RESPIRATORY FUNCTION TESTS

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The text of the videos presented on the seminar

We will plot the volume of air within the lungs as a function of time (*Figure 1*). Let us start off with a person breathing comfortably, not doing anything special just sitting still and breathing. The volume of air exchanged during each resting breath is called the **tidal volume**. Although it may feel to the person that here she is moving a significant amount of air, you can see that as a fraction of the total air contained in the lung, this is actually just a small fraction. Imagine that the patient is then specially instructed to inhale as deeply as possible. The amount of volume the person has now inhaled above the normal tidal volume is called the **inspiratory reserve volume**. The patient is now asked to breath out as completely as possible. The additional volume exhaled beyond what is exhaled during normal breathing is the **expiratory reserve volume**. And finally when every last milliliter of air that can be squeezed out of the lungs has been, a volume of air that is still left inside is called the **residual volume**. These are four definitions of our lung volume that add up to a maximum possible lung volume we typically do not consider the individual divisions doing pulmonary function test (PFT) interpretation as much as we consider specific groupings of volumes. These groupings are called capacities. For example, the **inspiratory capacity** is the sum of the tidal volume and inspiratory reserve volume. The **functional reserve capacity** is the sum of the expiratory reserve volume and the residual volume, the **vital capacity** is the tidal volume plus inspiratory and expiratory reserve volumes, and finally everything added together is called the **total lung capacity**.

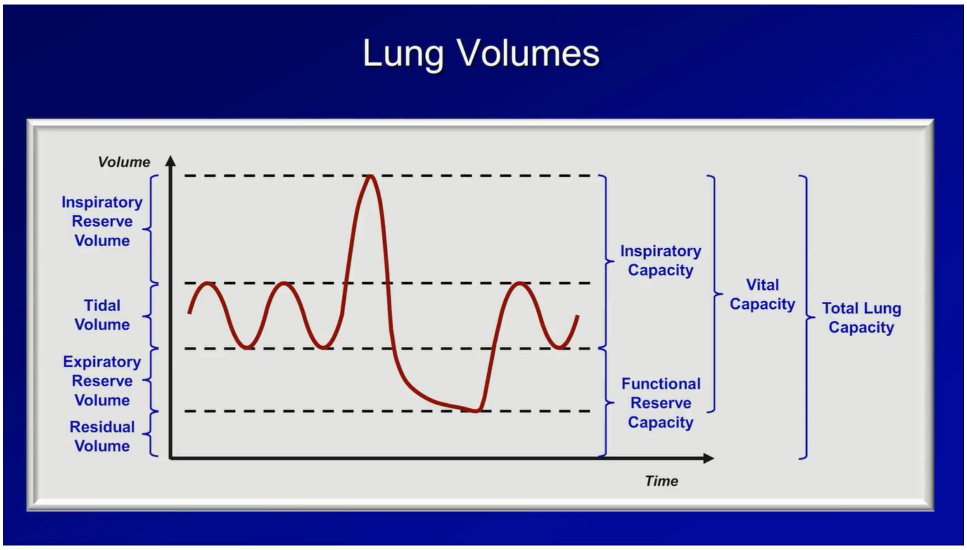

Figure 1. Static lung volumes

What is spirometry and how is it performed? It is essentially a technique used to measure airflow and some lung volumes. Spirometry has been around a long time. Here is the representation of the basic principle behind the original method. (*Figure 2*) A patient would breath in and out through a tube that was continuous with an upside-down partially submerged chamber. The height of the chamber was related to how much air have been exhailed or inhailed, and this volume of air has been plotted as a function of time. Thus providing rudimentary information about airflow. Of course modern spirometers look quite different. The actual procedure to measure spirometry is very simple. The patient places his or her mouth around the mouth piece of the device, inhales maximally and then exhales as fast as possible and continues to exhale for at least 6 seconds. The maneuver is repeated at least three times and the highest lung volumes and highest air flows are recorded, even if those two values are from different attempts.

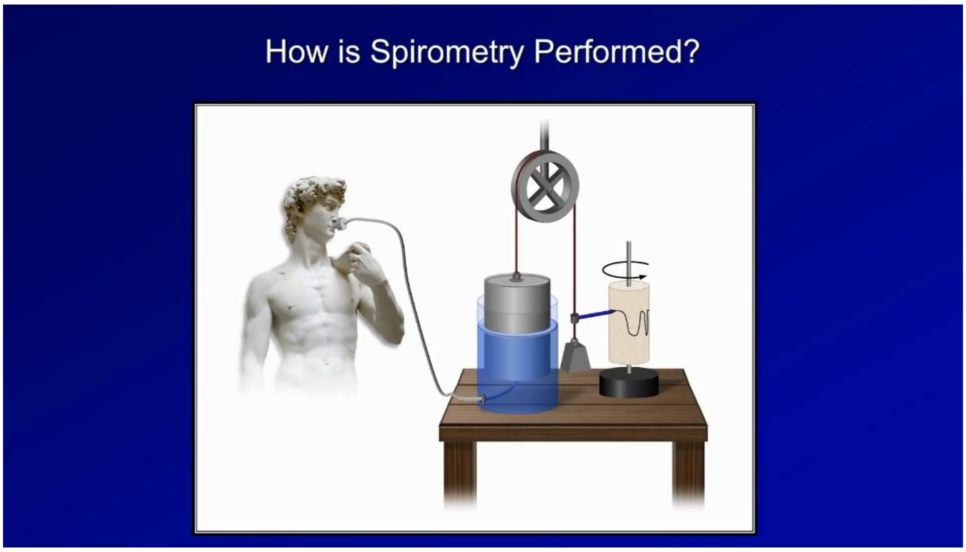

Figure 2. How is spyrometry performed?

Let us take a closer look at the measures of air flow and volumes. This graph probably looks familiar from the last video. For right now the only subdivision at the volume that will focus on is the vital capacity. And actually when the vital capacity is measured within the context of standard spirometry that is within the context of the patient exhaling as quickly as possible, it is known more specifically as the forced vital capacity or **FVC**. If we then look just a volume of air exhaled during the first second of the forced exhalation this is called the forced expiratory volume in one second or **FEV$_1$**. (*Figure 3*)

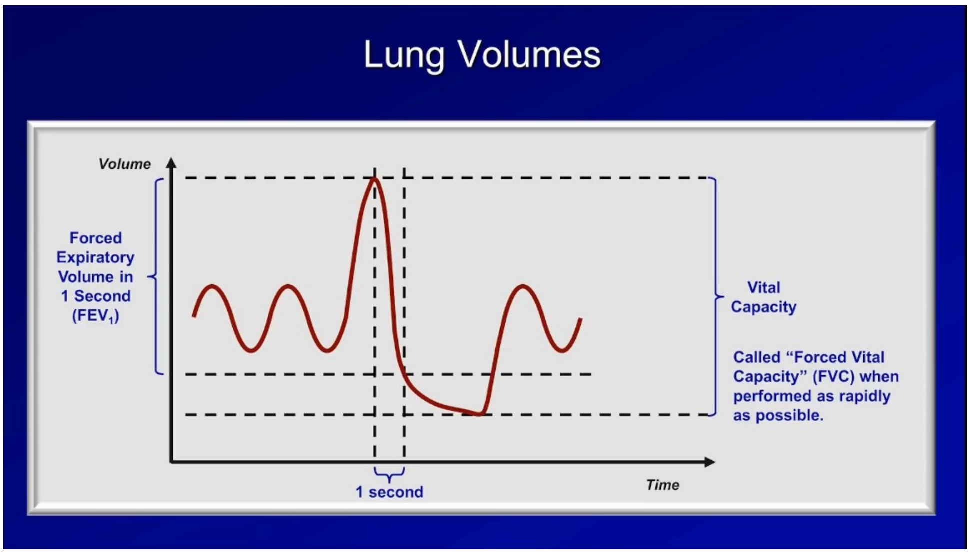

Figure 3. FEV$_1$

The FVC, FEV1 and the ratio of FEV1 to FVC are the three most important values in PFT interpretation as we will see in a few minutes.

Let us look at the FVC and FEV1 from a slightly different perspective (**Figure 4**). This graph of exhaled volume as a function of time will be more typical of the graph actually produced by the modern digital spirometer. Once again the patient starts with a forced maximal inspiration and then exhales out as quickly as possible. The volume exhaled within the first second is the FEV1 and the maximum exhaled volume typically achieved by six seconds or so is the forced vital capacity or FVC. And additional parameter can easily be measured from this graphic form. You may know that air flows a measure of the change in volume over the change in time therefore the maximum slope at this curve is equal to the peak expiratory flow rate, sometimes abbreviated **PEFR**.

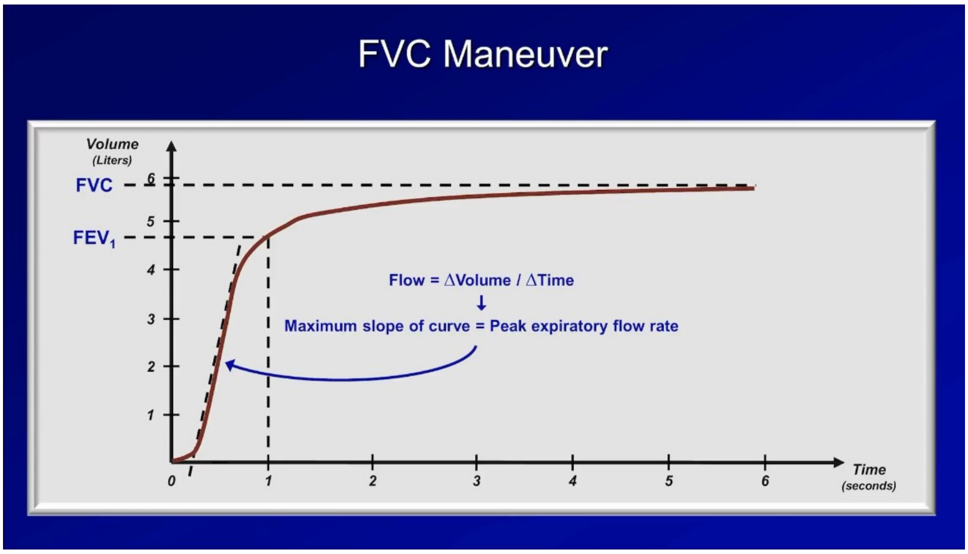

Figure 4 FVC maneuver

Let me compare that graph to another one something specifically called the flow-volume loop. The flow-volume loop is a graph of air flows as a function of volume (*Figure 5*).

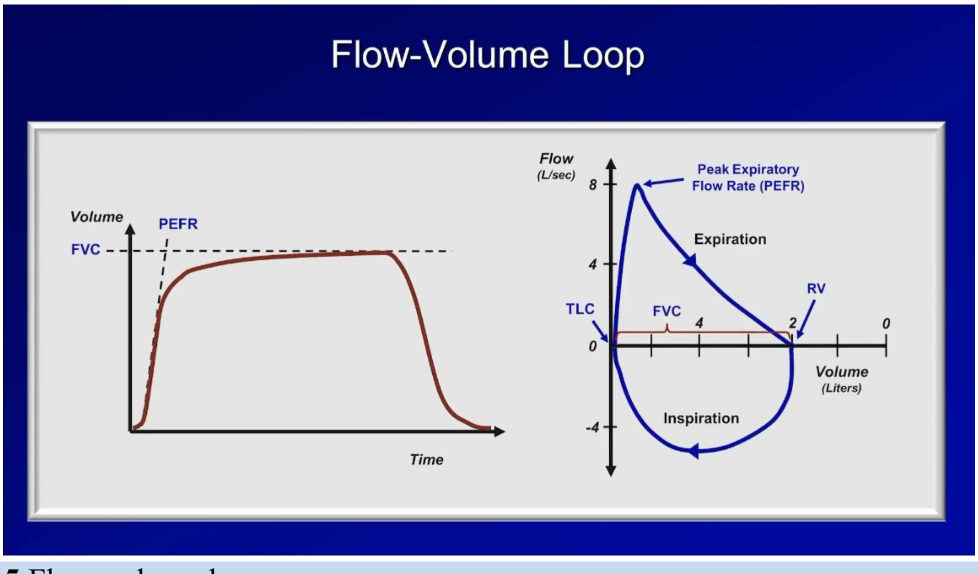

Figure 5 Flow-volume loop

During expiration there is an initial quick peek airflow and then the gradual reduction in flow to it reaches zero. The inspiratory half of flow-volume loop is much more symmetric. As it is just mentioned the maximum slope of the graph on the left is the peak expiratory flow rate, which is the same flow rate at the maximum point on the graph on the right. The volume present within the lungs at the transition for maximum inspiration to expiration is equal to the total lung capacity. The volume present within the lungs at the transition for maximum expiration to inspiration is the residual volume. As you may have already deduced using only spirometry it is impossible to know the starting point of the flow-volume loop X axis. That is, it is impossible to know the value of residual volume or the total lung volume. However, the difference between them is the forced vital capacity. Although at first glance it wood seen that the flow-volume loop does not provide any new information, however, the shape of the curve, itself irrespective of the peak flow and FVC, can provide important insight into a variety of lung disease, most prominently the different types of airway obstruction.

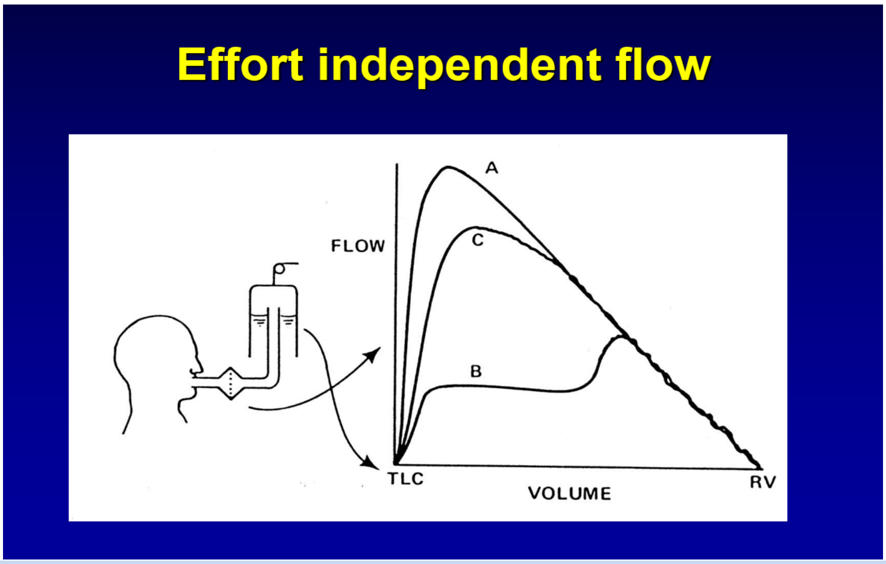

Figure 6 Effort independent flow

Analysis in terms of laminar and turbulent flow assumes that airways are rigid tubes. In fact, they are highly compressible. The compressibility of the airways underlies the important phenomenon of **effort independent flow** *(Figure 6)*; airflow rates during expiration can be increased with effort only up to a certain point. Beyond that point, further increases in effort do not increase flow rates. The explanation for this phenomenon relies on the concept of an equal pressure point. Pleural pressure is generally negative (sub-atmospheric) throughout quiet breathing. Peribronchiolar pressure, the pressure surrounding small, noncartilaginous conducting airways, is closely related to pleural pressure. Hence, during quiet breathing, conducting airways are surrounded by negative pressure that helps to keep them open (in the figure below, end of quiet expiration: I, the course of normal inspiration: II, end of normal inspiration: III). Pleural and peribronchiolar pressure becomes positive during forced expiration (IV), subjecting distensible conducting airways to positive pressure. The equal pressure point occurs where the surrounding peribronchiolar pressure equals or exceeds pressure inside the airway, causing dynamic compression of the airways, which leads to instability and potential airway collapse. Expiratory flow from this moment cannot increase any further (point „A" in the above figure), but rather it starts to decrease.

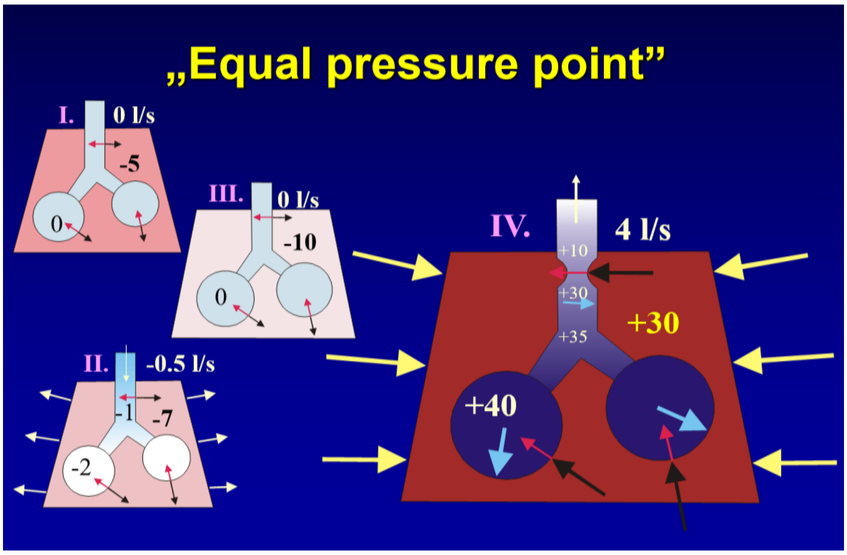

Figure 7 ’Equal pressure point’

The **equal pressure point** *(Figure 7)* is not an anatomic site but a functional result that helps to clarify different mechanisms of airflow obstruction. Because the driving pressure of expiratory airflow is principally lung elastic recoil pressure, a loss of lung elasticity that reduces recoil pressure without changing pleural or peribronchiolar pressure will lead to dynamic compression at higher lung volumes. The resultant air trapping contributes to symptomatic dyspnea in patients with obstructive lung disease. Patients with emphysema lose lung elastic recoil and may have severely impaired expiratory flow even with airways of normal caliber. The presence of airway disease will increase the drop in driving pressure along the airways and may generate an equal pressure point at even higher lung volumes. Conversely, an increase in recoil pressure will oppose dynamic compression. Patients with pulmonary fibrosis may have abnormally high flow rates despite severely reduced lung volumes.

So in summary the major values measured by spirometry are the FEV1, the FVC, the FEV1 to FVC ratio and the flow volume loop (*Figure 8*). There are also some minor or less important values measured. We just saw the peek expiratory flow rate, there is the $FEF_{25\text{-}75\%}$

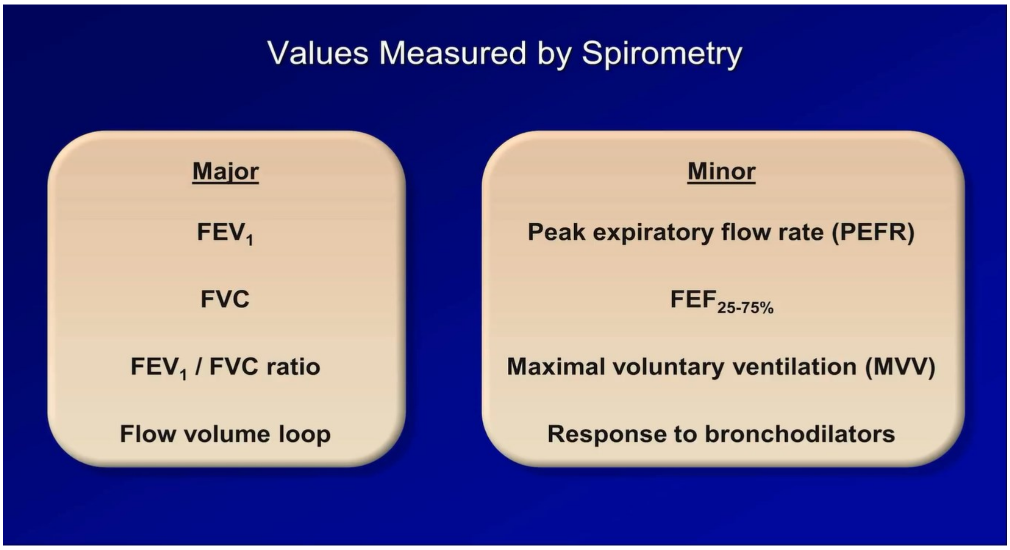

Figure 8 Values measured by spirometry

which is the average flow from the time 25% of the FVC has been exhaled to the time 75% has been exhaled. This value has historically been used to detect obstruction in the small airways, however some experts argue that the validity of this association is overstated. There is the maximal voluntary ventilation or MVV. The MVV is the maximum amount of air that can be inhaled and exhaled within 1 minute. Finally, after spirometry has been performed, the patient can be given a bronchodilator and spirometry then repeated to assess for any response.

And now discuss how the information provided by spirometry can help with the diagnosis. For now, we compare the values of FEV_1, FVC and the FEV_1 to FVC ratio, both obstructive and restrictive lung disease. In obstructive lung disease, for example COPD, the FEV_1 can be normal in very mild obstruction, but it is almost always decreased. This makes intuitive sense if the airways are constricted or obstructed it will take longer to push air through them. The FVC will be normal in mild or moderate obstruction, however, for a variety of reasons related to lung mechanics, the FVC would decrease with more severe degrees of obstruction. As a very consistent rule, in obstructive lung disease the FEV_1 would decrease to a greater degree than the FVC. Therefore, the ratio of the two would decrease below the normal value of 70%. This ratio is rather referred to as a **Tiffeneau Index**. In restrictive lung disease the FEV_1 is either normal or decreased and the FVC is decreased. As the FVC is usually decreased to a similar or greater degree than FEV_1, the ratio of the two is either normal or increased. Use of the FEV_1 to FVC ratio to distinguish obstructive from restrictive lung disease is literally the single most important thing to remember about interpreting PFTs.

Interpretation of FEV_1, FVC, and FEV_1/FVC Ratio

	FEV_1	FVC	FEV_1 / FVC Ratio (Tiffeneau Index)
Obstructive Lung Disease	Normal (very mild obstruction) or Decreased (mod/severe obstruction)	Normal (mild/mod obstruction) or Decreased (severe obstruction)	Decreased (< 70%)
Restrictive Lung Disease	Normal or Decreased	Decreased	Normal or Increased (≥ 70%)

Figure 9 Interpretation of FEV_1, FVC and FEV_1/FVC ratio

This chart that is published herein look pretty familiar (*Figure 1*). In the last video on spirometry I discussed the vital capacity which is the sum of the tidal volume and inspiratory and expiratory reserve volumes. However, there is one volume that spirometry can not measure: the residual volume. That is the amount of air left in the lungs when a person has exhaled as completely as possible. With an inability to measure residual volume using just spirometry we are left with an inability to measure the functional residual capacity or total lung capacity, the letter which is particularly helpful in PFT interpretation, therefore I must introduce some additional PFT methods. There are four methods that can be used to measure these remaining lung volumes and capacities. (*Figure 10*)

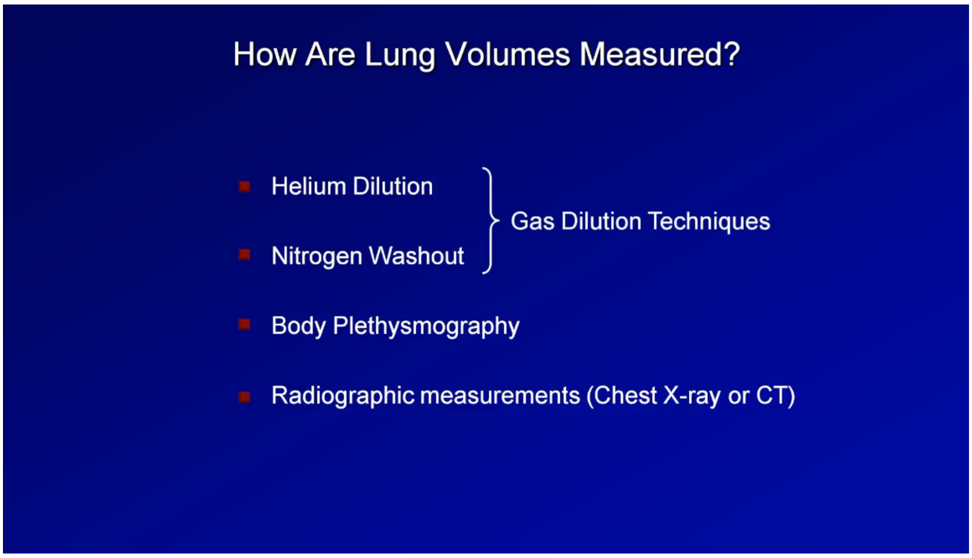

Figure 10 Methods for determining the functional residual capacity

They are helium dilution, nitrogen washout, body plethysmography, and the use of chest x-rays or CT to extrapolate volumes on radiographic measurements. The first two items on this list use a very similar principle and are collectively referred to as gas dilution techniques. Let me briefly review how each works.

The helium dilution technique we start with a reservoir which is attached to a device which can measure the concentration of helium contained within as well as a three-way stopcock and a mouthpiece. (*Figure 11*) The source of helium is attached and the reservoir is

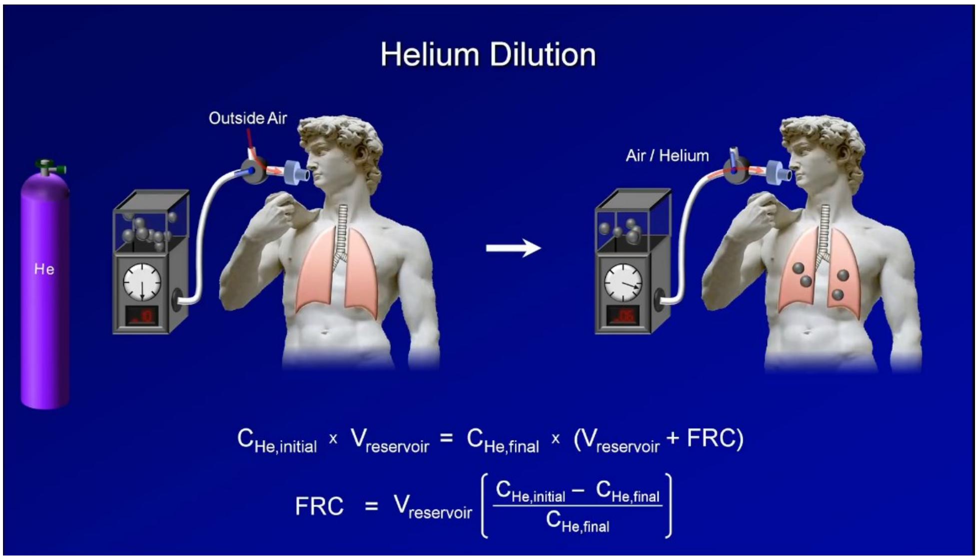

Figure 11 Helium dilution technique

filled to some predetermined concentration of helium. The patient then puts his mouth around the mouthpiece, first breathing in outside air with normal tidal volumes then when the patient is at a normal end-expiration, that is when the lungs are at the functional residual capacity, the technician turns to stopcock and the patient begins to breathe in the helium air mixture. With each breath helium flows out of the reservoir into the lungs until an equilibrium is reached and the helium concentration in the reservoir levels off. Since we are dealing with a close system and since helium is not absorbed across the alveolar capillary membrane, the initial amount of helium at beginning must be equal to the final amount of helium at the end. The initial amount is equal to the initial concentration of helium times the volume of the reservoir including the connecting tubing. The final amount is equal to the final concentration times the total volume over which the helium is distributed, which is the volume of the reservoir plus the functional residual capacity, assuming that the final concentration is measured with the patient at his or her FRC. And solving the equation for FRC, Advantages of the helium dilution technique are that it is simple and relatively inexpensive to perform, the major disadvantage is that it only measures the volume within the chest that communicates with the upper airways. In other words, it is not measured the volume of gas trapped in lung bullae.

Next is nitrogen washout. (*Figure 12*) In this technique the patient breaths through a mouthpiece that has two one-way valves. One valve connects to a source of 100% oxygen, the other connects to a device which records both the volume of gas exhaled, as well as the nitrogen concentration over many breaths. The patient starts at their functional residual capacity, breaths in 100% O2 and exhales out the nitrogen-containing gas initially left within the lungs into the device. Not all the nitrogen within the lungs will get expelled with each breath but with the patient taking successive breath in and out, over the course of several minutes, the nitrogen level in the exhaled gas will asymptotically approach 0. Using standard test methodology, the test is considered over once the nitrogen concentration is below 1.5% for 3 successive breaths. Similar to helium dilution, the initial amount of nitrogen in the lungs must equal the total amount of nitrogen exhaled. Thus the FRC is equal to the total volume exhaled over all the breaths during the test times the average concentration of the nitrogen in the exhaled gas divided by the estimated initial concentration of nitrogen within the alveoli. Nitrogen washout has the same general advantages and disadvantages as helium dilution, the one added disadvantage a possibly potentiating carbon dioxide retention in patients with severe COPD due to the 100% oxygen effect on overcoming pulmonary hypoxic vasa constriction thus worsening WQ mismatch.

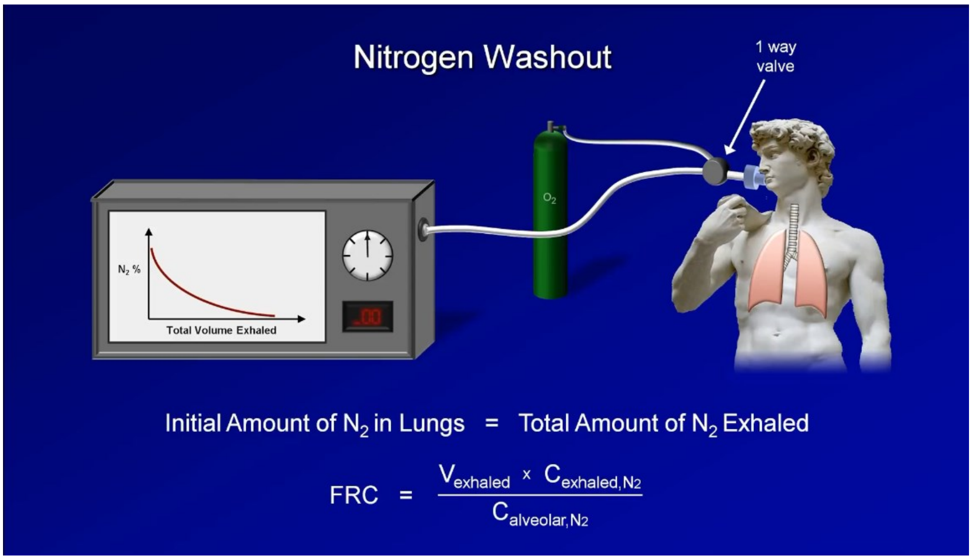

Figure 12 Nitrogen washout technique

Body plethysmography works on a completely different principle. (Figure 13) It starts with a clear plastic or glass box the size of a phone box. There is a mouthpiece inside and a tube to the outside air, attached to this tube outside of the box is a stopcock or other type of closer ball valve. There are pressure transducers which record the pressure within the inflow tube and within the box itself. The patient sits inside the box quickly panting with the airway open, when it suddenly shot while the patient continues to pant. This creates oscillations in the airway and the box pressures. The key physical principle used in plethysmography is Boyle's law which states that the product of pressure and volume is a constant for a closed system. Starting with this law, in applying some scenario specific algebra and physics, one ends up with an equation that looks something like this: where TGV stands for thoracic gas volume and is used to determine total lung capacity. Let sure PFT lab technician that the details of what these variables stand for, as well as the details at the skipped over steps here, will not be necessary to know for any routine clinical application. The primary advantage of plethysmography is that it is generally considered to be the most accurate method for determining lung volume. It is also the most expensive, by a sizable margin, as a results of the box and its assorted peripheral equipment.

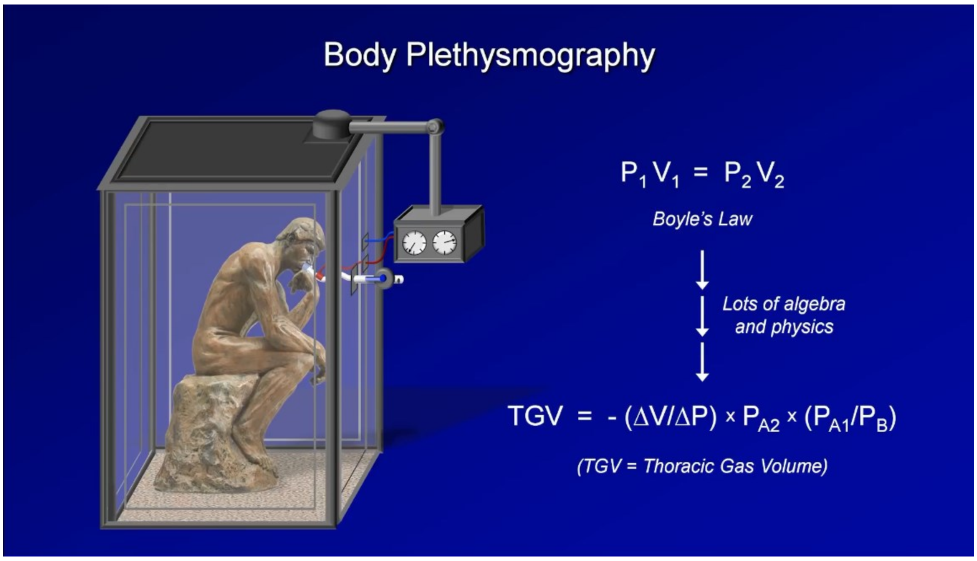

Figure 13 Body plethysmography

The final method for measuring lung volumes are radiographic techniques. (Figure 14) From the patient's chest x-ray, measurements of the lungs in the PA and lateral views can be taken and entered into an algorithm, estimate lung volume. From a chest CT, the cross sectional area of the lungs in each axial slice is multiplied by the thickness of the slice, and all of them are added together for lung volume. Both of these are easier to perform for the patient but are less accurate. The patient still needs to perform an adequate breath hold, and generally follow directions regarding his or her breathing pattern during the test.

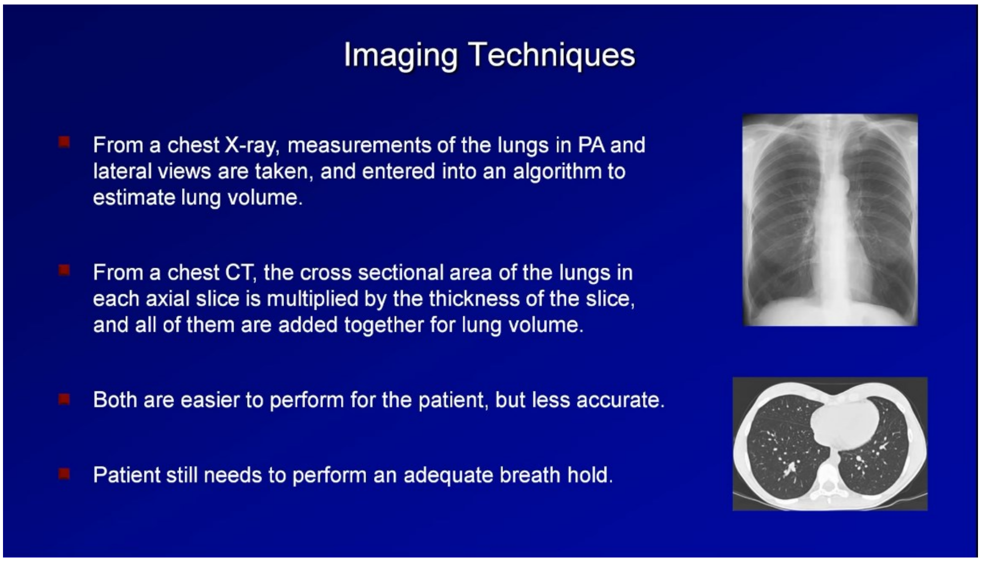

Figure 14 Imaging techniques

What about the variations of flow volume loop. (Figure 15) Aside from the normal there are six typical patterns which you should be familiar. Here we have a graph volume versus time on top and the flow versus time on the bottom for patients with mild obstruction. In the top graph you can see that FVC is preserved, however, it takes longer for the patient to get there which is represented by a late platou of the volume. In the flow volume loop the peek expiratory flow rate may be mildly reduced. But more significantly there is deformation in the middle of the expiratory limit of the loop, usually referred to as a coving. This qualitative finding is analogous to the quantitative finding of a reduced FEF25–75%. In the next situation, severe obstruction and reduction in the FVC is visible in both curves. In addition, in the flow-volume loop the peak flow is severely reduced and coving maybe even more pronounced. In restriction, since air flow is normal, the plateau in the upper graph is achieved quickly, however, FVC is reduced. Notice that the flow volume loop looks like a normal loop that has been shrinking in all directions with no coving presents.

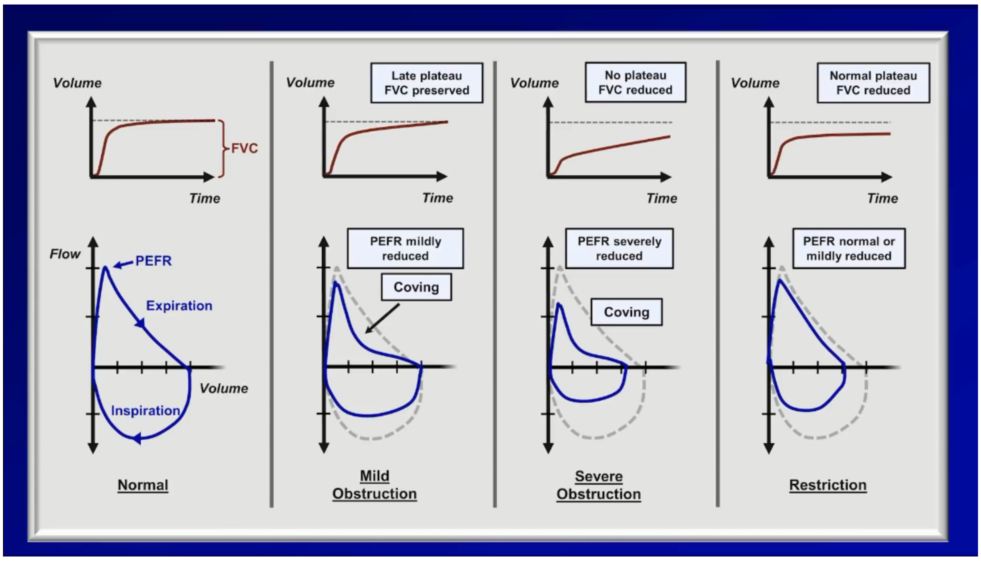

Figure 15 Variations of flow-volume loops

Here is how the 4 individual lung volumes break down for some categories of lung disease. (Figure 16) For comparison here is a normal patient's volumes with the vital capacity or FVC and the TLC. In a typical obstructive lung disease, the residual volume is greatly increased while the other volumes remain about the same, therefore the vital capacity is also about normal while the total lung capacity is often increased.

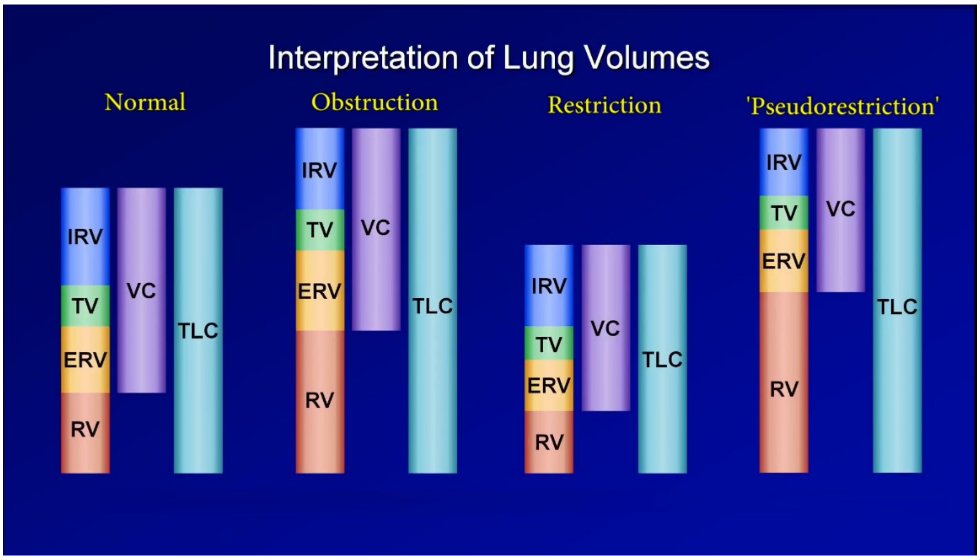

Figure 16 Interpretation of lung volumes

In restrictive lung disease, all the lung volumes are reduced resulting in both a reduction in vital capacity and the TLC. Last, there is a potentially confusing scenario, in which the residual volume is so increased above the normal that more or less crowd out the other lung volumes. Therefore, the vital capacity is reduced compared to normal, even as the total lung capacity is increased compared to normal. This pattern is known as pseudorestriction, because it will appear to be indicative of obstructive lung disease if only the lung volumes from spirometry are measured and examined. To make an accurate diagnosis in this case, that patient actually has severe obstructive disease, one will need the complete lung volume is measured. While the flow-volume loop from conventional spirometry can demonstrate severe coving of the expiratory limb and thus obstruction, it may be impossible to differentiate the pseudorestriction variant of obstruction from a mixed obstruction and restriction defect.