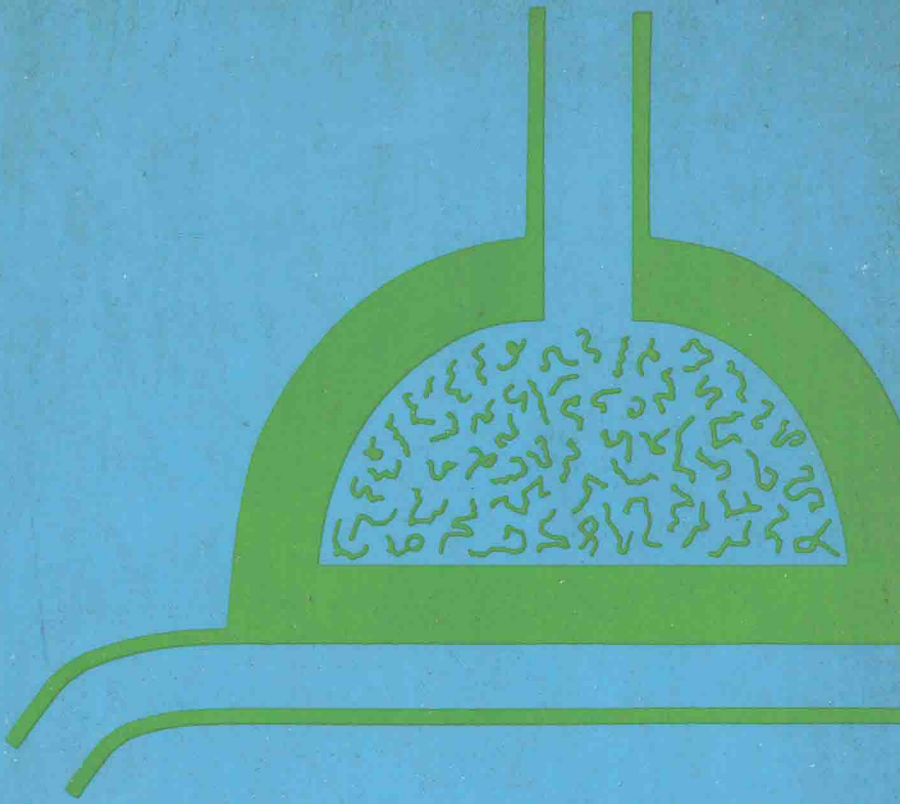

Pulmonary Pathophysiology

–*the essentials*
2nd Edition

John B. West, M.D., Ph.D.

Williams & Wilkins

Pulmonary Pathophysiology —the essentials

2nd edition

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Pulmonary Pathophysiology —the essentials

2nd edition

To R.B.W.

Preface *to the 2nd Edition*

The text of this book has been brought up to date in a number of areas including the flow-volume curve, tests of early airway disease, sleep apnea, chronic obstructive lung disease, bronchial asthma, and high frequency ventilation. However, since the human brain is apparently not increasing in size as fast as the body of knowledge, the length of the book has been kept more or less the same by judicious pruning of other areas. Many readers have raised questions about various points in the book; such queries are very useful.

Preface *to the 1st Edition*

This book is written as a companion to *Respiratory Physiology—The Essentials* and is about the function of the diseased as opposed to the normal lung. It is primarily intended for medical students in their second and subsequent years. However, a concise, amply illustrated account of respiratory function in disease may prove useful to the increasingly large number of physicians and paramedical personnel who come into contact with respiratory patients. These include anesthesiologists, cardiologists, intensive care personnel, and respiratory therapists.

Many medical schools are constantly trying to emphasize the relevance of the basic science of the first two years to the practice of medicine. Respiratory function can be a model for this. A discussion of a patient with asthma, for example, can cover the basic physiology of the airways, blood gases and lung volumes quickly and painlessly. It is hoped that this little book will be helpful in such a course.

This book emphasizes the relations between structure and function in the diseased lung. Indeed the reader will find more anatomic pathology than he might expect in a book about pathophysiology. But function cannot be properly understood without a knowledge of structure. It is assumed that students who read this book are also exposed to teaching in pathology.

Naturally such a concise book covering such a wide area must be dogmatic. However, the reader will find a full discussion of disputed issues in the references and reading list at the end of the book. I would be grateful for any comments on the selection of material and factual errors. A set of audiotapes with slides is available to supplement this book.*

Several colleagues have read parts of the manuscript and have suggested improvements. They include: Drs. Arend Bouhuys, Benjamin Burrows, David H. Dail, Ronald Dueck, James C. Hogg, Norman Jones, D. F. C. Muir, John F. Murray, Norman C. Staub, and Peter D. Wagner. Drs. Paul J. Friedman and Michael P. Hlastala helped with

* Information from John B. West, M.D., Ph.D., Department of Medicine, University of California San Diego, La Jolla, California 92093.

the selection of radiographs and Dr. Peter D. Wagner assisted with the diagrams. I am indebted to all of them. I would also like to acknowledge the secretarial assistance of Mrs. Elizabeth Silva and the friendly help of Mr. James Gallagher and others on the staff of The Williams & Wilkins Co.

The publishers of the following journals and books kindly gave permission for the use of material. The sources are cited in the figure captions: Academic Press Inc., New York, Figure 34B; *American Journal of Medicine*, Figure 68; American Lung Association, Figure 73; American Physiological Society, Figures 26, 39, 49, and 87; Blackwell Scientific Publications, Oxford, Figures 12 and 88; British Medical Association, London, Figure 27; Churchill-Livingstone Publishers, London, Figures 31, 32, and 34*A*, Marcel Dekker Inc., New York, Figure 77; McGraw Hill, New York, Figure 33; *New England Journal of Medicine*, Boston, Figure 28; New York Academy of Sciences, New York, Figure 71; Rockefeller University Press, New York, Figure 21; W. B. Saunders Co., Philadelphia, Figures 18, 25, 35, 36, 42, 45, and 59; and The Williams & Wilkins Co, Baltimore, Figures 51 and 79.

Editor's note: Some of the illustrations credited above have been renumbered in this 2nd edition. The current designations of those figures are as follows: American Physiological Society, Figures 26, 38, 48, and 87; W. B. Saunders Co., Figures 18, 25, 35, 36, 41, 45, and 58; Williams & Wilkins, Figures 50 and 79.

Information concerning audio tapes is now available from Audio Visual Medical Marketing, Inc., 850 Third Avenue, New York, N. Y. 10022.

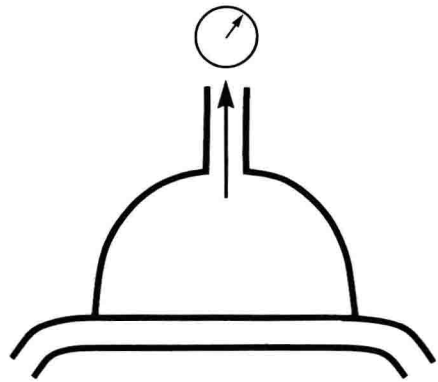
Contents

SECTION ONE

LUNG FUNCTION TESTS AND WHAT THEY MEAN

1. **Ventilation**
2. **Gas exchange**
3. **Other tests**

We learn how diseased lungs work by doing pulmonary function tests. Accordingly, this section is devoted to a description of the most important tests and their interpretation. It is assumed that the reader is familiar with the basic physiology of the lung as contained in the companion volume *Respiratory Physiology—The Essentials.*



chapter 1

Ventilation

The simplest test of lung function is a forced expiration. It is also one of the most informative tests and it requires a minimum of equipment and trivial calculations. Yet the majority of patients with lung disease have an abnormal forced expiration and very often the information obtained from this test is useful in their management. In this chapter we look first at the indices of a forced expiration, then the factors which determine the flow-volume curve, and finally single breath tests of uneven ventilation and closing volume.

TESTS OF VENTILATORY CAPACITY

Forced Expiratory Volume

The *forced expiratory volume* is the volume of gas exhaled in *one second* by a forced expiration from full inspiration. The *vital capacity* is the *total* volume of gas which can be exhaled after a full inspiration.

A simple way of making these measurements is shown in Figure 1. The patient is comfortably seated in front of a spirometer having a low resistance. He breathes in maximally and then exhales as hard and

as far as he can. As the spirometer bell moves up, the kymograph pen moves down, thus indicating the expired volume against time.

Figure 2A shows a normal tracing. It can be seen that the volume exhaled in 1 sec was 4.0 liters and the total volume exhaled was 5.0 liters. These two volumes are therefore the forced expiratory volume in 1 sec ($FEV_{1.0}$) and the vital capacity. The vital capacity measured with a forced expiration may be less than that measured without straining, so that the term forced vital capacity (FVC) is generally used. Note that the normal ratio of $FEV_{1.0}$ to FVC is about 80%. (See Appendix for normal values.)

Figure 2B shows the type of tracing obtained from a patient with chronic obstructive lung disease. Note that the rate at which the air was exhaled was much slower, so that only 1.3 liters were blown out in the first sec. In addition, the total volume exhaled was only 3.1 liters. $FEV_{1.0}$/FVC was reduced to 42%. These figures are typical of an *obstructive* pattern.

Contrast this pattern with that of Figure 2C, which shows the type of tracing obtained from a patient with pulmonary fibrosis. Here the vital capacity was reduced to 3.1 liters, but a large percentage (90%) was exhaled in the first sec. These figures mean *restrictive* disease.

If the equipment shown in Figure 1 is used, the spirometer should

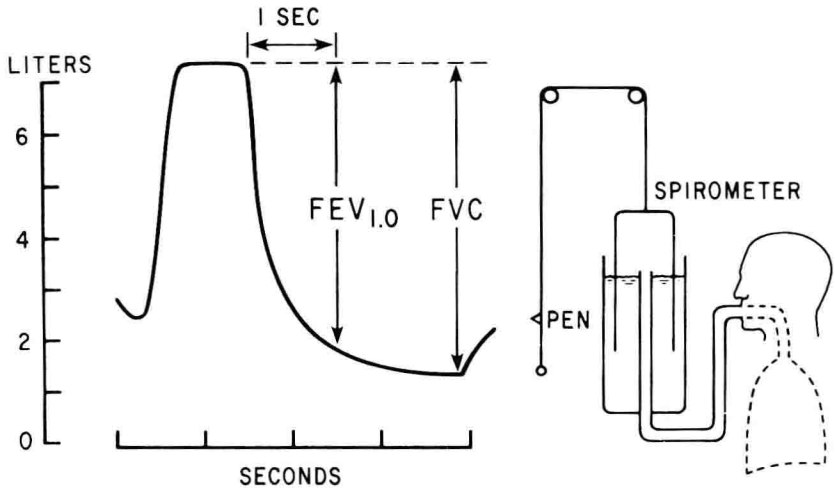


Figure 1. Measurement of forced expiratory volume ($FEV_{1.0}$) and vital capacity (FVC).

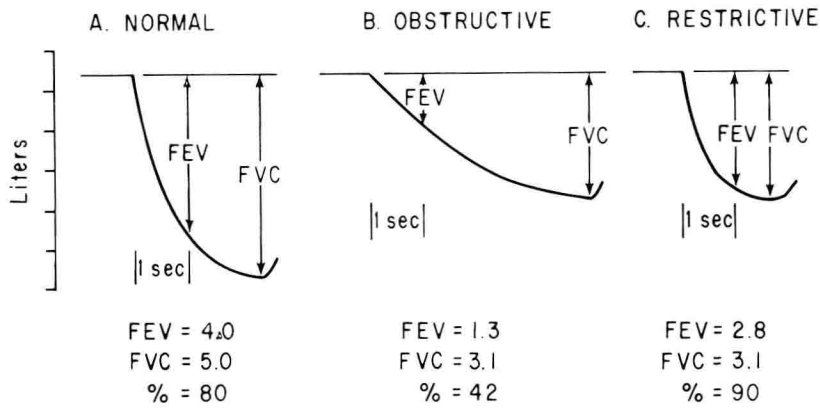


Figure 2. Normal, obstructive, and restrictive patterns of a forced expiration.

be light with a wide diameter, and the tubing should have a low resistance so that the spirometer can respond rapidly. Dry spirometers using the bellows principle are also available and are convenient for measurements at the bedside. Sometimes they provide a graph which can be filed with the patient's chart. Various electronic spirometers are also on the market, but these should be carefully calibrated.

The patient should loosen any tight clothing and the mouthpiece should be at a convenient height. One accepted procedure is to allow two practice blows and then record three good test breaths. The highest $FEV_{1.0}$ and FVC from these three breaths are then used. The volumes should be converted to body temperature and pressure (see Appendix). Further practical details can be found elsewhere (1).

The test is often of value in assessing the efficacy of bronchodilator drugs. If reversible airway obstruction is suspected, the test should be carried out before and after administering the drug (for example, 1% isoproterenol by nebulizer for 3 min). Both the $FEV_{1.0}$ and FVC usually increase in a patient with bronchospasm.

Maximum Midexpiratory Flow ($FEF_{25-75\%}$)

This index of forced expiratory flow is calculated from the tracing in Figure 3. The middle half (by volume) of the total expiration is marked and its duration is measured. The $FEF_{25-75\%}$ is the volume in liters divided by the time in seconds (2).

The correlation between $FEF_{25-75\%}$ and the FEV is generally close in

patients with obstructive lung disease. The changes in $FEF_{25-75\%}$ are often more striking, but the range of normal values is greater.

Maximum Voluntary Ventilation

This is the maximum volume of air that can be breathed in a minute. However, because maximal hyperventilation is so exhausting, the volume over 15 sec is measured and multiplied by 4. This test was used extensively for many years but has now been supplanted by single breath tests. Its chief disadvantages are that it is too tiring for ill patients and it depends so much on how hard the patient tries. Essentially the same information is obtained far more easily from the forced expiratory volume.

Interpretation of Tests of Forced Expiration

In some respects, the lungs and thorax can be regarded as a simple air pump (Figure 4). The output of such a pump depends on the stroke volume, the resistance of the airways, and the forced applied to the piston. The last factor is relatively unimportant in a forced expiration, as we shall presently see.

The *vital capacity* (or forced vital capacity) is a measure of the stroke volume, and any reduction in it will affect the ventilatory capacity. Causes of stroke volume reduction include diseases of the

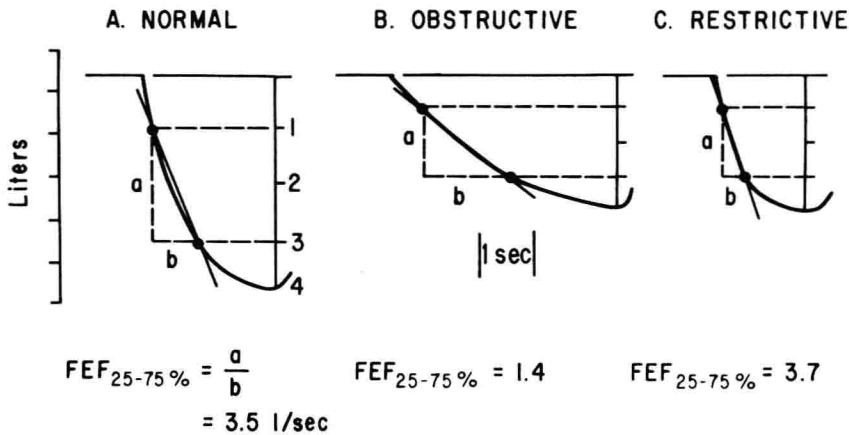
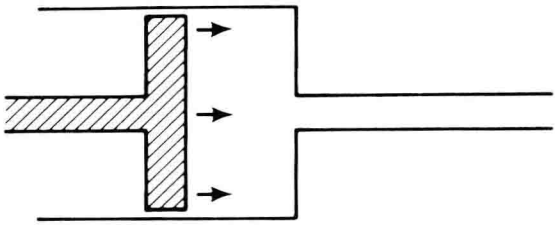


Figure 3. Calculation of the maximum midexpiratory flow ($FEF_{25-75\%}$) from a forced expiration.



Stroke volume	Airway resistance
Interstitial disease	Asthma
Poliomyelitis	Bronchitis
Muscular dystrophy	
Pleural disease	

Figure 4. Simple model of factors which may reduce the ventilatory capacity. The stroke volume may be reduced by diseases of the lung parenchyma, pleura, or respiratory muscle. Airway resistance is increased in asthma and bronchitis.

thoracic cage, such as kyphoscoliosis, ankylosing spondylitis, and acute injuries; diseases affecting the nerve supply to the respiratory muscles or the muscles themselves, such as poliomyelitis or muscular dystrophy; abnormalities of the pleural cavity, such as pneumothorax or pleural thickening; pathology in the lung itself, such as fibrosis, which reduces its distensibility, space-occupying lesions such as cysts, or an increased pulmonary blood volume, as in left heart failure. In addition, there are diseases of the airways which cause them to close prematurely during expiration, thus limiting the volume which can be exhaled. This occurs in asthma and bronchitis.

The *forced expiratory volume* (and related indices such as the $FEF_{25-75\%}$) is affected by the airway resistance during forced expiration. Any increase in resistance will reduce the ventilatory capacity. Causes include bronchoconstriction as in asthma or following the inhalation of irritants such as cigarette smoke, structural changes in the airways as in chronic bronchitis, obstructions within the airways such as an inhaled foreign body or excess bronchial secretions, and destructive processes in the lung parenchyma which interfere with the radial traction that normally supports the airways.

While the simple model of Figure 4 serves as an introduction to the

factors limiting the ventilatory capacity of the diseased lung, we need to refine the model to obtain a better understanding. For example, the airways are actually *inside* the pump, not *outside*, as shown in Figure 4. Useful additional information comes from the flow-volume curve.

Flow-Volume Curve

If we record flow rate and volume during a maximal forced expiration, we obtain a pattern like that shown in Figure 5A. A curious feature of the flow-volume envelope is that it is virtually impossible to penetrate it. For example, if we begin by exhaling slowly and then exert maximum effort, the flow rate will increase to the envelope but not beyond. Clearly, something very powerful is limiting the maximum flow rate at a given volume. This factor is dynamic compression of the airways.

Figure 5B shows typical patterns found in obstructive and restrictive lung disease. In obstructive disease such as chronic bronchitis and emphysema, the maximal expiration typically begins and ends at abnormally high lung volumes and the flow rates are much lower than normal. In addition, the curve may have a scooped out appearance. By contrast, patients with restrictive disease such as interstitial fibrosis operate at low lung volumes. Their flow envelope is flattened compared with the normal, but if flow rate is related to lung volume, the flow is seen to be higher than normal (Figure 5B). Note that the figure shows absolute lung volumes, though these cannot be obtained from a forced

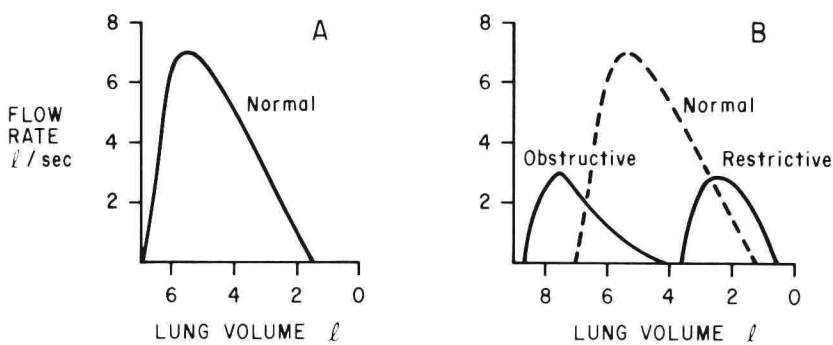


Figure 5. Flow-volume curves. B contrasts the obstructive and restrictive pattern with the normal.