest part of the FVC curve back to the exhaled zero volume line.[16]

The ratio of the FEV_1 to FVC may permit a rough distinction between restrictive, obstructive or a combination of both.[17] A normal FEV_1/FVC percent does not rule out small airway obstruction, which is better indicated by the forced mid-

expiratory or end-expiratory flows. The FEV_1/VC percent is preferable to the FEV_1/FVC percent for distinguishing between restrictive and obstructive impairment because of the reduction of the FVC by the air trapping related to obstructive airway disease.

The FEF200-1200 or maximum expiratory flow involves approximately the first 25 percent of the FVC in a normal adult. This is believed to be the effort-dependent portion and subject to variability. The peak flow also falls in this portion and suffers from this fault as well as its questionable functional importance as an unsustained flow. Both these tests may reflect abnormalities in the large airways or the larynx. The test of FEF25-75 percent or maximum midexpiratory flow has been available for 20 years and recently its value for early detection of small airways obstruction has been suggested.[18] Because the test reflects air flow in distal airways and is considered to be effort-independent, it has been preferred to the previously mentioned tests for the measurement of obstructive pulmonary disease. To increase the sensitivity to impairment of air flow in small airways, the forced end-expiratory flow (FEF75-85 percent) has been recently introduced. Our laboratory found the test to be more discriminatory than the FEF25-75 percent in distinguishing between male smokers and nonsmokers 30 to 49 years of age if 75 percent of predicted normal mean values was used to separate normal from abnormal.[19] It should be noted that premature termination of the



BTPS = body temperature, ambient pressure, saturated with water
FEF200-1200 = ratio of one-second forced expiratory flow
FEF25-75% = forced midexpiratory flow
FEF75-85% = forced end-expiratory flow
FEV_1 = one-second forced expiratory volume
FVC = forced vital capacity

Figure 2.—Prediction nomogram for normal men (BTPS).

FVC maneuver will cause serious errors in measurement, especially of the FEF25-75 percent and FEF75-85 percent.

To estimate the degree of reversible airway obstruction, aerosolized bronchodilator solutions may be administered. Ideally, the patient should not have had any type of bronchodilator drug for at least 12 hours before the test. When the spirometric tests are repeated five to ten minutes after inhalation of the bronchodilator aerosol, improvement greater than 20 percent may be considered significant. Failure to achieve this improvement, however, does not rule out possible benefit from a therapeutic trial of oral or aerosolized drugs.

The test of maximum voluntary ventilation (MVV) is a sustained exertional maneuver reflecting both thoracic and extrathoracic components. It has proved useful in evaluating work disability and exertional dyspnea. The patient is asked to breathe as rapidly as possible for 12 to 15 seconds using a depth of inhalation greater than his resting tidal volume. In carrying out this test, three pulmonary variables come into play, namely, amplitude of the tidal volume, frequency of breathing and the degree of lung inflation. Optimum frequency has been reported to vary between 70 and 110 breaths per minute. Because of

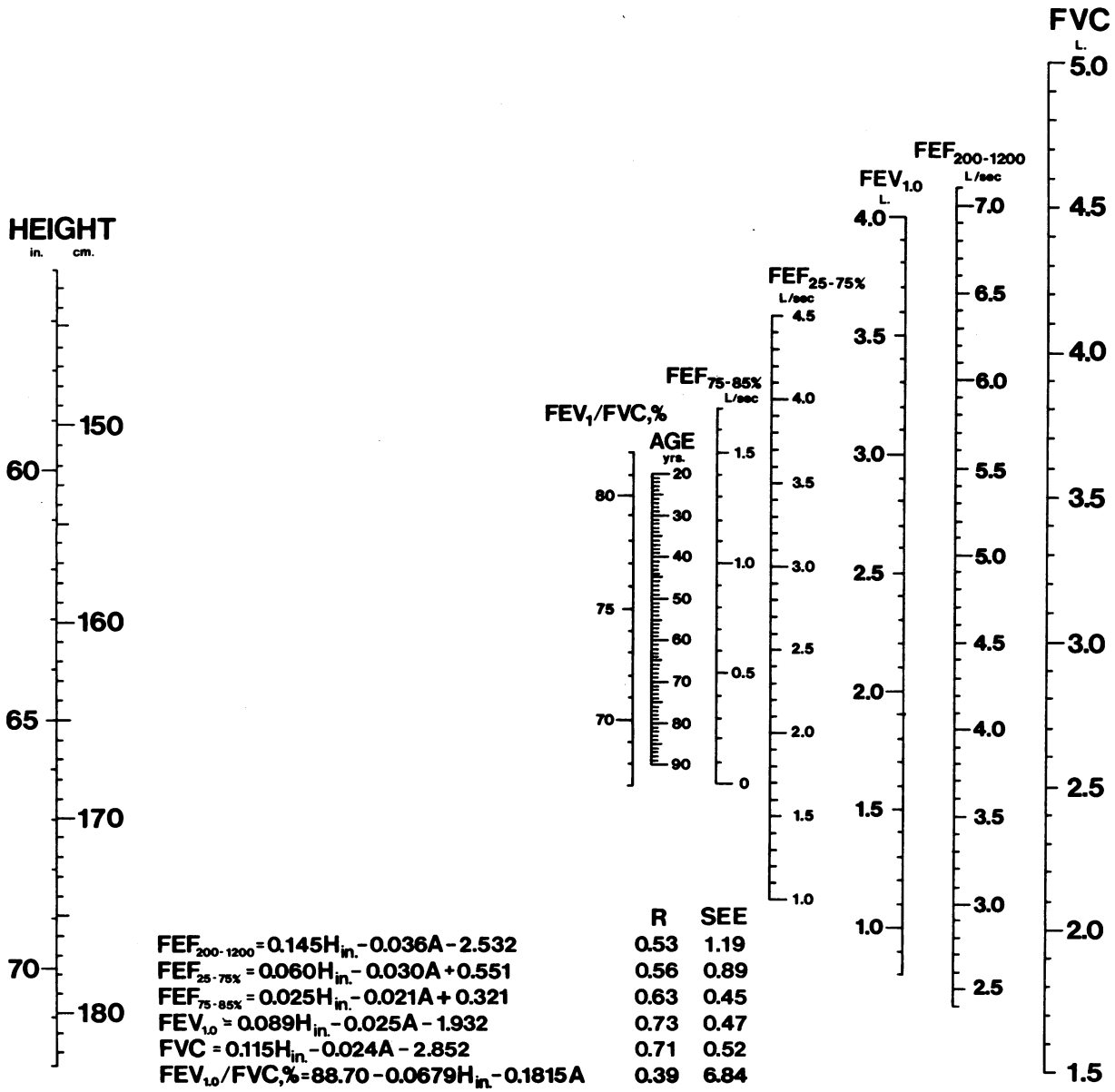


Figure 3.—Prediction nomogram for normal women (BTPS), see Figure 2 for abbreviations.

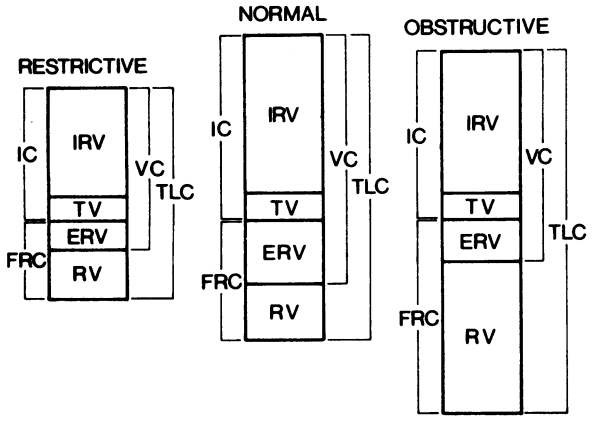
TABLE 2.—*Categories of Ventilatory Impairment*

	VC, FVC, FEV_1, MVV	*FEF200-1200, FEF 25-75%, FEF75-85%*
Normal	>80*	>75
Mild	65 - 80	60 - 75
Moderate	50 - 64	45 - 59
Severe	35 - 49	30 - 44
Very severe	<35	<30

*Percent of predicted normal
VC = vital capacity
FVC = forced vital capacity
FEV_1 = one-second forced expiratory volume
MVV = maximum voluntary ventilation
FEF200-1200 = ratio of one-second forced expiratory flow
FEF25-75% = forced midexpiratory flow
FEF75-85% = forced end-expiratory flow

the variables, it is not possible to know if a truly maximum ventilation has taken place. It is an exhausting test requiring a truly maximum effort. Various prediction formulas have been suggested, frequently based on a multiple of the timed vital capacity, a practice which has been justifiably criticized.[20] A rough guide for a maximum effort is the agreement between the percentages of the predicted normals for the FEV_1 and the MVV. Because the MVV involves both inspiratory and expiratory phases, obstruction in the larynx or trachea may preferentially reduce inspiratory flow.[21] This may result in a discrepancy between the percentages of the predicted FEV_1 and MVV despite maximal efforts. Predicted normal standards have been provided but the wide variations should be noted.[15,22] Techniques of measurement of all these ventilatory function tests have been previously described.[15,19]

Interpretation remains the least precise aspect



IC: Inspiratory Capacity
FRC: Functional Residual Capacity
VC: Vital Capacity
TLC: Total Lung Capacity
IRV: Inspiratory Reserve Volume
TV: Tidal Volume
ERV: Expiratory Reserve Volume
RV: Residual Volume

Figure 4.—Diagram of lung volumes and capacities in normals and patients with restrictive and obstructive pulmonary diseases.

of pulmonary function testing. Of first order is the need for useful normal standards. Figures 2 and 3 show nomograms developed in the author's laboratory based upon spirometric tests of healthy adult nonsmokers,[17,19,23] but it is unlikely that any single set of normal standards can be universally applied. Significant variables affecting the standards for ventilatory function include age, height, sex, size of the sample tested, racial and ethnic composition, criteria for normality, tobacco smoking, environmental conditions, altitude of residence, apparatus and techniques. Regardless of the normal mean values obtained, a distribution curve will result and the range of normality must be established. The sensitivity of the test will be influenced by selection of the extent of deviation from the predicted mean value separating normal from the abnormal subject. Ideally, a multiple of the standard error of estimate such as 1.65 standard errors of estimate which excludes 5 percent of normal persons with lesser values should be used. Alternately, a percentage of the predicted mean value can be used. This is the simplest and most commonly employed method.[24] Table 2 shows a classification of ventilatory impairment to be used with spirometric tests. The flow rates have wider variations from the mean values than the other tests. Prediction standards for normal children of 4 to 18 years old have been reported by Weng and Levison.[25]

It is popular to classify types of ventilatory impairment as restrictive, obstructive or a combination of both. Usually, reduction of vital capacity indicates restrictive impairment. With severe obstructive pulmonary disease, the vital capacity may be reduced due to airway closure. Distinction may be made by measurement of functional residual capacity (FRC), residual volume (RV) and total lung capacity (TLC). As shown in Figure 4, obstructive impairment is characterized by increased TLC, FRC and RV with a normal or reduced VC. Restrictive impairment consistently has a reduced VC and TLC with a normal or reduced FRC and RV. Measurement of FRC requires additional equipment and involves either a closed circuit helium or nitrogen equilibration technique or an open circuit nitrogen washout.[26] If TLC is not calculated, the flow diagram in Figure 5 may be of value in determining the type of ventilatory impairment. The use of Table 2 will provide the added dimension of the degree of impairment. This system can be adapted for automated in-

terpretation by a calculator that can be programmed or a computer.

Serial testing of a patient will be of greater value than comparing him or her with a sample group but many patients are seen only after some degree of impairment has occurred. Incorporation of routine spirometry into the periodic examinations of cigarette smokers or any persons with pulmonary symptoms cannot be too strongly advocated.

The expiratory flow-volume curve was introduced by Hyatt and co-workers in 1958.[27] Claims for advantages over volume-time curves of conventional spirometry include better visualization of the reduction of flow at specific volumes. Plotting maximum expired flow against volume provides useful information regarding obstructive and restrictive ventilatory impairment but it represents only a first order derivative of the forced expiratory flow. Its disadvantages include the requirement for simultaneous recording of two variables, usually on an X-Y recorder or storage oscilloscope, and the lack of applicable normal standards. Although useful in clinical research and the teaching of lung mechanics, it is doubtful if the flow-volume curve provides additional useful clinical information not provided by spirometry.

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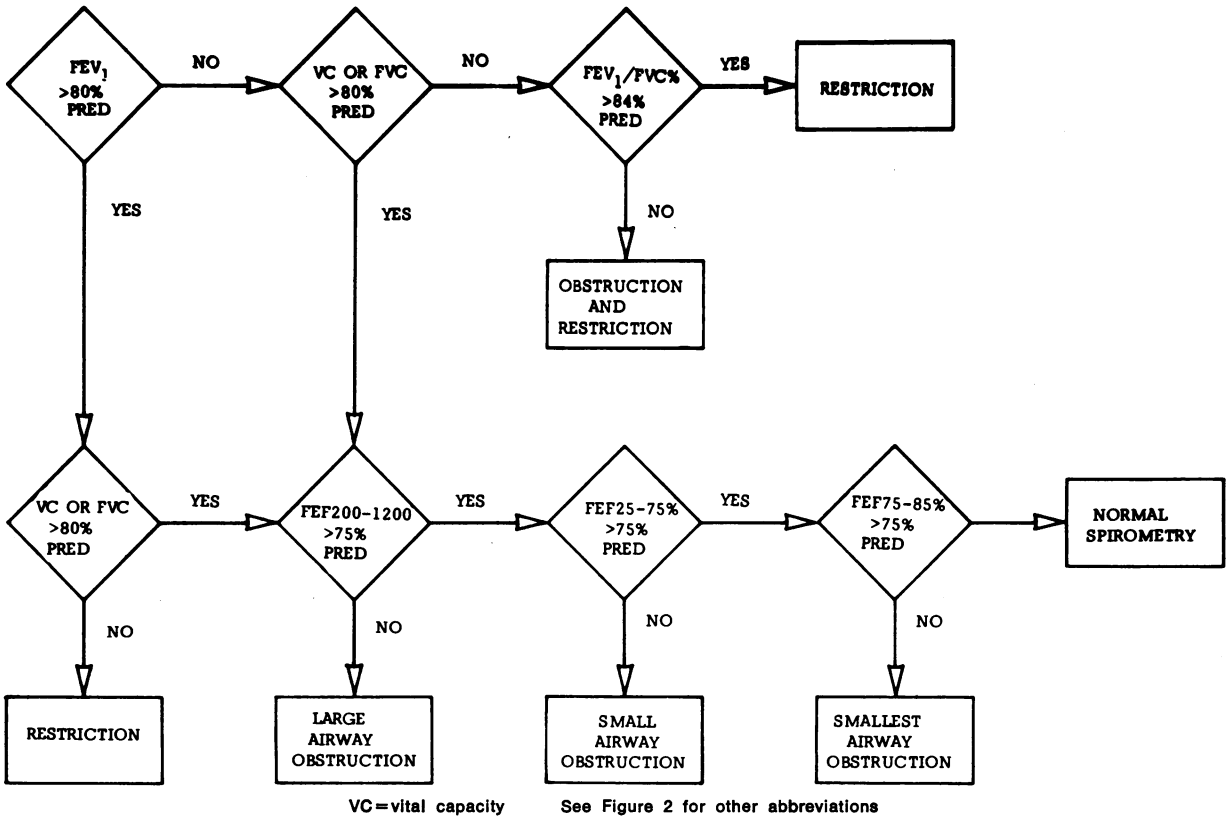

VC=vital capacity See Figure 2 for other abbreviations

Figure 5.—Flow diagram for interpretation of spirometric data.

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Errors in Blood Pressure Determination

. . . We may actually get false blood pressure readings (when taking them) and the first and most obvious cause is bad equipment. You have to have your equipment standardized and checked out every year, whether it is an aneroid or mercury sphygmomanometer. You should not bring the patient running into your office, have him sit down and roll up his sleeve and take his blood pressure. Talk to him for awhile so that there is at least five minutes of inactivity and peace. The antecubital fossa should be at the heart level in the sitting position when you take the blood pressure. If it is much higher, the blood pressure will be lower. If the arm is low in relation to the heart, the blood pressure will be higher. You certainly do not want to start in the auscultatory gap with your systolic blood pressure, so if there is any doubt where you are, feel the radial pulse. . . . An obese arm is a particular problem and I want to emphasize this. In women heavier than 200 pounds and in men heavier than perhaps 250 pounds, I do not think we often see a very reliable blood pressure utilizing a standard cuff. There are two things that you can do. One is to use your standard cuff on the forearm and listen over the radial artery. This is pretty good for systolic but I do not often hear very well the diastolic blood pressures by this technique. I think for any of you who are seeing a large hypertensive population or a lot of very heavy patients, you should get a thigh cuff, because I think you will be amazed at the difference in blood pressure readings between the two cuff sizes in very heavy arms.

Obstruction in a proximal artery may give a falsely low blood pressure on the involved side, so you should either take blood pressure readings in both arms or, more easily, feel the radial pulses for similar amplitude. And finally, there is an occasional patient, and this is more apt to occur in a diabetic patient, whose brachial artery is very rigid and calcified and it cannot be compressed. On the other hand, you will occasionally take a blood pressure measurement and not get any diastolic pressure at all; it will go all the way down to zero. Now, I do not know what that means.

—NEIL W. SWINTON, JR, MD, *Boston*

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