Pulmonary Pathophysiology —the essentials

JOHN B. WEST, M.D., Ph.D.

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JOHN B. WEST, M.D., Ph.D.

Professor of Medicine and Bioengineering,
School of Medicine
University of California San Diego,
La Jolla, California

The Williams & Wilkins Company · Baltimore

Made in the United States of America

Reprinted 1978

Library of Congress Cataloging in Publication Data

West, John Burnard.
Pulmonary pathophysiology.

Bibliography: p.
Includes index.
1. Lungs—Diseases. 2. Pulmonary function tests. 3. Physiology, Pathological. I. Title. [DNLM: 1. Lung—Physiopathology. WF600 W514p]
RC732.W47 616.2'4'07 77-2284
ISBN 0-683-08934-X

Composed and printed at the
Waverly Press, Inc.
Mt. Royal and Guilford Aves.
Baltimore, Md. 21202, U.S.A.

Preface

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

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

with 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.

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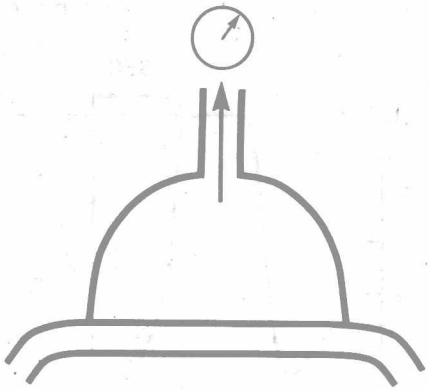
Contents

SECTION ONE

LUNG FUNCTION TESTS AND WHAT THEY MEAN

1. Ventilation
2. Gas exchange
3. Other tests

We learn how diseased lungs work by performing 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

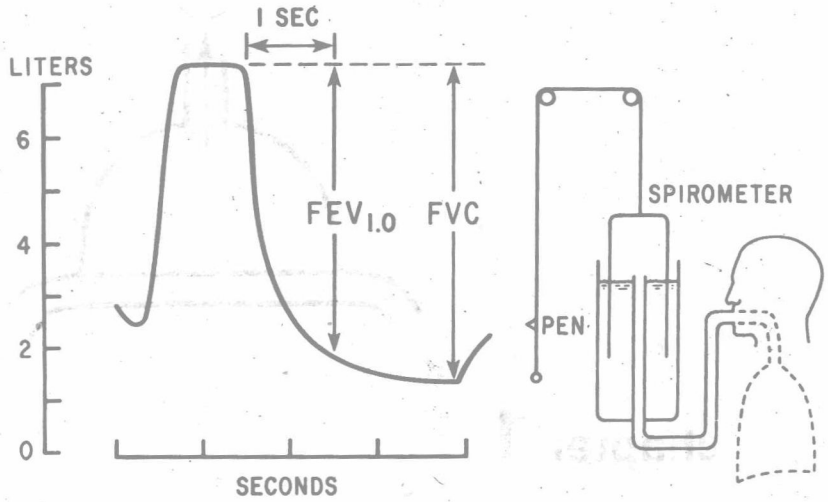


Fig. 1. Measurement of forced expiratory volume ($FEV_{1.0}$) and vital capacity (FVC).

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 one second ($FEV_{1.0}$) 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. The $FEV_{1.0}$/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.

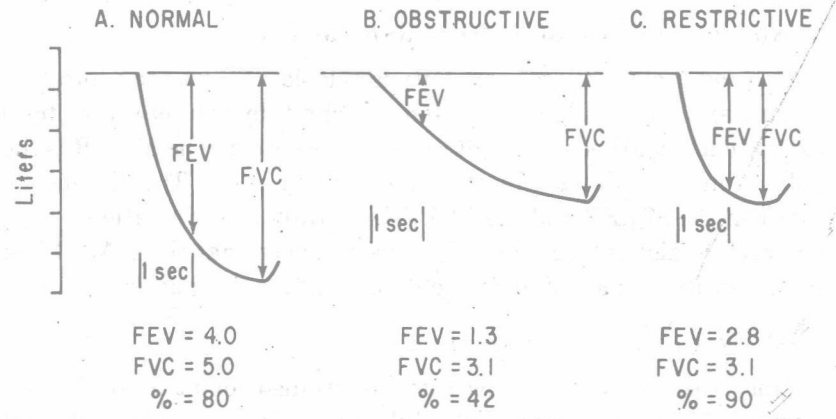


Fig. 2. Normal, obstructive, and restrictive patterns of a forced expiration.

If the equipment shown in Figure 1 is used, the spirometer should 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. Two practice blows are often allowed, and then the mean of the subsequent three breaths is used. A good practice is to disregard the first 200 ml of the expiration, because the patient may begin tentatively. 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.

The forced expiratory volume is sometimes measured over other periods of time, for example 0.75, 2.0 and 3.0 sec. The subscript (for example $FEV_{2.0}$) will indicate this. However the additional information provided by these other indices is generally small. If no subscript is given, the FEV in 1 sec is assumed.

Maximum Mid-Expiratory Flow Rate (MMFR)

This index of ventilatory capacity is calculated from the expiratory tracing as shown in Figure 3. The middle half (by volume) of the total expiration is marked and its duration is measured. The MMFR is the volume in liters divided by the time in seconds (2). The correlation between the MMFR and the FEV is generally close in patients with obstructive disease, but there is some evidence that the MMFR is a more sensitive index of airway obstruction in some patients.

Peak Expiratory Flow Rate (PFR)

This is the maximum flow rate maintained for at least 0.01 sec during a forced expiration from a full inspiration. It can be measured with the Wright peak flow meter (3) which has a spring-loaded vane that is deflected by the air stream. The PFR is related to the FEV and MMFR, though it may be less reproducible. The peak flow meter is rugged and portable, and is therefore convenient for measurements in the physician's office and for epidemiological work.

Maximum Breathing Capacity

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

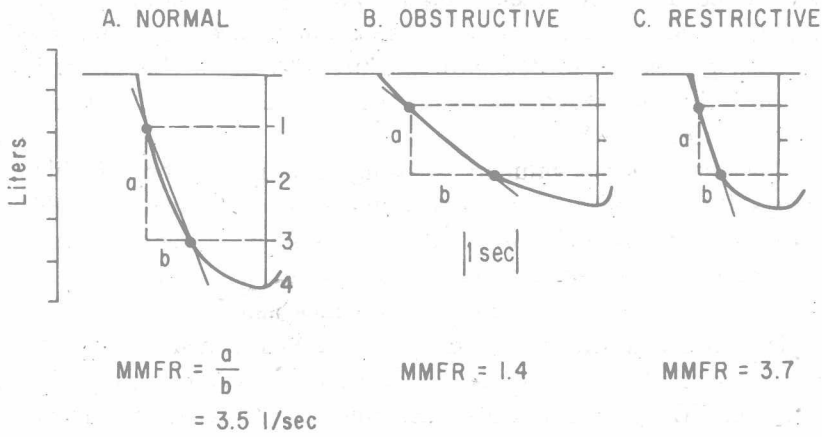


Fig. 3. Calculation of the maximum mid-expiratory flow rate (MMFR) from a forced expiration.

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 that 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 force 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 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,

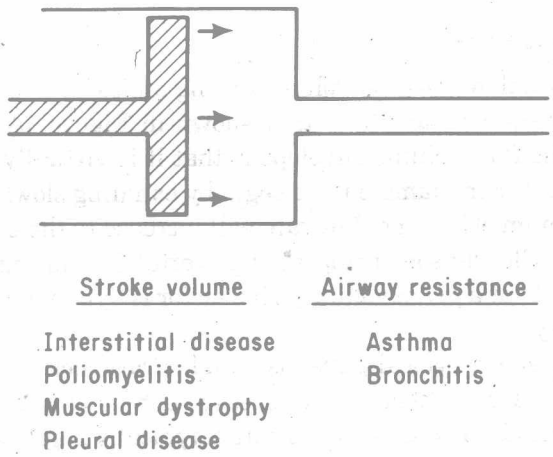


Fig. 4. Simple model of factors which may reduce the ventilatory capacity. The stroke volume may be reduced by diseases of the lung parenchyma, pleura, or respiratory muscle. Airway resistance is increased in asthma and bronchitis.

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 these 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 MMFR and PFR) are 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 such 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 which 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

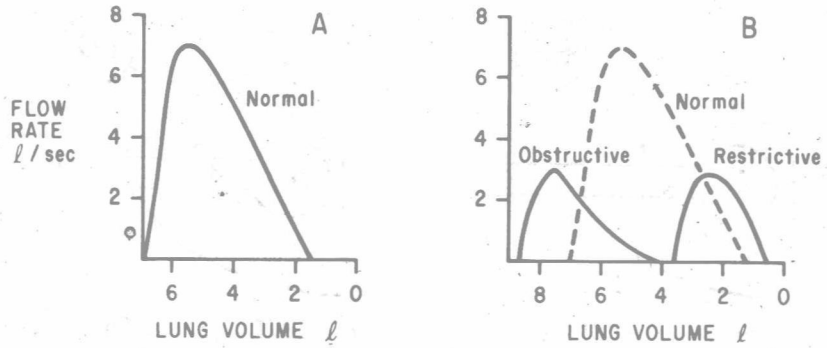


Fig. 5. Flow-volume curves. B contrasts the obstructive and restrictive pattern with the normal.

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 expiration. They require an additional measurement of residual volume.

To understand these patterns consider the pressures inside and outside the airways* (Figure 6). Before inspiration (A), the pressures in the mouth, airway and alveoli are all atmospheric because there is no flow. Intrapleural pressure is, say, 5 cm water below atmospheric pressure, and we assume that the same pressure exists outside the airways (though this is an oversimplification). Thus the pressure difference expanding the airways is 5 cm water. At the beginning of inspiration (B) all pressures fall and the pressure difference holding the airways open increases to 6 cm water. At the end of inspiration (C) this pressure is 8 cm water.

Early in a forced expiration (D) both intrapleural and alveolar pressures rise greatly. The pressure at some point in the airways increases, but not as much as alveolar pressure because of the pressure drop caused by flow. Under these circumstances we have a pressure difference of 11 cm water tending to *close* the airways. Airway collapse occurs, and now flow is determined by the difference between alveolar pressure and the pressure outside the airways at the collapse point (Starling resistor effect). Note that this pressure

* See *Respiratory Physiology—The Essentials* p. 108.

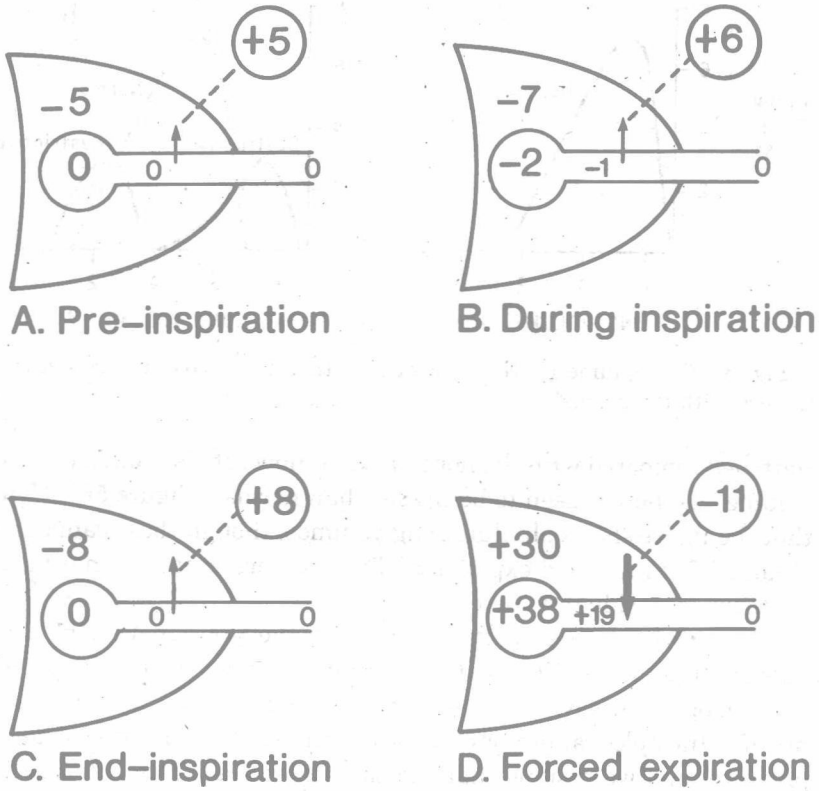


Fig. 6. Diagram to explain dynamic compression of the airways during a forced expiration. (See text for details.)

difference (8 cm water in D) is the static recoil pressure of the lung and is dependent only on lung volume and compliance. It is *independent* of expiratory effort.

How then can we explain the abnormal patterns in Figure 5B? In the patient with chronic bronchitis and emphysema, the low flow rate in relation to lung volume is caused by several factors. There may be thickening of the walls of the airways and excessive secretions in the lumen because of bronchitis which increase the flow-resistance. The number of small airways may be reduced because of destruction of lung tissue. Also the patient may have a reduced static recoil pressure even though his lung volume is greatly increased. Finally, the

normal support offered to the airways by the traction of the surrounding parenchyma is probably impaired because of loss of alveolar walls, and the airways therefore collapse more easily than they should. These factors are considered in more detail in chapter 4.

The patient with interstitial fibrosis has normal (or high) flow rates in relation to lung volume because his static recoil pressures are high and the caliber of his airways may be normal (or even increased) at a given lung volume. However, because of the greatly reduced compliance of the lung, the lung volumes are very small and absolute flow rates are therefore reduced.

This analysis shows that Figure 4 is a considerable oversimplification and that the forced expiratory volume which seems so straightforward at first sight is affected by both the airways and the lung parenchyma. Thus the terms "obstructive" and "restrictive" conceal a good deal of pathophysiology.

Partitioning of Flow Resistance from the Flow-Volume Curve

When the airways collapse during a forced expiration, the flow rate is determined by the resistance of the airways up to the point of collapse (Figure 7). Beyond this point, the resistance of the airways is immaterial. Collapse occurs at (or near) the point where the pressure inside the airways is equal to the intrapleural pressure (sometimes

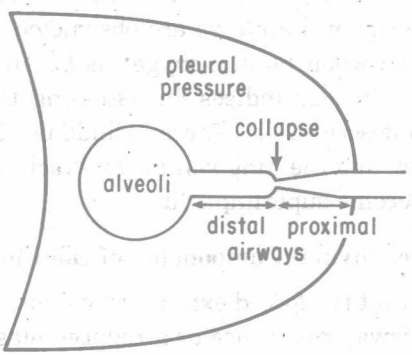


Fig. 7. When dynamic compression of the airways occurs during a forced expiration, only the resistance of the airways distal to the point of collapse determines the flow rate. In the last stages of a forced vital capacity, only the peripheral small airways are distal to the collapsed point and therefore determine the flow.