Pulmonary Function in Diseases of the Chest*

HURLEY L. MOTLEY, PH.D., M.D., F.C.C.P.**

Los Angeles, California

Pulmonary function tests are designed to provide accurate information of the extent and location of disturbed function thereby making available additional information for use with the history, physical, and roentgenological examination in the clinical management of the individual case. A battery of physiological test measurements are used, each possessing a wide range between the normal and the abnormal, and each covering an essential aspect in the evaluation of the adequacy of the gas exchange. One group of tests concerns the bellows action of the chest and lungs and evaluates the ability to move air in and out of the alveoli during the process of breathing. The other group of tests relate to the blood gas exchange across the alveolar-capillary or pulmonary membrane (oxygen and carbon dioxide transport). Pulmonary function measurements assist in the interpretation of the meaning of pulmonary disease from the standpoint of disability, operative risk and treatment.

The efficiency of the bellows action of the chest and lungs for moving air in and out of the alveoli is measured from spirogram tracings and from the residual capacity measurement. Spirogram tracings provide measurements of total vital capacity, timed vital capacity, maximal breathing capacity, and a permanent graphic recording of the exhalation pattern. Evidence of air trapping in the lung is also obtained from the spirogram tracings by having the individual take a deep breath in and then blow out rapidly a few times. Total vital capacity is determined both in the supine and standing position, being the difference between the volume of the lung in the maximal distended position in inspiration and the minimal volume present at the end of a forced maximal exhalation. The total vital capacity in a normal individual is usually slightly larger in the standing than in the supine position. A marked reduction in total vital capacity in the standing position as compared to the supine position indicates the presence of severe pulmonary insufficiency. However, vital capacity when recorded with respect to time becomes a much more significant measurement. The subject is instructed to take in as deep a breath as possible, hold the breath momentarily and then on command blow all of the air out of the lungs as rapidly and as completely as possible. The volume exhaled in the first three seconds measured from the exact beginning of expiration is recorded as the three second timed vital capacity. The three second timed vital capacity is normally the same as the individual's predicted total vital capacity, and represents the maximal functional portion of the vital capacity (a respiratory rate of 15 per minute allows


**Professor of Medicine and Director of the Cardio-Respiratory Laboratory University of Southern California School of Medicine.
four seconds per breath, but if one second is utilized for inspiration only three seconds are left for expiration). The predicted total vital capacity is best computed from the height of the patient.¹

The maximal breathing capacity reveals the largest volume of air which an individual is able to move in and out of the lungs in a given short unit of time (12-15 seconds), but is expressed as liters per minute. The individual should be instructed to breathe as deeply and as rapidly as possible for 12 seconds, (never longer than 15 seconds), and the rate and depth varied on successive trials (not less than three) to get the maximal value. The 13½ liter respirometer* was developed with the idea of providing an apparatus for mechanical recording with a minimal of breathing resistance for the deep fast breathing and to permit a quick accurate determination of the maximum breathing capacity value (5-10 minutes). The drum on the respirometer has a paper speed which provides a time interval of 12 seconds between the vertical lines. When the rate and depth of breathing are properly varied one can obtain precisely the highest maximal breathing capacity of which an individual is capable and the learning factor as such is not a significant feature. The maximal breathing capacity is a measure of the ability to use the lungs as a bellows and a very wide spread may exist between the normal and the most abnormal cases (10-200 liters per minute). The predicted** maximal breathing capacity is based on the type of apparatus and procedure used and the age, sex, height and weight of the person.¹ If the maximal breathing capacity is normal, the individual is able to use the diaphragm well, the elasticity of the lungs is good, bronchospasm is not a factor and a significant degree of pulmonary emphysema does not exist. The degree of bronchospasm is measured quantitatively by comparing the maximum breathing capacity measurement before and immediately after one bronchodilator treatment using the intermittent positive pressure breathing method for administering a potent bronchodilator substance such as isuprel and veponefrin.³⁴ The maximal breathing capacity and the timed vital capacity are independently variable measurements. It has been found in men that if the maximal breathing capacity is above 120 liters per minute, the degree of pulmonary emphysema present is insignificant and significant if less than 40 liters per minute, but between 40 and 120 liters per minute indeterminate.⁵ The maximal breathing capacity is a sensitive test and this measurement frequently reveals early abnormalities and hence is valuable for screening purposes, either in the selection of problem cases requiring more complete pulmonary function evaluation or in the detection of poor risks in industrial workers exposed to irritating dusts.⁶

The shape of the spirogram tracing as observed on the rapidly moving kymograph drum (32 mm. in 12 seconds) reveals characteristic features of the expiratory flow. A slow and prolonged exhalation curve indicates obstruction to air flow, either of a fixed type or due to bronchospasm and

**For the 13½ liter Collins respirometer the predicted maximal breathing capacity in liters per minute is men equal (97-Age/2) x BSA in. Sq. meters for women equal (83-Age/2) x BSA in. Sq. meters.
the failure of the end exhalation point of the tracing to return at least to the beginning level indicates air trapping. If the spirogram tracings show a marked rise in the respiratory level during the maximal breathing capacity test with the rapid voluntary respiratory movements, this high inspiratory position indicates the presence of increased breathing resistance and usually the presence of a significant degree of pulmonary emphysema. Air trapping is a characteristic feature of asthma due to the bronchospasm as the bronchioles are narrower during expiration than inspiration, with a result that expiration is more difficult and prolonged.

The pulmonary function tests described thus far are easy to perform and the only special equipment required is the $13\frac{1}{2}$ liter Collins Respirometer. These tests can be done in the office and on an average only five to 10 minutes are required to obtain satisfactory spirogram tracings. When the degree of bronchospasm is evaluated a slightly longer time period is required, since the bronchodilator should be administered over a period of at least 10 minutes to be certain of obtaining the maximal results.$^8$ These tests are useful in evaluating the response to treatment, in following the clinical course of a disease by comparing serial spirogram tracings taken at intervals (similar to the chest roentgenogram) and in screening tests of candidates for surgery, anesthetic risk, workers exposed to lung irritants (either dust or gases) and other problem types of cases.

A second important basic measurement relating to the bellows action of the chest and lungs is the residual air capacity, which by definition is the volume of air remaining in the lung at the end of a maximal forced exhalation. The residual air occupies normally about 25 per cent of the total lung capacity, being slightly smaller in the younger age group (20 up to 35 years) and slightly larger in the older age group (30 over 60 years). In pulmonary emphysema the volume of residual air is increased in relation to the total lung volume and if this ratio is over 35 per cent a significant degree of pulmonary emphysema exists. The residual air is measured quantitatively using the oxygen open circuit method, and checked routinely on two runs to within 100 ml., if not the run is repeated. If the alveolar air contains more than 1.5 per cent nitrogen after breathing oxygen for seven minutes, impairment in the uniformity of air distribution in the lung exists.$^1$ The ratio of the residual air to the total lung capacity is most important in the individual case since this corrects for changes in total lung volume which may exist (either normal, increased or decreased). If the residual air occupies 35-45 per cent of total lung capacity a moderate degree of emphysema is present, from 45-55 of total lung capacity an advanced or severe degree and above 55 a far advanced or very severe degree of emphysema exists. The accurate diagnosis of pulmonary emphysema in some cases requires measurements of residual air, as the physical examination and the chest roentgenogram may be misleading or inconclusive. Pulmonary emphysema is frequently missed on the chest roentgenogram when a severe degree actually exists.

The three measurements of pulmonary function thus far described of greatest importance relating to the bellows action of the chest and lungs...
and measuring independently variable aspects are: (1) the timed vital
capacity for three seconds, (2) the maximum breathing capacity and (3)
the residual per cent of total lung capacity.

A numerical ventilation factor (V.F.) has been used to evaluate the
efficiency of the chest and lungs as a bellows from the average of the
three measurements, all expressed as per cent of the normal predicted,
namely: the three second vital capacity, the maximal breathing capacity
and the residual air as per cent of total lung capacity. The ventilation
factor provides a single figure value of the patient's ability to use the
chest and lungs as a bellows for aerating the alveoli and this is well
correlated with the arterial pCO₂ in mm. Hg. as determined by direct ten-
sion measurements.

The second basic aspect of pulmonary function, namely the blood gas
exchange across the alveoli-capillary membrane, is evaluated from studies
of the arterial blood and the expired air. Normally, at sea level pressure,
the arterial blood hemoglobin is 96-98 per cent saturated with oxygen
both at rest and during exercise. The arterial blood oxygen saturation
is obtained by dividing the corrected oxygen content by the corrected
oxygen capacity as volumes per cent for each sample of blood. The
Van Slyke manometric apparatus is used for the measurements of oxy-
content and capacity. The double scale oximeter using the cuvette
appears to be a fairly satisfactory procedure for determining the arterial
blood oxygen saturation. A drop in the arterial blood oxygen satu-
ration of 5 to 10 per cent or more below the resisting level with exercise
(after the one minute step-up test) indicates severe disability. An in-
crease in the exercise oxygen saturation above the resting level indicates
less disability than implied by the resting level measurement. It is thus
of great importance to compare in each case where possible the rest and
exercise arterial blood oxygen saturation, as often the exercise arterial
blood oxygen saturation is of much greater value than the resting in
evaluating the pulmonary function status. If the exercise arterial blood
oxygen saturation drops 5 to 10 per cent below the resting level the in-
dividual should be restricted in such activities as walking up steps or up
grades. In general, the exercise saturation tends to decrease in severe
emphysema, but this is not always the case, and in pulmonary fibrosis
without emphysema, a marked drop in the exercise arterial blood oxygen
saturation frequently occurs.

An elevated arterial CO₂ content indicates difficulty in blowing off CO₂
and warns of the possibility of developing respiratory acidosis during
infections or if the respiration be depressed by sedative drugs, anesthetics,
or by other means. The arterial blood pH is the best single measurement
revealing the exact status of the acid base balance concerning the presence
of acidosis or alkalosis. If the patient has a marked degree of arterial
blood oxygen unsaturation with an elevated CO₂ content, then the ad-
ministration of high oxygen concentrations with a mask or even with a
catheter or tent may precipitate respiratory acidosis, drowsiness and even

*Waters-Conley, Rochester, Minn.
coma or death. In such a patient the sudden change to high oxygen breathing decreases the minute ventilation as a result of removing part of the stimulus to the respiratory center from the carotid bodies, as these are stimulated by the low oxygen in the blood and reflexively stimulate the respiratory center. The high oxygen breathing relieves the arterial blood unsaturation and removes the stimulus from the carotid bodies and the ventilation decreases, in some to a critical level unless supplemented by mechanical aids.

The expired air from the patient is studied with respect to the minute ventilation (total volume of air breathed during a test period of three to five minutes), the total oxygen uptake and the per cent of oxygen extracted from the inspired air breathed. The minute ventilation is measured with respect to the number of liters per minute per square meter of body surface area. If the minute ventilation is below the normal range, hypoventilation is indicated and if above hyperventilation. In some cases hyperventilation may be the only abnormality revealed from the pulmonary function evaluation. The one minute step-up exercise test (30 steps on an eight inch stool in one minute) has been standardized with respect to the normal range. In some cases of marked pulmonary insufficiency the exercise minute ventilation may be inadequate in proportion to the step-up test requirement. In general, the minute ventilation as a single measurement is often indeterminate as revealed from extensive statistical studies on a large series of cases. The minute ventilation along with the data provided from the expired air gas analysis provides the necessary data to calculate the oxygen uptake. The oxygen uptake is determined both at rest and with exercise. The resting oxygen uptake tends to be in the normal range regardless of the degree of pulmonary insufficiency, and hence, is of little value in pulmonary disability evaluation. On the other hand, the measurement of step-up exercise oxygen uptake is a very significant value. A marked reduction in the exercise oxygen uptake in the presence of an adequate minute ventilation reflects the inability of the individual to expand the pulmonary bed and increase the pulmonary blood flow or to increase the cardiac output from the right heart to the elevated level representing a normal response proportionate to the degree of exercise given. If the normal amount of oxygen is removed from the expired air during the one minute step-up exercise an increased blood flow is necessary. If the oxygen uptake is normal during exercise this indicates that the pulmonary blood flow is increased in proportion to the degree of exercise and that the pulmonary vascular resistance is not significantly altered. A decreased oxygen uptake during step-up exercise indirectly indicates increased pulmonary vascular resistance, without the necessity of catheterizing the right heart to measure mean pulmonary arterial pressure and the cardiac output.

The per cent of oxygen extracted from the inspired air breathed is a measure of the lung ventilation efficiency, and this figure is used to determine the oxygen uptake along with the pulmonary ventilation volume measurement. Normally 4 to 5 per cent of the oxygen is extracted from
the inspired air at rest and 5 to 6 per cent during the step-up exercise. Thus, if a patient is removing only 2.5 per cent of the oxygen from the inspired air during exercise, twice the normal volume of air would be required for breathing to furnish the oxygen. In chronic pulmonary disease the per cent of oxygen extracted from the inspired air is usually decreased somewhat, but this measurement is usually indeterminate as to the degree of pulmonary function impairment present unless the decrease is of marked extent. Excitement with hyperventilation may result in a low abnormal value, which might be normal if the individual were breathing at a lower volume rate. A severe degree of pulmonary insufficiency may exist with hyperventilation present during step-up exercise and a normal per cent of oxygen extracted, but the total oxygen uptake would be decreased markedly.

The duration of dyspnea with a standard exercise test (such as the one minute step-up) is of value in pulmonary function evaluation. The one minute step-up test increases the oxygen uptake normally three to four times above the resting level and is designed as a test of pulmonary function rather than physical fitness. This test is satisfactory for routine use in studying patients with chronic pulmonary disease. The exercise study is of great value in demonstrating disturbances in ventilation-perfusion relationships (changes in the arterial blood oxygen saturation and total oxygen uptake). The duration of the dyspnea with the one minute step-up test is a subjective sensation on the part of the patient and it is subject to limitations as such, but careful observations by trained personnel minimize the subjective element. For the normal individual, the one minute step-up test is a mild exertion and the subjective dyspnea is less than 90 seconds in duration. A marked prolongation of the dyspnea constitutes a significant finding and indicates a severe degree of function impairment either cardiac or pulmonary. In general, the pulse and the respiratory rates are unreliable measurements on which to assess pulmonary function impairment. Statistical analysis of a large series of data on respiratory rate, pulse rate, and minute ventilation has revealed the inadequacy of these measurements alone as shown by the magnitude of the standard deviation. Breath holding time has been found to be of no value. Tests of circulation times with ether and decholin, blood volume, hematocrit, hemoglobin level and venous pressure, and the electrocardiogram are frequently very helpful in differentiating the pulmonary and cardiac aspects of a given case.

Great advances have been made in research investigations relating to pulmonary function in recent years and many of these new tests are interesting and give promise of clinical value in the future, but as yet they are not sufficiently well established or the necessity proved to be routinely included in a pulmonary function evaluation. The direct tension measurements of arterial \( pO_2 \) and \( pCO_2 \) is a valuable research procedure, but it is difficult to acquire a satisfactory proficiency in performance, hence subject to many errors by inadequately trained personnel. The use of the nitrogen meter appears promising, but as yet the practicability and reli-
ability of both test and apparatus have not been adequately demonstrated. Pulmonary compliance, relating to the pressure volume relationship of the lung, is a popular study at the present time, but whether this will provide any more practical clinical information over that which can be obtained with simple spirogram tracings remains to be demonstrated. Similarly the pneumotachograph is an interesting research instrument, but whether it provides any more information than can be obtained from the spirogram tracings on the respirometer remains to be demonstrated.

SUMMARY

An accurate evaluation of the degree of pulmonary function impairment may be made from the following physiological tests: (1) Ventilation measurements from spirogram tracings (total vital capacity, three second timed vital capacity, maximal breathing capacity and the shape of the exhalation curve following a deep breath), (2) the degree of bronchospasm present, (3) the residual air capacity and alveolar nitrogen per cent after seven minutes oxygen breathing, (4) the arterial blood oxygen saturation at rest and immediately after step-up exercise, (5) the oxygen uptake during step-up exercise, (6) the per cent of oxygen extracted from the inspired air breathed and (7) the character and duration of dyspnea after step-up exercise.

RESUMEN

Una exacta valuación del grado de daño a la función pulmonar, puede lograrse mediante las siguientes pruebas funcionales: (1) Medidas de ventilación por los trazos espirométricos (capacidad vital total, capacidad vital en tiempo de tres segundos, capacidad vital máxima y la forma de la curva de la exhalación después de una respiración profunda), (2) el grado de broncoespasmo presente, (3) la capacidad de aire residual y el nitrógeno alveolar por ciento después de siete minutos de respirar oxígeno, (4) la saturación de oxígeno de la sangre en reposo e inmediatamente del ejercicio del escalón, (5) la toma de oxígeno durante el ejercicio del escalón, (6) el porcentaje de oxígeno extraído del aire inspirado y (7) el carácter y la duración de la disnea después del ejercicio del escalón.

RESUME

Les troubles de la fonction pulmonaire peuvent être évalués par les tests physiologiques suivants: (1) mesure de la ventilation par tracés spirographiques (capacité vitale totale, capacité vitale mesurée pendant trois secondes, capacité ventilatoire maxima et aspect de la courbe expiratoire suivant une respiration profonde), (2) degré du bronchospasme existant, (3) capacité de l'air résiduel, et du pourcentage d'azote alvéolaire après sept minutes de respiration dans l'oxygène, (4) saturation oxygénée du sang artériel au repos, et immédiatement après des exercices de montée d'escalier, (5) augmentation de l'absorption d'oxygène au cours des exercices de montée d'escalier, (6) pourcentage d'oxygène retiré de l'air inspiré et (7) caractère et la durée de la dyspnée après exercice de montée d'escalier.
REFERENCES