CLINICAL FOCUS SERIES

# Pulmonary Function Testing & Interpretation



JAMES E HANSEN

JAYPEE

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CHAPTER

# 4 Basic Spirometry

## WHAT SPIROMETRY DOES AND DOES NOT MEASURE

A spirometer is the most basic and commonly used device for measuring lung function, whether for population surveys in the field, for clinical assessment of individual patients in the clinical pulmonary laboratory or hospital wards, or for evaluating normal subjects or patients in research laboratories. Spirometry is excellent for measuring airway obstruction, both expiratory and inspiratory, and for measuring changes over time or in response to interventions or therapy. It measures VC, but not RV, FRC or TLC, so although it can suggest, or even strongly suggest, restriction, it cannot alone identify or quantitate restriction. Once a restrictive process is proven by adequate reduction of TLC, spirometric measures can usually be used to follow the progression or regression of restriction. Spirometry cannot assess the presence or absence nor progression or regression of pulmonary vascular disease. However, since VC decreases with pulmonary edema or pleural effusions, laboratory or bedside spirometry can be useful in quickly assessing the regression or progression of left heart failure.

## EQUIPMENT CALIBRATION

Each spirometer, whether measuring volume directly and flow indirectly (rolling seal, wedge, bell or other) or measuring flow directly (pneumotachograph, heated wire, turbine or other) should be certified to meet ATS standards.[1,2] Volume spirometers should be checked for leaks weekly and flow spirometers should be calibrated at least daily, using a 3.00 L or other size syringe of known volume. The room temperature and barometric pressure should be known; either directly measured, or obtained from a local airport or government agency. Calibration should follow manufacturer's directions, but usually consists of six or more complete inhalations or exhalations into the spirometer using complete and smooth cycles. Each cycle must be very slow, very fast or of intermediate velocities. The usual acceptable range for repeated measurements at all three velocities is ±3%.

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## DISPLAYING TIME VERSUS VOLUME AND VOLUME VERSUS FLOW

### Time versus Volume Display

Most spirometers display time on the X axis, usually moving from left to right. Volume is displayed on the Y axis, with TLC either superiorly or inferiorly and RV necessarily the opposite. Slow or unforced vital capacities can be measured initially or later. For all measurements, the patient should be seated comfortably upright on a chair so he/she can bend forward as necessary. A nose clamp is applied and the patient asked to sniff. If air cannot pass through the nose, the clamp position is satisfactory. A clean mouthpiece of comfortable size, often with a flange between the lips and the teeth is placed in the mouth and the patient instructed to hold the mouthpiece tightly so that no air can leak around it. A low resistance filter may also be placed in line to reduce the likelihood of contamination.

**Unforced VC**

As the patient breathes comfortably, resting tidal volumes are recorded. The patient is then asked to take a maximal inhalation, hold it momentarily, and then asked to exhale completely but not necessarily rapidly until he/she cannot exhale further (Figure 4-1). The expiratory maneuver should last several seconds in normal adults, and longer in those with significant airway obstruction. This maneuver can be followed with a deep or partial inhalation (Figure 4-2).

### Adding Volume Versus Flow Display

Most spirometers can also display concurrently volume on the X-axis and flow, both expiratory and inspiratory on the Y-axis. Time signals may or may not be evident.

**Forced VC**

The patient is asked to return to resting tidal breathing, then inhale maximally, pause very briefly, and then exhale with maximal effort for at least six seconds. If there is no further change in expired volume after 6 seconds, a full forced inspiration follows. If expiratory flow continues after 6 seconds, it is ordinarily continued until the flow ceases and the volume plateaus, or for 10-15 seconds. It is usually unnecessary or unwise to continue forced exhalation longer than that, because forced exhalation impedes the flow of blood back to the thorax and may result in light-headedness due to impaired blood flow to the brain. The forced maneuver should be repeated at least two more times to obtain adequate duplicate measures, but rarely repeated more than six times to avoid patient frustration and exhaustion. Such forced maneuvers are displayed in figures 4-3 and 4-4. At least once, after measuring the slow or forced

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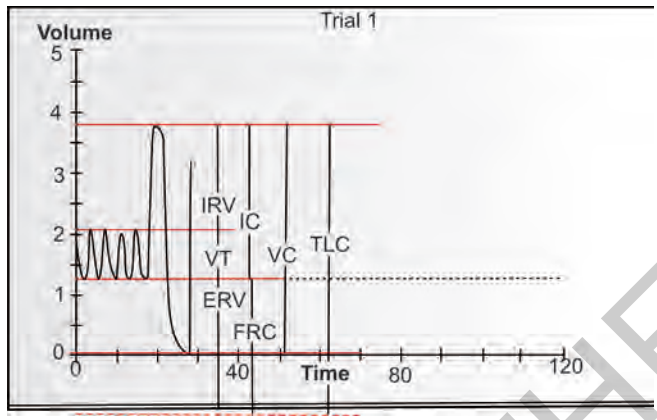


**Figure 4-1** Spirometric volume versus time display, from left to right, of tidal breathing, a maximal inspiration, a slow maximal expiration and a partial inspiration in a normal subject. Horizontal red lines separate volumes and capacities. RV, FRC and TLC cannot be measured from spirometry alone. (ERV = expiratory reserve volume, FRC = functional residual capacity, IC = inspiratory capacity, IRV = inspiratory reserve volume, RV = residual volume, TLC = total lung capacity, VC = vital capacity, VT =

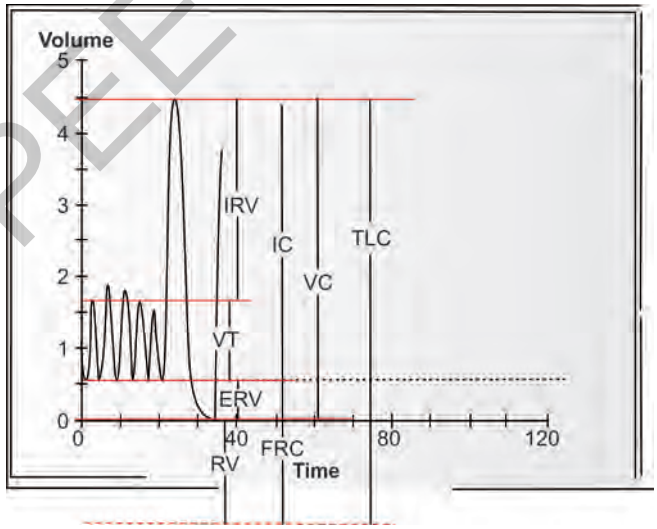


**Figure 4-2** Spirometric volume versus time display, from left to right in a more obese otherwise normal subject. Note smaller ERV and higher IC/ERV ratio abbreviations as in (Figure 4-1).

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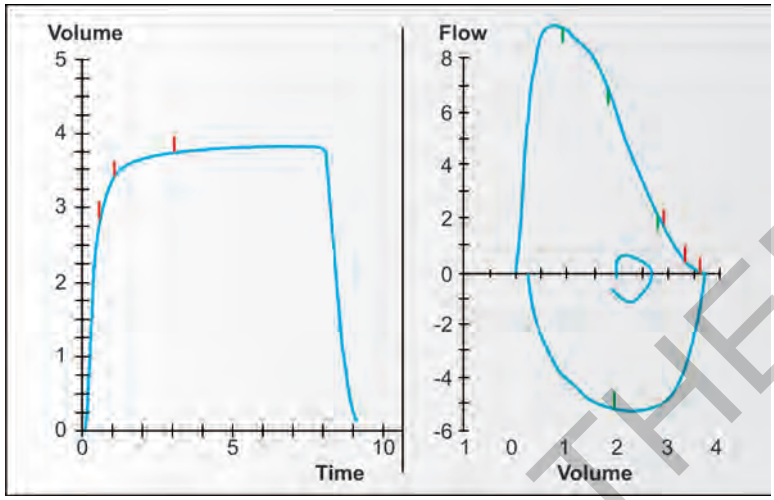


**Figure 4-3** Forced expiratory and forced inspiratory maneuvers on time-volume (left) and volume-flow (right) tracings of a 37-year-old man. On the volume-flow tracing, resting tidal breathing with IRV, VT and ERV are not marked but can also be identified. On both tracings, upward tick marks colored red can be seen at 0.5 sec, 1.0 sec and 3.0 sec. On the volume-flow tracing, inward green tick marks during forced expiration indicate the $FEF_{25\%}$, $FEF_{50\%}$ and $FEF_{75\%}$ while the green tick mark on forced inspiration indicates the $FIF_{50\%}$. Some other values are: $FEV_{0.5}$ = 2.95 L, $FEV_1$ = 3.30 L, $FEV_3$ = 3.62 L, $FEV_6$ = 3.63 L, FVC = 3.70 L, peak flow = 9.2 L/sec, IRV = 1.90 L, VT = 0.80 L, ERV = 1.00 L. [Abbreviations as in Figure 4 1 plus FEF = forced expiratory flows at several percentages of the forced vital capacity (FVC), $FEV_x$ = forced expiratory volumes at several times.]

vital capacity, a forceful rapid measurement should be made of the inspiratory vital capacity and flow from RV to TLC. Ideally, the best inspiratory vital capacity should approximately be the best expiratory vital capacity. If the inspiratory VC and FVC measures differ by more than 5%, it means that the patient did not exhale or inhale completely with the smaller VC maneuver.

In adults without moderate or more severe obstruction, the best slow vital capacity and best forced vital capacity should also differ by less than five percent. With more severe obstruction, the slow vital capacity may exceed the forced vital capacity due to compression of the intrathoracic airways by the high intrathoracic pressures generated during the forced maneuvers.

On the volume-time or flow-volume recordings (Figures 4-1 to 4-4), the VT, ERV, IRV, IC and VC can be easily and directly measured. It is important to note that for VC the maximal value from any maneuver is taken as valid and reported. On the

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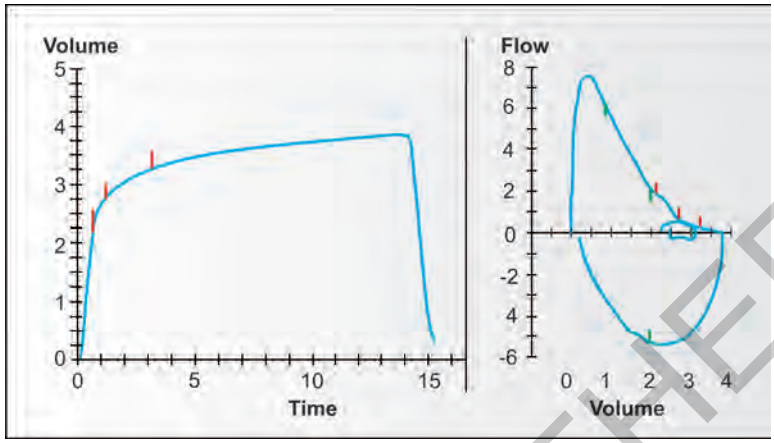


**Figure 4-4** Forced expiratory and forced inspiratory maneuvers on time-volume (left) and volume-flow (right) tracings of an 83-year-old man. On the volume-flow tracing, resting tidal breathing with IRV, VT and ER

-flow tracing, inward green tick marks during forced expiration indicate the $FEF_{25\%}$, $FEF_{50\%}$ and $FEF_{75\%}$ while the green tick mark on forced inspiration indicates the $FIF_{50\%}$. Some other values are: $FEV_1$ = 2.72 L, $FEV_3$ = 3.27 L, $FEV_6$ = 3.53 L, FVC = 3.82 L, peak flow = 7.6 L/sec, IRV = 2.32 L, VT = 0.70 L, ERV = 0.80 L.

other hand the measures of VT, ERV, IRV and IC are the average of values rather than the individually highest averages so that the values of IC and ERV should add up to the same value as the VC.

On the volume-time display, the $FEV_{0.5}$, $FEV_1$, $FEV_3$, $FEV_6$, FVC and any other timed volume can be easily and accurately measured (Figures 4-1 and 4-2). Although not commonly done, flows can be accurately measured at any time on the time-volume display as the slope of the recorded curve at any one time. Such a line can be drawn parallel to a short segment of the curve, or as a straight line between two points on the curve. For example, the slope at 50% of the FVC is the $FEF_{50\%}$. The line exactly connecting the points at 25% of the FVC and at 75% of the FVC measures the $FEF_{25\text{-}75\%}$ flow for that maneuver. If a recorded line on the time-volume display is exactly linear, it means that flow is constant over that time period. If the line is linear and parallel to the X-axis, that constant flow is "zero". Note the difference in tracings with aging.

## Maximum Voluntary Ventilation

The direct maximum voluntary ventilation (MVV) (previously known as the maximal breathing capacity) is measured by having the patient breathe in and out

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as forcefully as possible for 12-15 seconds (Figure 4-5). The spirometer tracing shows the tidal volumes and breathing frequency while a mechanical or electronic device sums the total inspiratory OR expiratory volumes over the same 12-second period. There is often a tendency for technicians to have the patient breath too rapidly and too shallowly. If the subject breathes at a frequency above 60-80 breaths per minute during the maneuver, it is suggested that the technicians tutor the patients to breathe more deeply and at a slower frequency. Fortunately, however, as shown by figure 4-6 in a cooperative patient, the MVV is only minimally affected by breathing frequency.

The measurement of the direct MVV over a 12-second period is useful to assess not only the lungs but also the patient's strength, coordination and ability to cooperate (Figures 4-5 and 4-6). As such, it may be useful in assessing preoperatively a borderline patient's operability or prior to exercise testing to help ascertain whether or not a patient is ventilatory limited during exercise.[3] The indirect MVV can be calculated by multiplying the $FEV_1$ by a factor. Although the factor of 35 times the $FEV_1$ was initially recommended for calculation of the MVV,[4] the authors only reported that the $FEV_1 \times 35$ was highly correlated with the direct MVV. However, any numeric factor used would also have been highly correlated. In our and others' experience, 40 is a better factor to multiply times $FEV_1$ in L to calculate indirect MVV in L/min for normal individuals and patients with obstructive lung disease.[5,6] With interstitial lung disease, the indirect MVV so calculated often greatly exceeds the direct MVV due to a high elastic recoil of the lungs, strong breathing muscles and

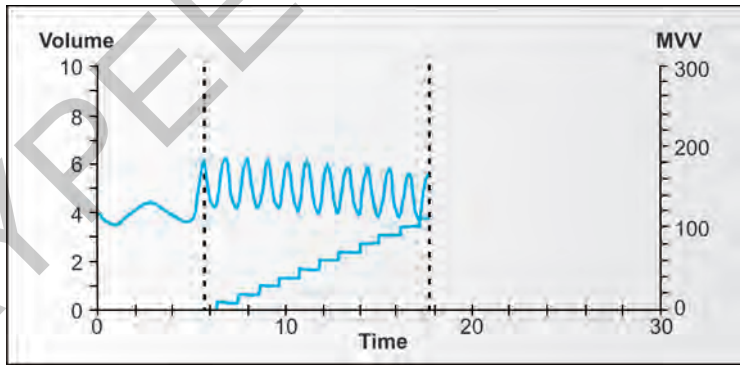


**Figure 4-5** Direct maximum voluntary ventilation (MVV) measured for 12 seconds in an 83-year-old man. After ~5.5 seconds of quiet breathing maximal inspiratory and expiratory efforts are made at a frequency of 60 cycles per minute. The upper tracing show the actual volumes in L on the left Y-

-axis to express the value in L/min.

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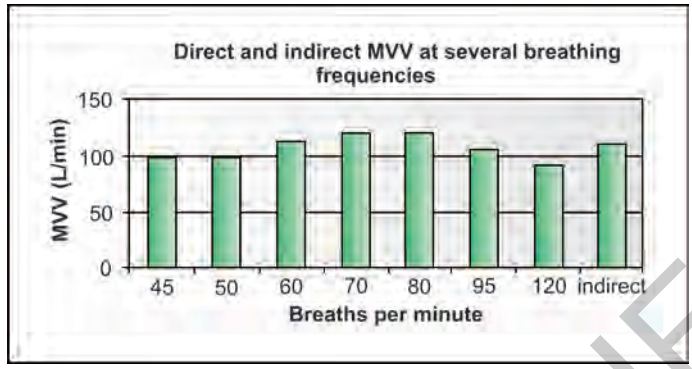


**Figure 4-6** Maximum voluntary ventilation measured at 7 breathing frequencies. There is some dependence of MVV on breathing frequency, with frequencies of 60 to 80 per minute giving the highest values. The indirect MVV, calculated by $FEV_1$ of 2.72 L times 40 equals 109 L/min; quite similar to the average volumes/min of the direct MVV.

high breathing frequency.[3] With severe obesity, the direct MVV is often lower than 40 × $FEV_1$ due to the inertia of rapidly changing the direction of movement of the thorax and abdomen.

Before examining patterns of volume and flow further, it is reasonable to consider the variability of these variables in apparently normal populations.

## VARIABILITY OF DATA IN INDIVIDUALS THOUGHT TO BE NORMAL

Figure 4-7 shows $FEV_1$ from over 700 apparently healthy never-smoking black men sorted by age. Figure 4-8 shows FVC from over 1,300 apparently healthy Latin women sorted by height. Figure 4-9 shows the deviations of actual $FEV_1$ from predicted $FEV_1$ for healthy never-smoking white women after accounting for differences in age and height. Figures 4-10 and 4-11 show scatter around a narrow age and height range for several volumes and flows for 45-47-year-old never-smoking white men 177.5–180 cm tall. Figure 4-12 shows variability of $FEF_{25-75\%}$ in 20 never-smoking black women within 1.0 cm of height all of the 3rd decade of age, when differences between subjects in lung volumes and flow rates are minimized.

From these figures it is apparent that there is marked variability in apparently normal never-smoking adults within narrow age ranges and narrow height ranges in $FEV_1$ and FVC (Figures 4-7 and 4-8). Even with excellent predicting equations accounting for age and height, considerable variability remains for $FEV_1$ (Figure 4-9). As one can see, the range of actual values for $FEV_1$ (or $FEV_3$, $FEV_6$, or FVC) on the

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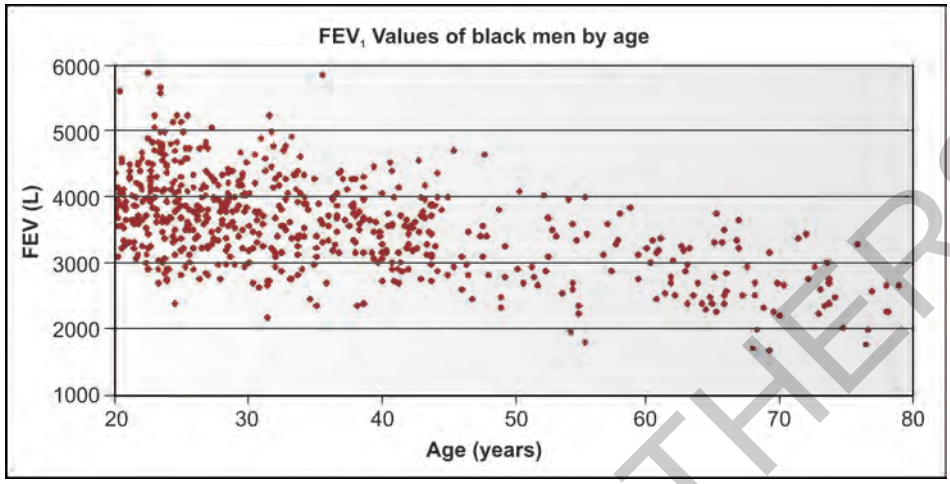


**Figure 4-7** $FEV_1$ measurements of 700 NHANES-3 never-smoking normal black men of varying heights arranged by age. Note wide scatter of values.

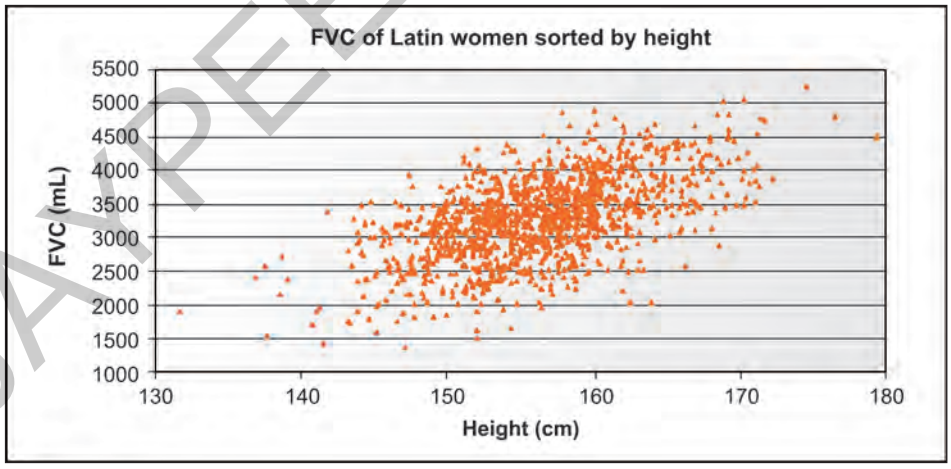


**Figure 4-8** FVC measurements of 1,300 normal never-smoking NHANES-3 Latin women aged 20-78 years, arranged by heights. Note wide scatter of values.

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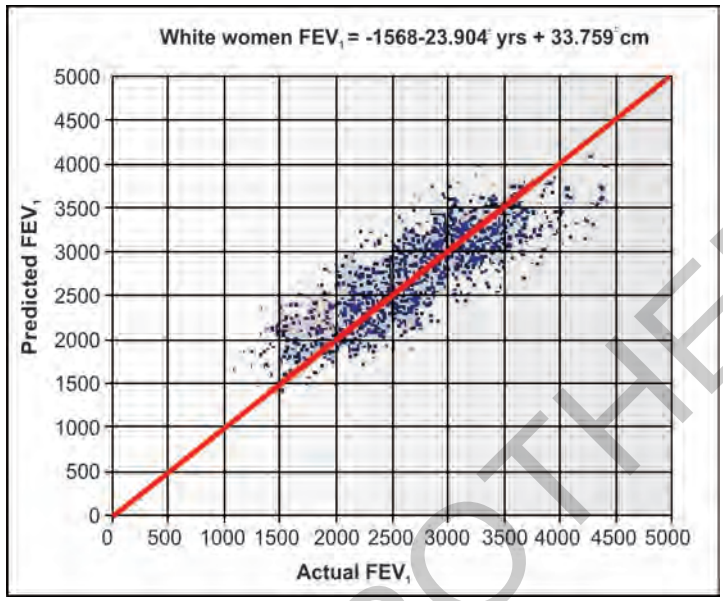


**Figure 4-9** $FEV_1$ measurements of 1,400 never-smoking NHANES-3 white women compared with the predicted values of the same population. The equation $FEV_1$ (mL) = –1548 – 23.904 × age in years + 33.759 x height in cm minimizes deviations of actual from predicted values for both X- and Y-axes.

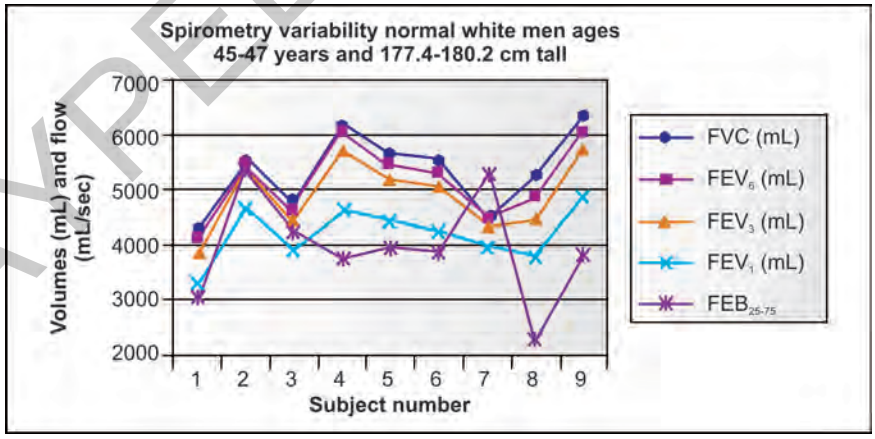


**Figure 4-10** Timed-lung-volume and $FEF_{25-75\%}$ measurements of the 9 normal never-smoking NHANE -3 white men of similar age (45-47 years) and height (177.4-180.2 cm). Note the moderate variability of the lung volumes and the higher variability of the $FEF_{25-75\%}$ measurements.

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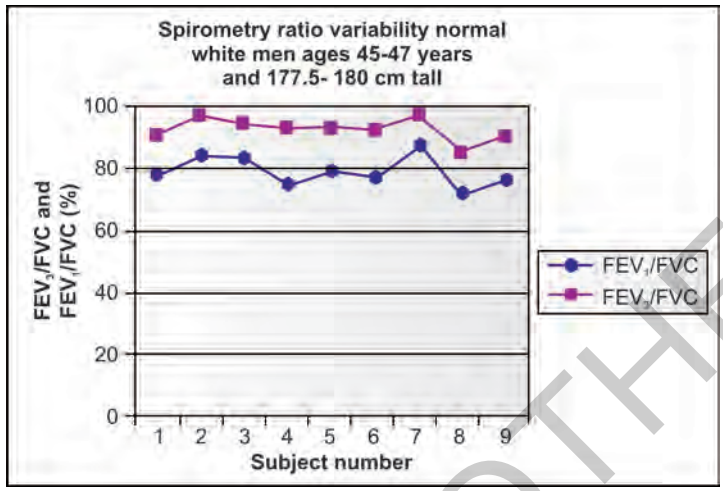


**Figure 4-11** %$FEV_1$/FVC and %$FEV_3$/FVC ratio values from the same men as in Figure 4-10. Note the much lesser variability of these ratios than the absolute values from which they are derived.

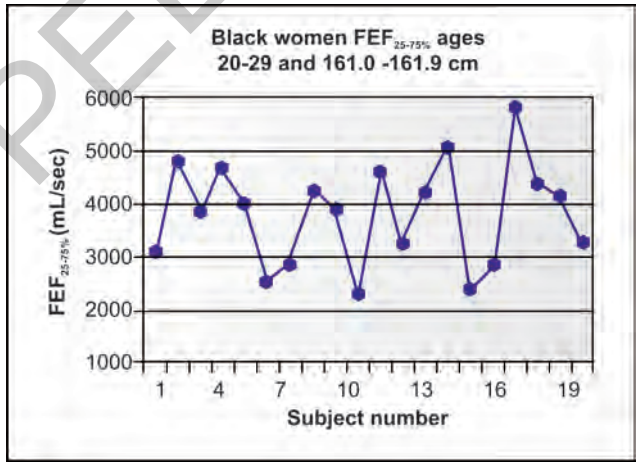


**Figure 4-12** $FEF_{25-75\%}$ in 20 consecutive never-smoking NHANES-3 black women of ages 20-29 and heights of 161.0-161.9 cm. In this age range, FVC and $FEV_1$ values are relatively stable while variability of $FEF_{25-75\%}$ is considerably higher.

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X-axis can exceed 1500 mL for a given predicted volume of $FEV_1$, $FEV_3$, $FEV_6$ or FVC on the Y-axis. When the range of ages and heights (Figures 4-10 to 4-12) in individuals of the same gender and ethnicity are markedly limited, the variability of volumes is moderate (FVC, $FEV_1$, $FEV_3$ and $FEV_6$), the ratio of volumes to volumes is much less ($FEV_1$/FVC and $FEV_3$/FVC) but the variability of the $FEF_{25-75\%}$ (a flow/volume) is very high. This pattern of variability is inherent in all published predicting equations and suggests some caution in identifying and quantifying obstruction and even more caution when we use volume to diagnose and quantify restriction. But there is hope. In table 4-1 and the following figures the most useful flow and volume measurements will be emphasized.

## SPIROMETRIC MEASUREMENTS WORTH RECORDING, VIEWING AND INTERPRETING

The patterns of airflow obstruction seen on volume-flow axes are also easy to recognize. Normally, in early youth, the forced expiratory tracing may bow outward; soon thereafter, the flow declines in a relatively straight line from peak flow early in the forced maneuvers to zero flow at the end of the maneuver (Figures 4-13 and 4-14). With normal aging flow tends to sag downward or become concave (Figures 4-3 and 4-4). With increasing obstruction at any age (Figures 4-15 to 4-17) the forced expiratory flow patterns become markedly depressed so that forced expiratoy flow is less than expiratory flow during quiet breathing in the tidal volume range.

**Table 4-1** Spirometric Measurements Likely to be of Clinical Value

| |
|---|
| Slow vital capacity (SVC) |
| Forced vital capacity (FVC) and/or Forced expiratory volume in 6 seconds ($FEV_6$) |
| Inspiratory capacity (IC) |
| Expiratory reserve volume (ERV) |
| Forced expiratory volume in 1 second ($FEV_1$) |
| Forced expiratory volume in 3 seconds ($FEV_3$) |
| %$FEV_1$/FVC or %$FEV_1$/$FEV_6$ |
| %$FEV_3$/FVC or %$FEV_3$/$FEV_6$ or 1 $FEV_3$/FVC or 1-$FEV_3$/$FEV_6$ |
| Peak expiratory flow or mid-expiratory flow |
| Peak inspiratory flow |
| Maximum voluntary ventilation (MVV), direct |

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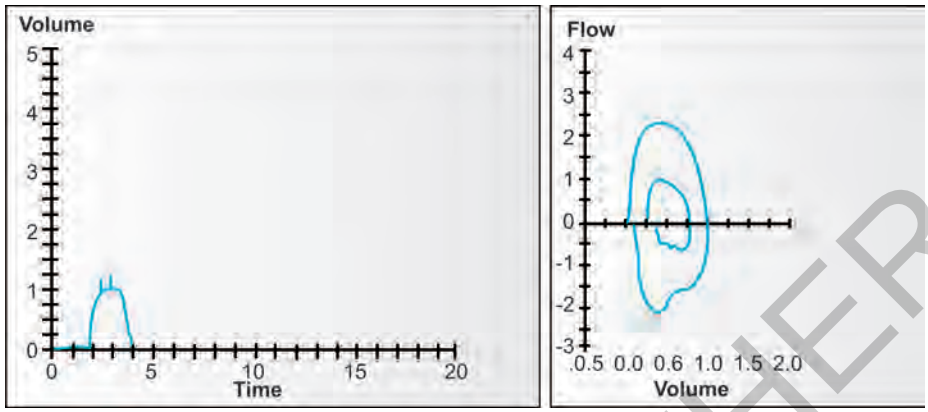


**Figure 4-13** Time versus volume and volume versus flow tracings of a normal 9-year-old boy, 117 cm tall and weighing 32 kg. Expiratory flow is mildly concave in volume versus flow tracing.

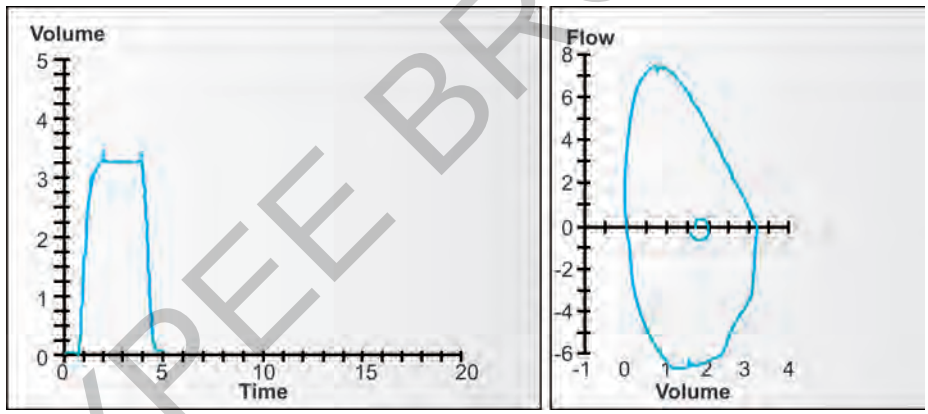


**Figure 4-14** Time versus volume and volume versus flow tracings of a normal 18-year-old adolescent male. Decline in expiratory flow is quite linear in volume versus flow tracing.

## Volumes

In patients, it is reasonable to obtain the best slow or unforced VC and necessary to obtain the best FVC, since the SVC may be larger than the FVC when there is significant airway obstruction. If there is no airway obstruction and the SVC differs from the FVC by more than a few percent, the spirometry is of low quality. This may be due to circumstances beyond the control of the patient or technician. The

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# Pulmonary Function Testing & Interpretation

**The primary target audiences for this volume are pulmonologists, allergists, graduate students, thoracic surgeons, and their assistants, in training and in practice, who evaluate and treat patients who have or may have respiratory damage or disease.**

- Unique insights into the interpretation of spirometric, lung volume, diffusing capacity, and other measurements commonly made in pulmonary function laboratories. Normal values are dependent on gender, age, and body size.
- Review of the best available reference equations and selection of the optimal equations, not only for the "White" populations but also, for the first time, for the non-Caucasian populations of the world.
- New ways to assess the effectiveness of aerosol bronchodilator drugs on obstructive airways disease in the laboratory, since current practices fail to identify nearly half of the statistically significant responders.
- New ways of interpreting spirometric values of cigarette smokers to better identify and inform those who, though still within the wide range of normal, are at greater risk.
- Ten interesting cases to guide interpreting pulmonary function tests.

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