# THE LUNG

## CLINICAL PHYSIOLOGY

## *and* PULMONARY FUNCTION TESTS

*by*

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# Preface to the Second Edition

THE FIRST EDITION OF *The Lung* has been translated into Spanish, Japanese, French and Italian. Some wit then remarked, "It would be nice if someone translated it into English!" This second edition represents the "English translation." Practically all of the equations and their derivations have been moved to the Appendix and much of the original text has been rewritten with the intent of clarifying difficult concepts.

The most important change in this edition has been the addition of five chapters designed for the clinician. The first of these classifies pulmonary function tests into office, cardiopulmonary laboratory, or research procedures and indicates what can be learned from simple tests and when to ask for special, more complex studies. The second presents typical patterns of altered pulmonary function and cases illustrative of each. The third deals with special respiratory and pulmonary problems encountered by the anesthetist and surgeon and the fourth with the important questions of pulmonary disability and objective evaluation of pulmonary function in compensation cases. The fifth is a chapter on physiological therapy of pulmonary disease, which presents the rationale for treatment of acute and chronic respiratory and pulmonary disorders.

We wish to express our appreciation to reviewers of the first edition who pointed out the major omissions in it; we have followed their suggestions and hope that this second edition will be more useful to both clinicians and medical students.

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# Preface to the First Edition

PULMONARY PHYSIOLOGISTS understand pulmonary physiology reasonably well. Many doctors and medical students do not. One reason is that most pulmonary physiologists, in their original and review articles, write for other pulmonary physiologists and not for doctors or medical students. This is *not* a book for pulmonary physiologists; it is written for doctors and medical students. Like the Beaumont Lecture* upon which it is based, it has only one purpose—to explain in simple words and diagrams those aspects of pulmonary physiology that are important to clinical medicine.

A few words of explanation:

1. This is not an illustrated book but a monograph constructed largely around illustrations. Most of the illustrations are schematic; artistic license has been used freely to achieve clarity.
2. Our monograph strives for understanding of physiological principles and broad concepts more than for technical completeness. Details of procedures have been presented in an earlier publication (*Methods in Medical Research* [Chicago: Year Book Publishers, Inc., 1950], Vol. 2).
3. Pulmonary physiology can be explained in words, pictures, or equations. Most physicians shudder at equations; therefore words and pictures predominate and the occasional equation is accompanied by a verbal explanation and full apology. However, all important equations are presented in an Appendix for the enjoyment of those who have difficulty with words and pictures.
4. There are no references in the text. This is not because we wish to slight pulmonary physiologists (including ourselves) but because doc-

* "The Physiological Diagnosis of Pulmonary Disease," delivered by J. H. Comroe, Jr., to the Wayne County Medical Society, Detroit, February 1, 1954.

umentation often breaks the continuity of thought. Selected references are given in the Appendix, but even these represent only a small fraction of important articles that have been written on this subject.

5. The case reports (Part II) have been presented deliberately with minimal clinical detail, and the reader is asked to accept that the diagnoses have been based on adequate clinical study.
6. This is not a primer; a primer would not enable the physician to cope with some of the more baffling concepts such as ventilation/blood flow ratios, diffusing capacity, physiological dead space, distribution, compliance, alveolar ventilation, or transpulmonary pressure. On the other hand, this is not an encyclopedia, and no attempt has been made to include all contributions in this small volume.

—J. H. COMROE, JR.
—R. E. FORSTER, II
—A. B. DUBOIS
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—E. CARLSEN

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# *PART ONE*

## CHAPTER 1

# Introduction to Pulmonary Physiology

THE MAJOR FUNCTION of the cardiovascular and respiratory systems is to provide an adequate amount of *arterialized* blood at each moment to all of the tissues of the body. The lungs alone cannot accomplish this. Several processes are involved: First, mixed venous blood, low in $O_2$ and high in $CO_2$, is returned to the right atrium and ventricle to be pumped through the pulmonary circulation. Second, the mixed venous blood flowing through the pulmonary capillaries is arterialized, i.e., receives $O_2$ from the alveolar gas and gives off excess $CO_2$. Third, the arterialized blood is distributed to all of the tissues of the body according to their needs. Fourth, exchange of $O_2$ and $CO_2$ occurs between the blood in the tissue capillaries and the tissue cells themselves. The first, third and fourth of these processes are the major function of the cardiovascular system. The second process, the loading of mixed venous blood with enough $O_2$ at a high enough pressure and the unloading of excess $CO_2$, is the primary function of the lung; this monograph discusses only *pulmonary* function.

In the past two decades, a large number of physiologic tests has been developed for the qualitative and quantitative evaluation of pulmonary function in patients with suspected abnormalities of the cardiopulmonary system. These are now as important to the practice of medicine as are tests of hepatic, renal, cardiovascular and neuromuscular function, developed earlier. Tests of pulmonary function have proved to be of definite value both in diagnosis and in guiding therapy of patients with cardiopulmonary disorders. They have led to a better understanding of pulmonary physiology in healthy men and women of all age groups and to more

precise knowledge of the pathologic physiology and natural course of pulmonary disease. They have aided in the early detection of pulmonary dysfunction in some patients considered to be normal on the basis of clinical and radiologic examination and have assisted in differential diagnosis in patients with a known disease in whom a specific diagnosis could not be made with certainty by other methods. They have been used for the objective evaluation of therapeutic measures such as the use of oxygen, helium-oxygen, pressure breathing, bronchodilators, cortisone, antibiotics, artificial respiration and surgical procedures and so have contributed to the development of more rational measures of treatment. Finally, they have been invaluable in securing physical, measurable data in patients who may or may not have pulmonary disability, and in determining, during the lifetime of the patient, the specific function of the lung that has been impaired.

The introduction of physiologic tests does not mean that these have supplanted other diagnostic procedures. Physiologic tests indicate only how disease has altered *function;* they cannot make an anatomic, a bacteriologic or a pathologic diagnosis. For example, function tests may reveal the existence of a right-to-left shunt but in themselves cannot locate it anatomically as being intracardiac or intrapulmonic. Again, physiologic tests may indicate that there is impairment of diffusion across the alveolocapillary membranes but cannot differentiate interstitial edema from intra-alveolar edema, nor can they determine whether the intra-alveolar fluid is exudate or transudate. Furthermore, they do not reveal alterations in all types of pulmonary disease but do so only when the lesion disturbs *function* and disturbs it sufficiently that present tests can recognize with certainty the deviation from normal values. In general, they cannot detect slight reduction in functioning pulmonary tissue or the presence of small regions in the lungs that have neither ventilation nor blood flow. Results of physiologic tests will be normal in the presence of lesions such as fibrotic tuberculous cavities, cysts or carcinomatous nodules unless these lesions occupy so much space that they reduce the lung volume well below normal limits or are located so strategically that they disturb pulmonary function. Pulmonary function studies will not tell *where* the lesion is, *what* the lesion is or even that a lesion exists, if it does not interfere with the function of the lung. Therefore they supplement and do not replace a good history and physical examination, radiologic, bacteriologic, bronchoscopic and pathologic studies.

As in the case of physiologic tests of other systems, no *single* pulmonary function test yields all the information desired in any single patient.

The primary function of the lung is, as already stated, to arterialize the mixed venous blood. This involves the addition of adequate amounts of $O_2$ and the elimination of proper quantities of $CO_2$. This is achieved by pulmonary gas exchange which involves a number of processes (Fig. 1). The first of these is VENTILATION; this includes both *volume* and *distribution* of the air ventilating the alveoli. A large enough *volume* of inspired air must reach the alveoli each minute, and this air must be *distributed evenly* to the hundreds of millions of alveoli in the lungs; i.e., the volume of air going to each alveolus should be in proportion to the volume of that alveolus. The second of these is the process of DIFFUSION, by which $O_2$ and $CO_2$ pass across the alveolocapillary membranes. The third is PULMONARY CAPILLARY BLOOD FLOW; this must be adequate in *volume* and all of the mixed venous blood must be *distributed evenly* to all the ventilated alveoli.

This admittedly is an arbitrary division of the complex and interrelated functions of the lungs which have as their primary purpose the uptake of an adequate amount of $O_2$ and the elimination of excess $CO_2$. Furthermore, it ignores a matter of great importance, namely, that this gas exchange should be achieved with a minimal expenditure of energy by the respiratory and circulatory systems. The *work* involved in arterializing the venous blood formerly was largely neglected. However, the *mechanical factors* in ventilation are of great importance, because in some patients adequate pulmonary gas exchange may be achieved only by a considerable increase in the work of the respiratory muscles; indeed, in patients with advanced pulmonary disease, the crucial factor in survival may be whether the maximal effort available can produce adequate ventilation. Finally, the work required of the right ventricle in pumping blood through a restricted pulmonary vascular bed may also be of critical importance in survival. Figure 1, *5*, presents a schematic summary of some of the mechanical factors involved in gas exchange. The left side summarizes the processes involved in gas exchange between the alveoli and the pulmonary capillary bed; the right side illustrates that, for adequate inspiration, sufficient force must be applied to the lungs (by expansion of the thorax) to stretch elastic tissue components (coiled spring) and to overcome frictional resistance in the pulmonary tissues (shaded area in the coil) and in the airways (parallel lines). These mechanical factors in breathing are discussed in detail in Chapter 7.

The quantitative measurement of *all* of these processes requires a large number of physiologic tests. Not all of these tests are required in the management of each patient. Some of the tests are very simple and may

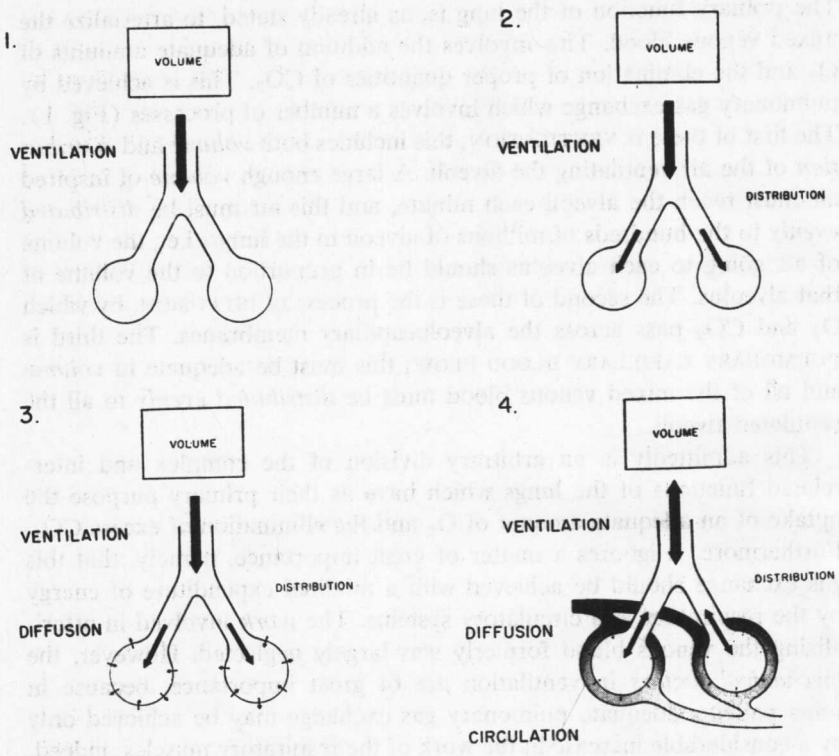


FIG. 1.—PROCESSES INVOLVED IN PULMONARY GAS EXCHANGE

The alveoli, where rapid gas exchange occurs, are represented by rounded areas; leading into these are tubes depicting the conducting airways or anatomic dead space (light gray in *4*) in which no effective gas exchange occurs. Rectangular blocks indicate the minute volume of breathing. The two arrows entering the alveoli show distribution of total inspired gas (large arrow) to various alveoli. In *3* and *4*, small arrows crossing alveolar walls designate the process of diffusion of $O_2$ out of the alveoli into the blood and of $CO_2$ from the blood into the alveoli. The shaded channel surrounding the alveoli in *4* represents pulmonary blood flow; it enters the capillary bed as mixed venous blood (dark) and emerges as arterialized blood (light). In *5*, the left side is a summary of the processes of ventilation, diffusion and circulation. The right side represents the pulmonary "tissues" responsible for the mechanical properties of the lung: parallel lines in the conducting airways represent the fine airways responsible for airway resistance; the springlike coil surrounding the alveoli represents the elastic tissues of the lung, and stippled areas in the coil are the non-elastic tissues (see Chapter 7).

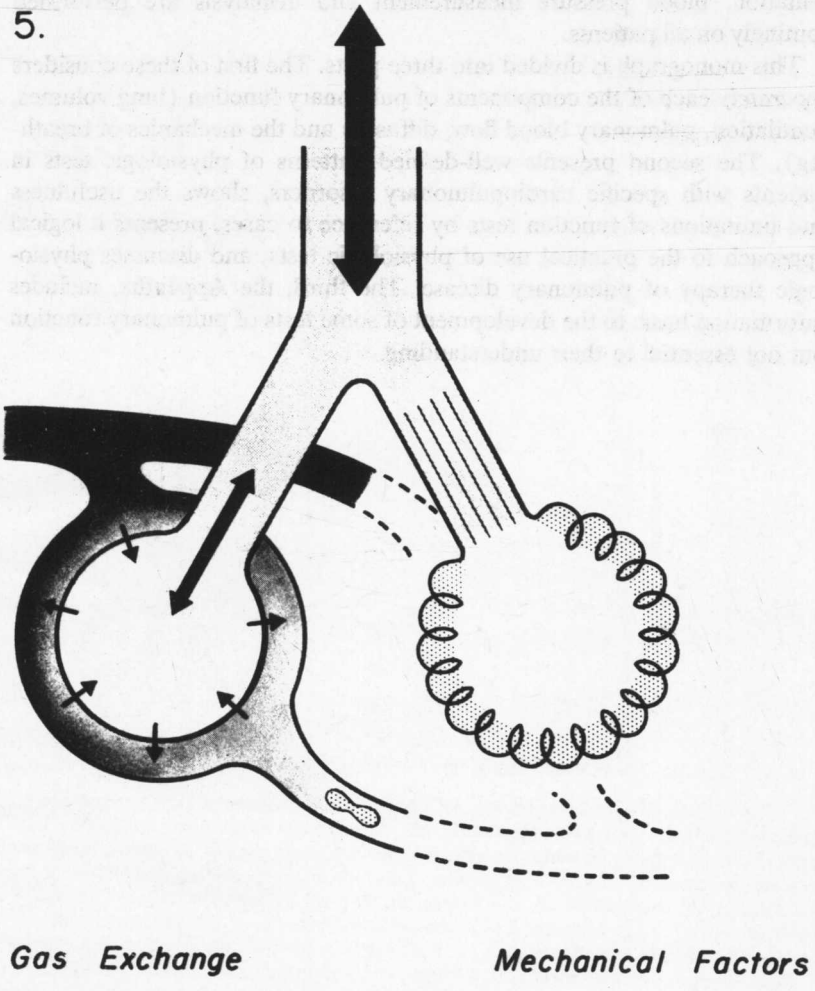


FIG. 1 (*cont.*)

be carried out in a physician's office (p. 205); others require expensive apparatus or considerable technical experience and are normally carried out in a hospital cardiopulmonary laboratory; still others are research procedures and at present are available only in a few medical centers. However, some tests should now be performed on every patient with known or suspected cardiopulmonary disease, just as a hemoglobin deter-

mination, blood pressure measurement and urinalysis are performed routinely on all patients.

This monograph is divided into three parts. The first of these considers *separately* each of the components of pulmonary function (lung volumes, ventilation, pulmonary blood flow, diffusion and the mechanics of breathing). The second presents well-defined patterns of physiologic tests in patients with specific cardiopulmonary disorders, shows the usefulness and limitations of function tests by reference to cases, presents a logical approach to the practical use of physiologic tests, and discusses physiologic therapy of pulmonary disease. The third, the Appendix, includes information basic to the development of some tests of pulmonary function but not essential to their understanding.

CHAPTER 2

# The Lung Volumes

FOR MANY YEARS, the only tests of pulmonary function were the measurements of the lung volumes (Fig. 2). Actually, these do not evaluate *function* since they are essentially anatomic measurements. Changes in the lung volumes, however, are often caused by alterations in physiologic processes, and for this reason it is important to know normal values and how to interpret deviations from these.

Because too many names had been applied to the same lung volumes, a group of American respiratory physiologists agreed in 1950 to use the terms and definitions in Table 1 in order to avoid confusion.

Normal values for lung volumes and subdivisions in recumbent men and women are given in Table 2. The standard deviations from the mean (see Table 28, p. 325) show that there is considerable variation even in a homogeneous group; consequently deviations from "normal" must be large to be significant in diagnosis.

## A. VITAL CAPACITY AND ITS SUBDIVISIONS

The vital capacity and its subdivisions (inspiratory reserve volume, expiratory reserve volume and tidal volume) can be measured directly by the use of simple volume recorders such as bellows or spirometers. Approximate values are given in Table 2. The standard test is performed by asking the patient to inspire maximally and then expire completely into a bellows or spirometer.* In this test, no time limit is imposed on

* Some investigators also measure (*a*) the maximal volume *inspired* after a complete expiration or (*b*) the sum of the separately performed inspiratory capacity and expiratory reserve volume, and compare these with the standard measurement of vital capacity. Since some air may be "trapped" in alveoli by forced expiration beginning from the position of maximal inspiration, the test performed in the standard manner may yield lower values than (*a*) and (*b*) in patients with emphysema (see p. 197).

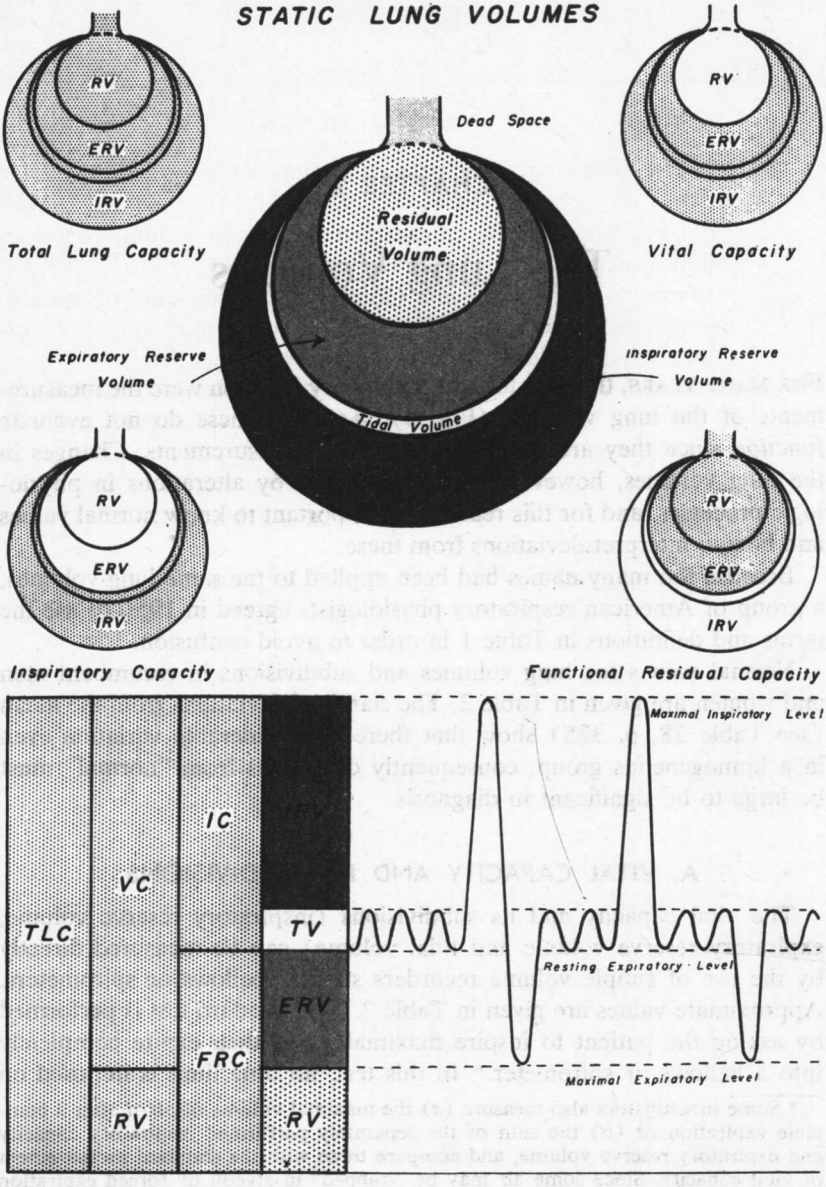


FIG. 2.—LUNG VOLUMES