STATIC BIOMECHANICS OF THE MAMMALIAN RESPIRATORY SYSTEM[1]

Summary: We begin a consideration of breathing in mammals. We will start with the definitions of a series of sub-volumes of the total volume of air that the lungs can hold. Each of these has a certain functional significance as we will see over the next several classes. Then our discussion moves to a topic reminiscent of elastic elements in muscles -- the role of the elastic forces in respiration. These are discussed in terms of recoil forces (pressures) of the thorax, lungs and the total respiratory system.

I. RESPIRATORY VOLUMES and RESPIRATORY CAPACITIES

A. These are **sub-volumes of the lung volume**. Learn the following definitions and visualize them with aid of the figure:

B. **Definitions of Various Lung Volumes and Capacities:**

1. **TOTAL LUNG CAPACITY (TLC)**: The total amount of air that can be contained in a totally expanded lung (in a chest).

2. **VITAL CAPACITY (VC)**: the total amount of air that can be forcibly expired after a maximal inhalation.

3. **RESIDUAL VOLUME (RV)**: the total amount of air remaining in the lungs after a maximal, forced exhalation. You will see later in these notes that this is a considerable amount (a liter or so) of air. A related concept is:

4. **MINIMAL AIR**: which is the volume of air found in the lungs after a total **pneumothorax** (total lung collapse, it is smaller than the RV). This volume of air is the air in the conducting system; at minimal air the alveoli are collapsed.

The lung capacities defined above can be further broken down as:

5. **TIDAL VOLUME (TV, V_t, V_E)**: the amount of air that is inspired or expired in a single breath. In normal adults at rest, it is usually around 500 ml.

6. **EXPIRATORY RESERVE VOLUME (ERV)**: the amount of air that can be forcibly expired after completing a normal tidal expiration. It is essentially, the difference in volume between the air in the RV and the air left after a tidal expiration.

7. **INSPIRATORY RESERVE VOLUME (IRV)**: the volume of air that can be inspired after completing a tidal inspiration.

8. **FUNCTIONAL RESERVE CAPACITY (FRC)**: the total amount of air that is left in the lungs after a normal tidal expiration, it is equal to the RV + ERV

9. **INSPIRATORY CAPACITY (IC)**: the maximum amount of air that can be inspired starting at the respiratory resting point volume (the "top" of the FRC). It is equal to V_E + IRV (see figure on the top of the next page).

Thus:

1. $VC = ERV + IRV + V_E$

$= ERV + IC$

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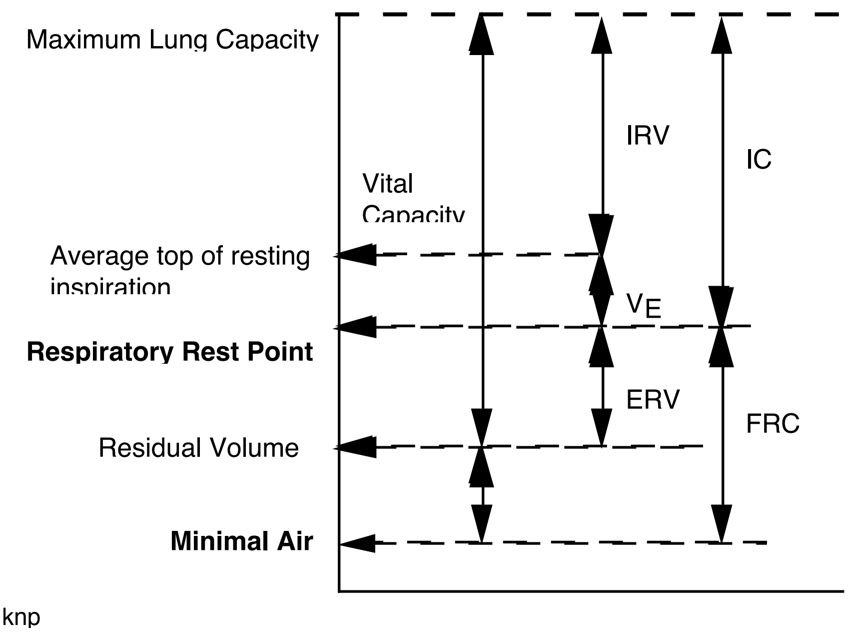
and

2. TLC = VC + RV = IC + FRC



II. THE INFLUENCE OF ELASTICITY ON BREATHING:

A. Introduction to the problem:

1. In the preceding sections we saw that the elastic properties of the lung can be varied by changes in the lung tissue and the fluid/air interface in the alveoli.

2. In this section we will see that elastic properties of the lungs and also of the chest wall have important effects on a number of respiratory parameters. These include:

a. the volume of air when the respiratory system is at rest.
b. The amount of energy required to breathe a certain volume of air
c. the rate at which air can be expired or inspired

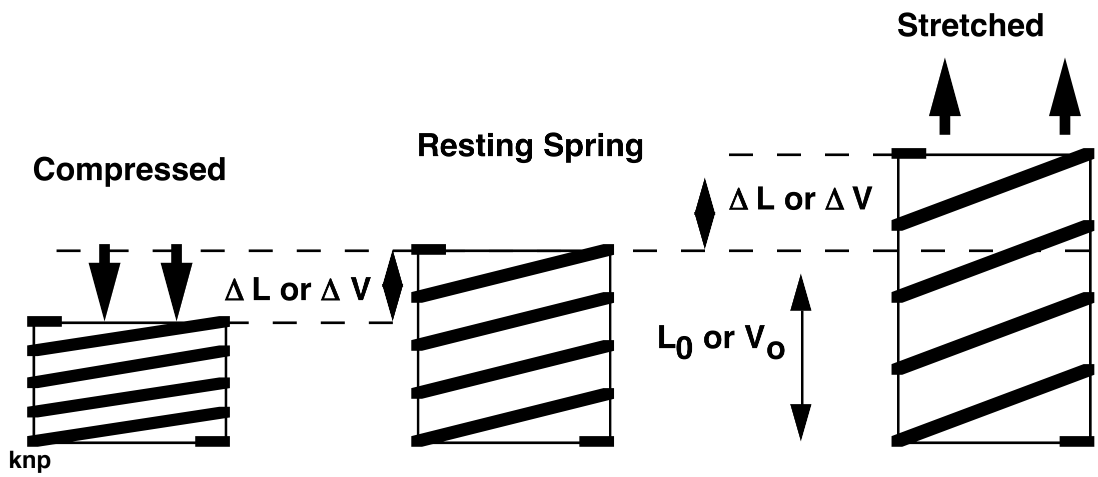
Notice that two of the items on this list (b and c) imply a dynamic (changing) situation while the other is static. In the consideration of elasticity that follows, we will begin with an investigation of respiratory elasticity under static conditions and then apply what we learn to the dynamics of breathing.

B. Elastic properties of the lungs and chest wall and the concept of Recoil Pressure

1. **Review and Introduction**:

(a) All elastic objects have some natural shape to which they will return when there are no net forces acting on them. Examples are rubber bands and muscles (both of which have a resting length -- go back and review the material on muscles if you find this confusing).

(b) However, to discuss the respiratory system we need a more appropriate analog than a rubber band or muscle. So we will use a **spring** instead. The key difference between a spring and a rubber band is that a spring can be elastically loaded in two directions. Starting at L_o it can be loaded by pulling or by compression:



c. Note that we can also think of each of the **springs as volumes**. Therefore, just as each has a resting length, it also possesses a **resting volume**. Compression and stretching affects both length and volume. Since we will be talking about the respiratory system, from here on out, we will speak about changes in volume instead of length.

2. At any static (non-changing) volume, we can view the net forces acting on the object as being of two types:

a. **any forces that are imposed on the object from external sources (i.e., from some source beside its inherent elasticity)** -- e.g., in the case of the springs a push or a pull or both.

b. an **internal, restorative force within the elastic material that is equal and opposite to the applied force**. Since this force within the object is equal and opposite to the applied force, it can be thought of as a **restorative or RECOIL FORCE**.

c. **AT THE NATURAL (RESTING) VOLUME, THERE IS NO FORCE OR TENSION (EITHER EXTERNAL OR RESTORATIVE) ACTING**.

d. Mathematically we can say that:

3a.i. $$F_{net} = F_{appl} + F_{recoil}$$

where F_{net} **is the net force acting on the spring;** F_{appl} **is the applied force and** F_{recoil} **is the recoil force**. Equation #3 is appropriate for all cases (static and dynamic).

(i) If there is any net force, the object must be changing shape. Thus, **if** $F_{net} \neq 0$ then we are dealing with a **dynamic state**.

(ii) in the **static case** F_{net} = **0** and therefore:

3b.i. $$F_{appl} = - F_{recoil}$$

3. Now let us consider one final wrinkle. **Since we are dealing with volumes, distorting and restorative forces are better treated as pressures**. Thus equations 3a.i and 3b.i can be re-written as:

3a.ii. $$P_{net} = P_{appl} + P_{recoil}$$

3b.ii. $$P_{appl} = - P_{recoil}$$

Let's use a balloon to understand this. At equilibrium (static state) the volume does not change because the applied pressure is resisted by an equal and opposite force in the walls of the balloon. Now while **you might not normally think of the restorative force from within the balloon as being a pressure, nevertheless the restorative force must behave as a pressure in order to oppose the applied pressure P_{appl}.** Therefore, the restorative force is called the recoil pressure even though it is present in material making up the balloon and not the air!

Important Note: The last point is very important and is difficult for some to accept. Be sure you understand why a restorative force in an object (for example, the tissue of the lung) can be thought of as a restorative pressure. Until you can accept this, you will have difficulty understanding what will follow in the rest of this packet.

Now, let's apply what we have just done to the respiratory system.

C. Lung Recoil Pressure

1. Instead of a balloon, let's consider the static lung. Under static conditions the total applied pressure on the lung is opposed by an equal and opposite restorative recoil force. We will now call any **net pressure applied to the lung P_L**. Thus:

4. $$P_{appl\ on\ lung} = P_L = -P_{recoil\ of\ lung\ tissue}$$

Now a slightly confusing shorthand enters.

(a) **From now on we will refer to P_L as the recoil pressure of the lung**. We can see that it isn't really -- the actual recoil pressure of the lung has the opposite sign from P_L (eq. #4).

(b) However, since we understand that these two forces are equal and opposite, **we refer to P_L as the recoil of the lung** (even though it isn't) because **it is the one that we can measure directly**, as we will see below.

(c) Thus, we simply understand that the real recoil of the lungs is equal and opposite to P_L under static conditions and don't worry too much about signs (but see below).

2. Thus, we can find the elastic recoil pressure of a lung, P_L, by knowing the applied pressures since it must equal them.

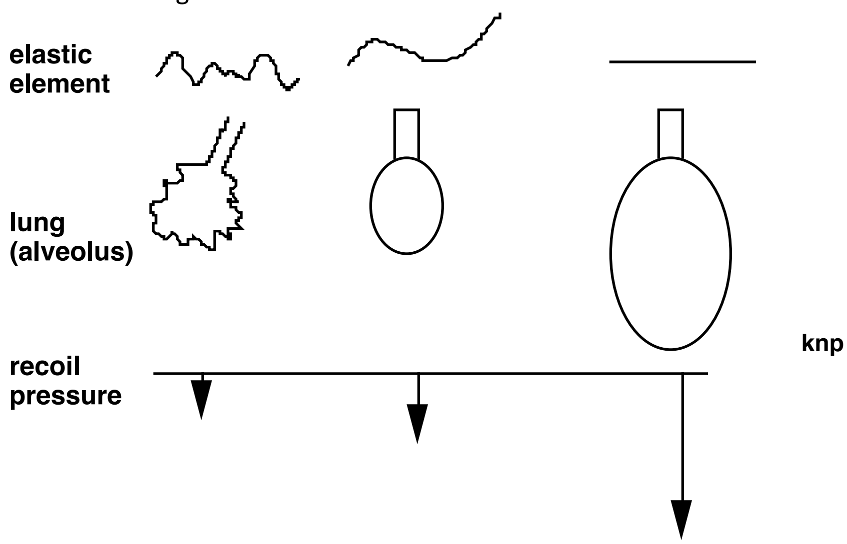
3. With lungs (as with the balloon considered above), pressure can be applied in one of two places: **internally** through the alveoli or **externally** by acting on the lung's surface.

(a) Pressures exerted via the air in the alveoli are termed (not surprisingly) **alveolar pressures, P_{alv}.**

(b) **Outer surface pressures** are said to originate in what is the termed the **pleural space** -- this is the tiny volume of fluid that normally is found between the surface of the lungs and the chest wall, diaphragm, and other thoracic structures. We will learn more about the pleural space and the pressures found in it below. Pleural pressure is abbreviated P_{pl}.

(c) to calculate the total distorting pressure acting on the lung walls we must consider **how pleural and alveolar pressures interact to result in an overall distorting pressure on the lung.** (This of course, will be opposed by an equal and opposite restorative (recoil) force).

(i) Clearly, a positive pressure inside the lung will tend to increase the lung's volume. This will have the effect of stretching the lung's compliances and therefore causes an equal and opposite restorative force (under static conditions).
On the next page is an illustration that shows the effects of increased alveolar pressure on volume and on length and therefore recoil of lung elastic tissue:



(ii) On the other hand, a positive force acting from the pleural space will tend to reduce the volume and recoil force on the lungs (under most conditions, see below).

(iii) How about **negative (subatmospheric) pressures**? A negative pressure on the pleural space side of the lung will tend to pull it outward while one on the alveolar side will tend to pull it inward. In both cases think of Ross Perot's famous "great sucking sound" -- as being capable of sucking the lung into larger or smaller volumes and therefore loading it elastically.

(d) If we wish to calculate the effect of alveolar and pleural pressure on lung volume and therefore on recoil forces, **we must subtract pleural pressures from alveolar pressures** since pressures of the same sign that act from the two different sides of the lungs always have opposite effects. The recoil of the lungs, P_L, is therefore calculated as:

5. $$P_L = P_{alv} - P_{pl}$$

Before going any further do the following exercises -- successful completion will greatly enhance your understanding of all that follows.

1) At the start of this packet (page #2) there is a graph that shows a lung volume called minimal air. This is the volume that a removed lung will collapse to.
At minimal air:
What is the alveolar pressure, P_{alv} ? What is the pleural pressure P_{pl}? What is the recoil pressure of the lung, P_L?

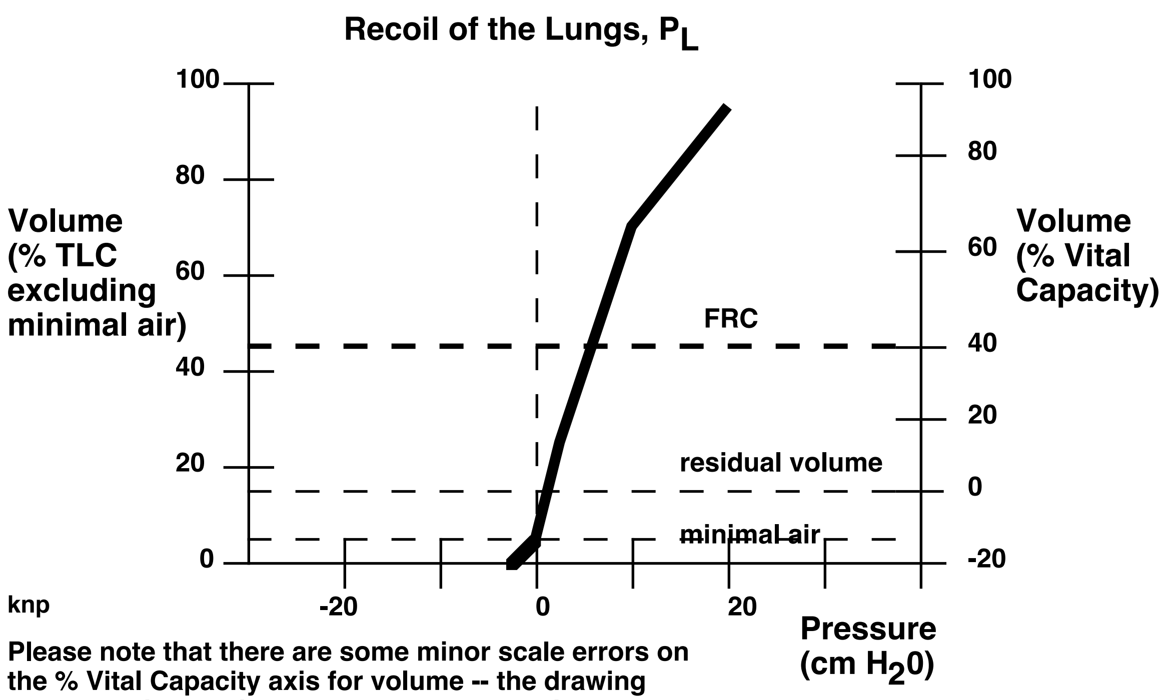
2) If P_{alv} is positive and greater than P_{pl}, what will the sign of the lung recoil P_L be? Under these conditions, what must the volume of the lung be compared to minimal air? What will happen if the net applied force (equal and opposite to the recoil force) is removed?

3) If P_L is negative, what will the volume of the lung be relative to minimal air? What type of distorting forces from the pleural and alveolar spaces would give a negative P_L. What will happen if the distorting force is removed to the lung volume?

ANSWERS: (1) $P_{alv} = P_{pl} = P_L = 0$; **(2)** positive, greater than minimal air, the lung will collapse to minimal air; **(3)** below minimal air, negative alveolar and/or positive pleural pressures, the lung would spring back to the minimal air volume.

Notice that all of these behaviors are identical to what a toy balloon would do!

(f) If one takes a fresh lung, removes it from the body, and then takes this collapsed lung and deflates or inflates it to a series of volumes by using changes in alveolar pressure, pleural pressure, or some combination of the two (see equation #4) a graph is obtained like the one below.



Please note that there are some minor scale errors on the % Vital Capacity axis for volume -- the drawing program will not give me any better resolution. The most obvious error is between 40 and 60% max VC.

(i) This is a volume pressure (compliance curve).

(a) The **pressure graphed on the x-axis is the total recoil pressure, P_L**

(b) Volume is plotted two different ways -- % total lung capacity and % vital capacity. As you learned at the start of this packet, vital capacity is the maximum amount of air you can inspire after a forced maximal expiration puts you at residual volume (or vice versa). At residual volume, there is still a considerable amount of air in the lungs -- a liter or so). Thus, zero for vital capacity is not the same as zero for total lung capacity since the later includes the residual volume but the former does not. <u>We generally will talk about volumes with respect to %vital capacity since it is easier to measure than TLC (TLC measures require dilution techniques)</u>.

(ii) Notice that at any lung volume associated with normal function (i.e., above minimal air and in terms of function, above the residual volume) the net recoil pressure is positive. The bigger the amount of air in the lungs, the more positive P_L and (not surprisingly) the more stretched the lungs are. Notice that at normal respiratory volumes (FRC and above) the lungs are normally very stretched and contain a lot of recoil energy.

! Note: It should now be obvious that a positive recoil pressure will only be found when the net force tends to increase a structure's volume (such as the lung volume) to a value greater than the resting volume V_0 (minimal air for the lung). Likewise a negative net pressure acting on a structure will reduce the volume. THUS, OUR CONVENTION, WHEN SPEAKING OF RECOIL PRESSURES FOR THE LUNGS, THORAX OR ENTIRE RESPIRATORY SYSTEM IS THAT POSITIVE NET RECOIL PRESSURES TEND TO MOVE THESE STRUCTURES TO VOLUMES LARGER THAN THEIR NATURAL (UNLOADED, NO RECOIL) VOLUMES. NEGATIVE NET PRESSURES REDUCE VOLUMES BELOW V_0.

! Second Note: Another name for P_L (see eq. 5) is **transpulmonary pressure** (since it is the pressure that exists across the wall of the lung (outside referenced to inside). Know this term.

D. **THORAX (CHEST WALL) RECOIL PRESSURE**: the elastic recoil of the thorax is calculated in a manner similar to that of lung. We will **define the thorax as the solid tissues that cover the thoracic cavity** -- the ribs and associated muscles and the diaphragm and elastic guts beneath it. Once again, pressure the inside (from the pleural space) and outside (body surface) is used. This time the form of the equation is:

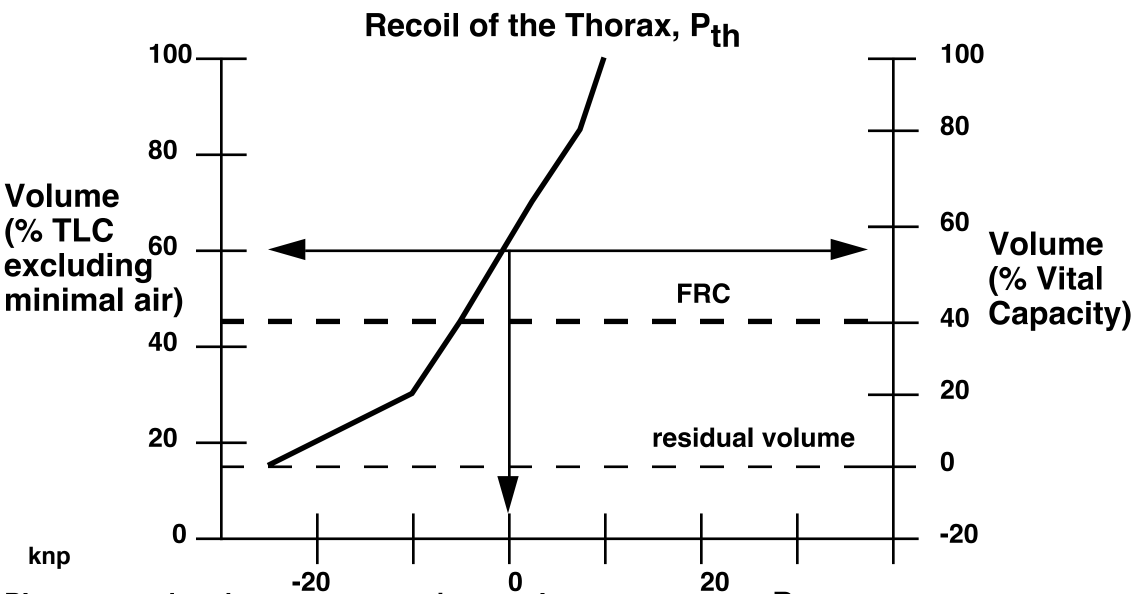
6. $P_{th} = P_{pl} - P_{surface}$

where **P_{th} is the thoracic recoil pressure**, **P_{pl} is the pleural pressure** and **$P_{surface}$ is the pressure at the body surface**.

The derivation of this equation should be obvious. In the case of the chest, any positive pressure on the body surface will act to force the chest inward. Likewise, **if** the pleural pressure is negative this also tends to pull the chest wall inward, towards the lungs.

? Can you imagine a condition where $P_{surface}$ is negative?

Let's image that we have removed the lungs from some unfortunate for the lung recoil curve. If we now fill the lung cavity with a bladder that we can either pressurize or de-pressurize and measure the volume within it, then we can find the recoil of the thorax at any volume. Notice that in this case, we are only changing pressure from the pleural side. However, we could also change it from the body surface side and still measure the volume and pressure in the bladder and use these to calculate thoracic recoil (eq. #6). Here is a graph of chest wall volume vs. chest wall recoil pressure similar to the one shown above for the lung:



Please note that there are some minor scale errors on the % Vital Capacity axis for volume -- the drawing program will not give me any better resolution. The most obvious error is between 40 and 60% max VC.

NOTE: please note that in many treatments, the thorax is referred to as the chest wall and therefore this recoil pressure is called chest wall recoil P_{cw}. Be advised that this is exactly the same thing as P_{th}

Questions:

? What is the volume of the thorax (expressed as % total lung capacity) when there is no elastic loading on the thorax? What is sum of the pleural and body surface pressures at this point?

? If the thorax is expanded to 100% of vital capacity by some force and this force is totally withdrawn, what volume will the chest assume? Why?

? If the thorax is moved in to minimal air by some force and the force is removed, what volume will the thorax assume?

E. The Elastic Properties of the Intact Respiratory System

1. The considerations above of the lung and chest wall (thorax) were for isolated systems. They are useful because they allow us to understand how the behavior of individual components affects the operation of the overall system, which we will now consider.

2. Normally, the lungs and thorax are in contact via the very thin layer of fluid on the outer surface of the lungs and inner surface of the chest wall, diaphragm, esophagus, and pericardial chamber. This fluid makes up the **PLEURAL SPACE** (introduced above).

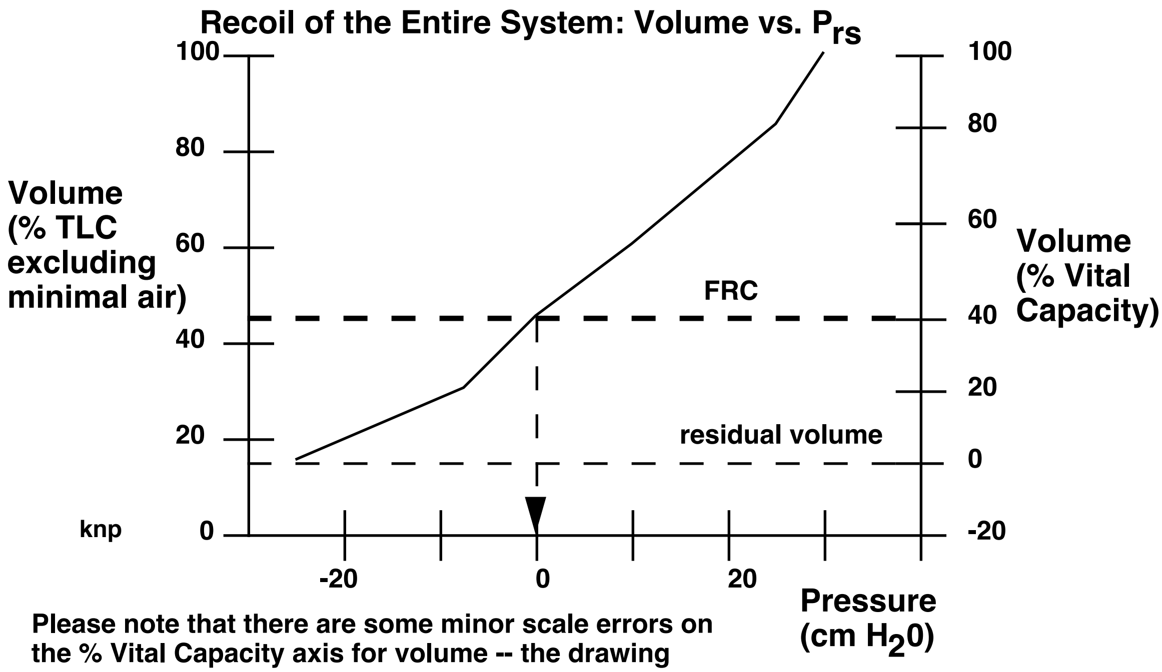
(a) the lungs and thorax are held together via polar interactions between the water with itself and with the polar portions of the chest wall and lung cell membranes. <u>It is a strong bond that is not easily disrupted, akin to two pieces of glass being held together by water</u>. Like the glass/water system, <u>the thorax and lungs do not separate easily</u> but <u>they can easily slide past each other,</u> as normally occurs during breathing.

(b) thus, the two are not held together by tissue bridges -- when such bridges occur they are called **<u>adhesions</u>** and are often painful or worse and certainly are disruptive of normal lung/chest wall sliding. They are usually caused by some form of wounding.

3. **Since the two are bound together into one system, the elastic nature of the intact respiratory system is determined by the two components**. Since they are in series with each other, these are added:

7. $P_{rs} = P_L + P_{th}$

where: $\mathbf{P_{rs}}$ is the recoil pressure of the entire respiratory system (lungs and thorax), $\mathbf{P_L}$ is the recoil pressure of the lungs; and $\mathbf{P_{th}}$ is the recoil pressure of the thorax.
Once again a plot can be made of the volume of the respiratory system (as above, lung volume) vs. recoil pressure of the respiratory system. The ways the data for such a plot will be obtained is a bit different from our considerations of isolated lungs and thorax and for the moment, let's not worry about how we get the data and just look at the curve. Keep in mind that the rules for understanding and interpreting this graph are the same as for the lung and chest wall graph; problems after the curve will help show this similarity.

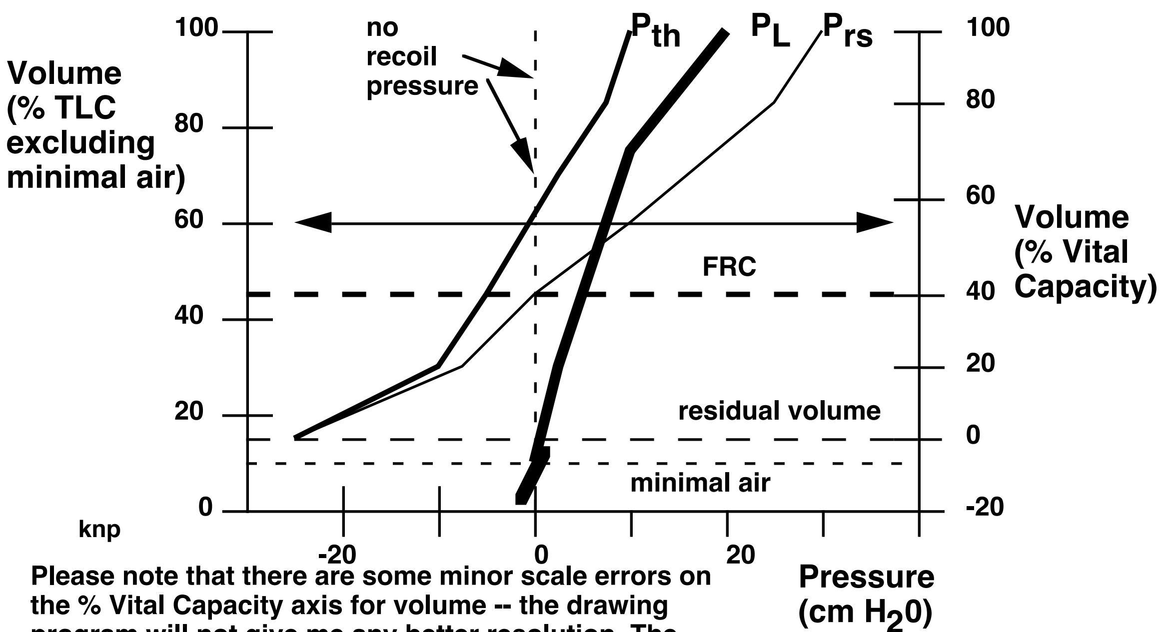


Please note that there are some minor scale errors on the % Vital Capacity axis for volume -- the drawing program will not give me any better resolution. The most obvious error is between 40 and 60% max VC.

? What is the volume of the respiratory system when no muscular or external pressure forces act on it? Express your answer in terms of %TLC and % VC.
? If the lungs are maximally inflated and then the force required to inflate them is removed, what will the respiratory system volume go to?
? At the FRC, are the lungs at their rest point? How about the thorax? What is the mathematical relationship between any tension in the lungs and the thorax? To answer this, look at the P_L and P_{th} graphs and consider eq. #7.

Since eq. #7 says that P_{rs} is the sum of the other two recoil pressures, it is useful to plot all three together.

Recoil Pressures of the Elements of the Respiratory System



Please note that there are some minor scale errors on the % Vital Capacity axis for volume -- the drawing program will not give me any better resolution. The most obvious error is between 40 and 60% max VC.

? <u>Be ready to discuss this graph in detail -- be sure you understand the inter-relationships between the three plots.</u>

F. Measurement of lung, thorax, and total recoil pressures in an <u>intact individual</u>:

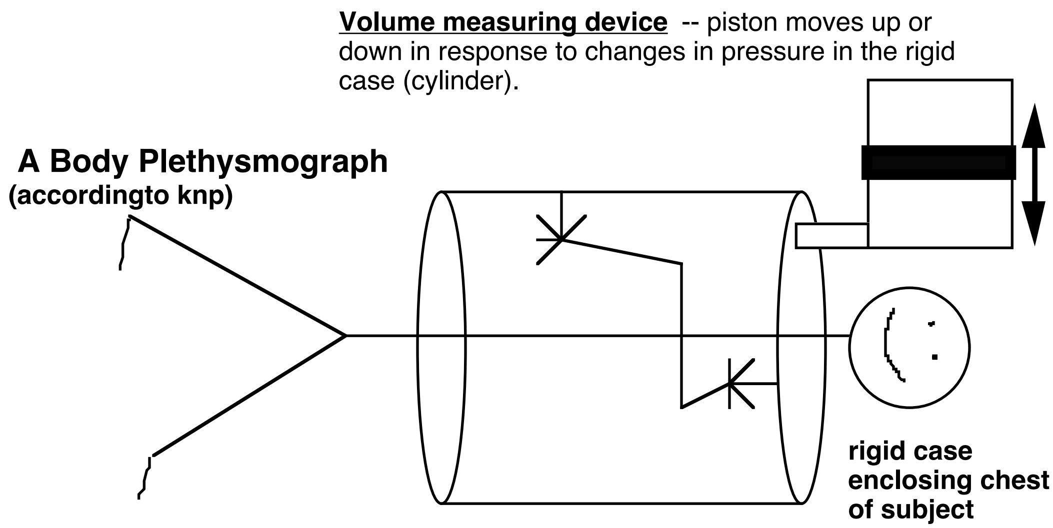
1. To make these measurements <u>we will need simultaneous measurements of lung volume and the pressure components of recoil pressure</u>.

2. **Volume** can be measured by two means.

(a) the less accurate means is to monitor the amount of air a subject breathes using a **spirometer or vitalometer** (like the ones we use in lab).

? What is the problem with using a spirometer for these measurements?

(b) By contrast, the most accurate is to enclose the person's thorax in an airtight box and measure volume changes using the Archimedes' Principle. Such a device is termed a **BODY PLETHYSMOGRAPH:**



if anyone had any doubts as to my artistic abilities, I believe that they should now be firmly laid to rest.

> **<u>Important Note</u>**:
> The <u>volumes found from the spirometer or body plethysmograph are used for all three recoil plots</u>. That is, **<u>a given lung volume is the same as a thoracic volume</u>** (since the lungs fill the thorax) **<u>and respiratory system volume</u>** (same reason). Thus, in generating the curves we have just seen, the object will be to measure the P_{alv}, P_{pl}, and $P_{surface}$ at a series of volumes and calculate P_L, P_{th}, and P_{rs} for each volume.

3. <u>PRESSURES</u>: Of the <u>three pressures</u> that determine P_{th} and P_L (**P_{alv}, $P_{surface}$, and P_{pl}**), **<u>alveolar and body surface can be determined rather directly with a pressure transducer located on either the body surface or in the subject's mouth</u>**. However, pleural pressure is much more difficult. Below are some notes on the measurement of each of these three pressures:

(a). <u>BODY SURFACE PRESSURE</u> (*$P_{surface}$*): For most situations, $P_{surface}$ will be the same as atmospheric pressure (P_b). A graph of Respiratory System volume vs. $P_{surface}$ will show that $P_{surface}$ is (obviously) independent of the respiratory system volume (in other words, no matter how big of a breath you take, the total pressure outside of your body does not change).

(b) <u>ALVEOLAR PRESSURE</u> (*P_{alv}*): the pressure measured in the alveoli.

(i) <u>When all airflow has stopped, P_{alv} equals the pressure at the mouth</u>.

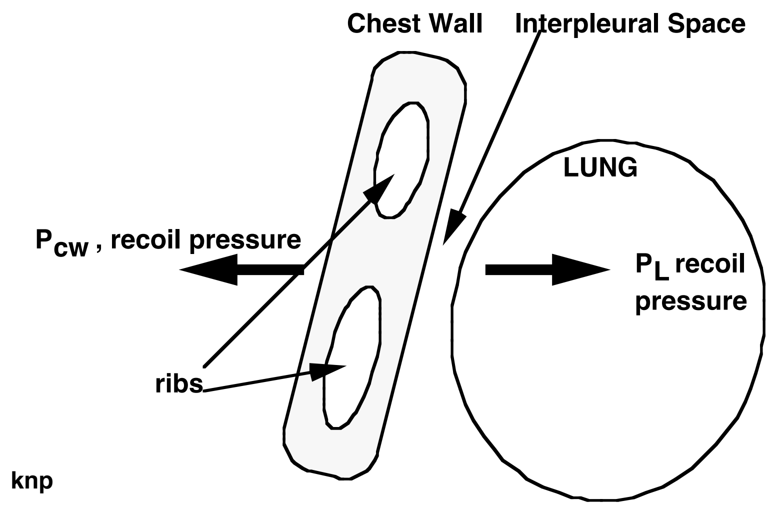
(ii) Normally, <u>if we use the muscles of the thorax to hold the lungs at a certain volume</u>, once all airflow has stopped, the **pressure at the mouth will equal $P_{surface}$**. However, <u>we want to factor out the influence of the respiratory muscles</u> and only ***<u>measure the pressure of the air in the alveoli that is required to hold the lungs at a certain volume</u>***.

(a) Have the subject inhale or exhale a known amount of air through a tube that contains a pressure transducer. It is possible to close this tube beyond the subject's mouth and prevent s/he from exhaling. The chest volume is recorded by a body plethysmograph.

(b). Once the proper amount of air is in the lungs, **the inhalation/exhalation tube is closed and the subject relaxes all of his/her breathing muscles. The pressure that is then recorded at the mouth is the P_{alv}.** It will be above atmospheric if the subject's lungs are more inflated than after a normal exhalation and it will be below atmospheric if the subject has exhaled a more than normal amount of air prior to trying this maneuver.

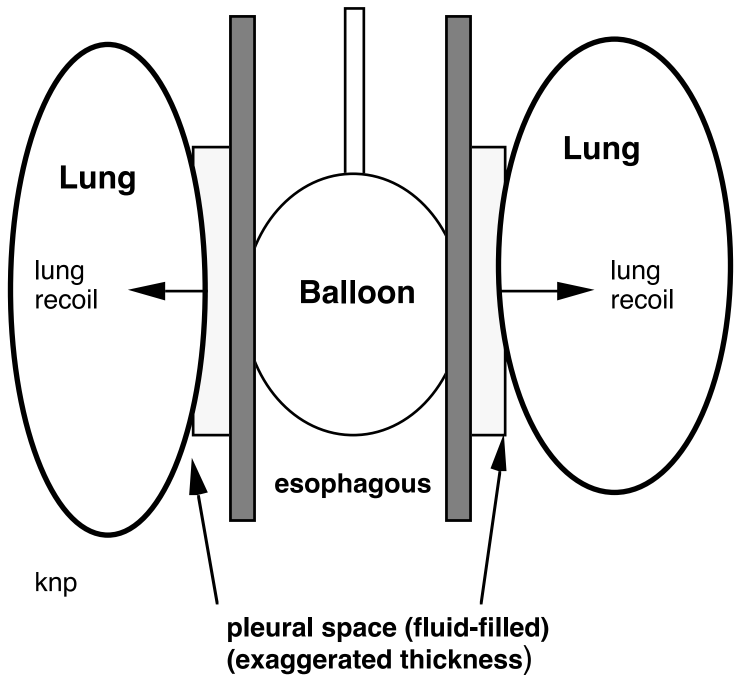
(iii). Try it for yourself. Inhale deeply, put your hand over your mouth, pinch your nose shut and relax your inspiratory muscles. There will be a (+) pressure at your mouth that is equal to P_{alv} when no flow is occurring. More about all of this in a moment.

(c) <u>Pleural Pressure:</u> is the pressure between the lungs and the chest wall, essentially, it is the pressure in the layer of fluid that adheres the lungs to the chest wall:



(i) P_{pl} is measured with an **<u>esophageal balloon</u>**. A tube with a small balloon on the end is fed through the subject's nose and down her/his esophagus. Air is then pumped through the line to inflate the balloon so that it is in contact with the walls of the esophagus (i.e., with the part of the GI tract that runs through the thorax). The pressure now found in the balloon and tube (everywhere the same) will be similar to the pleural pressure (see below).

(ii) This gives an estimate of pleural pressure because the lungs adhere to one side of the very thin-walled esophagus and the body wall to the other. Since the pleural pressure is everywhere transmitted through the thin pleural fluid to the tissues surrounding then if the balloon is full and touches the wall it will give a <u>good (but not exact) indication</u> of the pleural pressure because the thin walled esophagus is being pulled by both of these elastic elements. This arrangement is depicted on the top of the next page:



! A more invasive but far more accurate way to obtain pleural pressure is to surgically implant a pressure catheter in the pleural space. This is often done by implanting a small plastic sphere with small holes in it and then attaching this sphere to a fluid-filled tube that leads to a pressure transducer. The fluid in the sphere is continuous with the pleural fluid and therefore has the same pressure.

d. FINDING LUNG RECOIL PRESSURE: Recall the equation for lung recoil pressure:

5. $P_L = P_{alv} - P_{pl}$

Thus, to measure P_L, it is necessary to measure simultaneously $\mathbf{P_{pl}}$ (with and esophageal balloon) **and** $\mathbf{P_{alv}}$ (with a pressure transducer in the mouth). We can then calculate P_L. If we also know the volumes associated with each P_L (recall that the volumes for the lungs, chest wall, and respiratory system are all the same) then we can make a plot of volume on lung recoil pressure.

f. FINDING THORACIC RECOIL PRESSURE, $\mathbf{P_{th}}$, can be easily found as the difference between the lung recoil pressure (P_L) and the total recoil pressure (P_{rs}). Otherwise, it is usually the pleural pressure since $P_{surface}$ usually is equal to zero and therefore recall equation #6:

6. $P_{th} = P_{pl} - P_{surface} = P_{pl}$

g. FINDING THE RECOIL PRESSURE OF THE ENTIRE SYSTEM. We can show mathematically that the **recoil of the respiratory system is equal to the alveolar pressure when the mouth is closed and no external forces are acting on the body surface** (i.e., a pressure any different from atmospheric). Recall equation #7:

7. $P_{rs} = P_L + P_{th}$

If we substitute eqs. 5 and 6 for the P_L and P_{th} into eq. #7 then:

8. $P_{rs} = (P_{alv} - P_{pl}) + (P_{pl} - P_{surface})$

$= P_{alv} - P_{surface}$

However, $\mathbf{P_{surface}}$ **usually equals 0**. Therefore, when that is the case:

9. $P_{rs} = P_{alv}$

This is obviously the same thing as adding P_L to P_{th}; it is just simpler since we already have measurements of P_{alv} that we have used to calculate P_L.

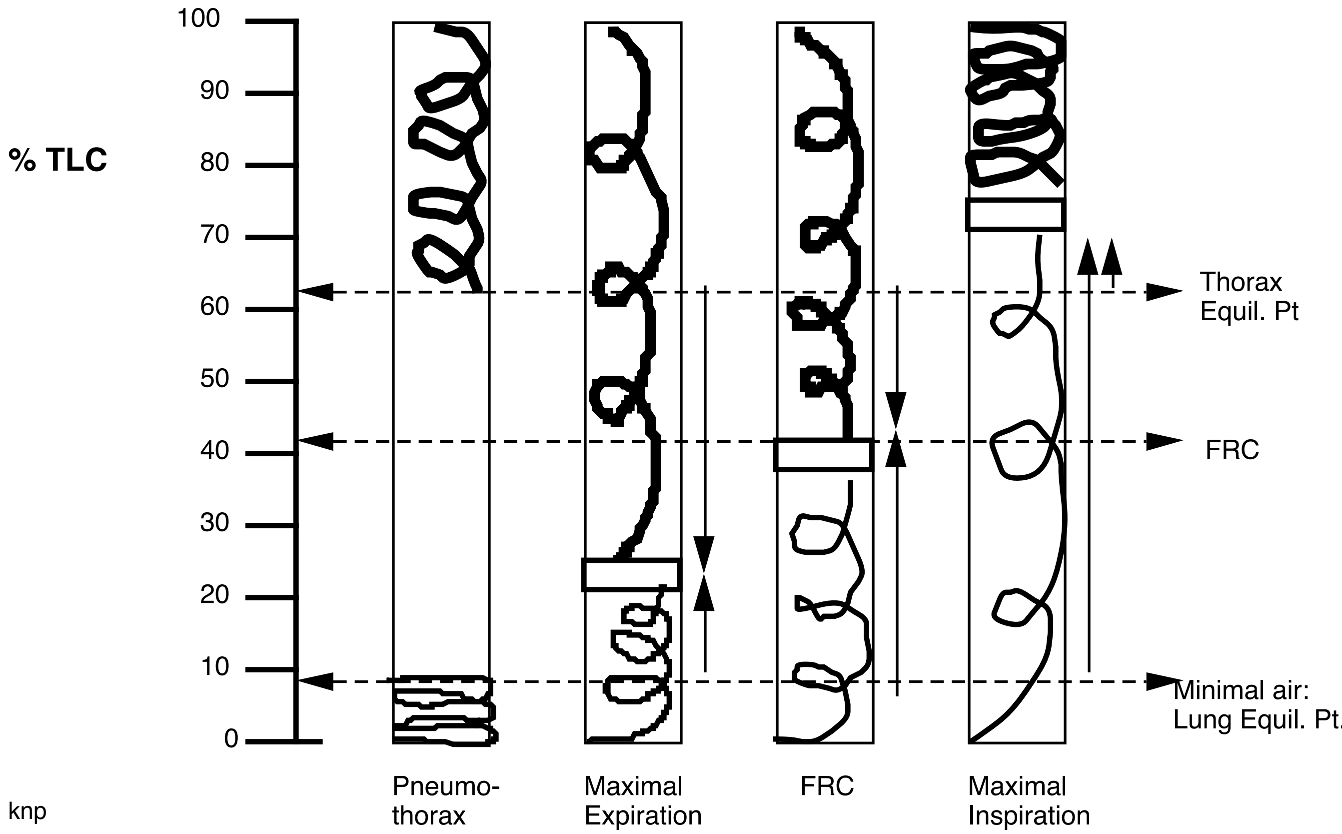
! Examine the spring model on the next page. In it the position of each spring is used to indicate the elastic operation of the chest wall, lungs and entire system.

? A **pneumothorax** occurs when air is introduced into the pleural space and the connection between the lungs and chest wall is to some degree disrupted. What should happen to the chest and lung volumes in the event of a complete pneumothorax?

? When the lungs are expanded to complete vital capacity, how much muscular tension (as muscle output) is being produced by the inspiratory muscles? How much tension is needed to exhale all the way to the residual volume? Express your answers in cm water. **HINT:** think about the relationship between elastic restorative forces and muscle force output in a static state.

? What happens to the size of the FRC in emphysema? Fibrosis? Be able to explain your answer in terms of recoil pressure of the lung and thorax and also in terms of amount of distortion from V_0 for each structure and elastance of each structure

A Spring Model of the Elastic Elements of the Respiratory System



The springs are used to show the displacement (not the tension -- that is given in the recoil pressure graph above) when the respiratory system is at different points. The first panel, pneumothorax, shows the resting volumes of the lungs (bottom) and thorax (top). Note that the volume of the lung is the portion of the graph occupied by the lower spring -- the volume of the thorax is the portion from the bottom of the graph to the bottom of the thorax spring. Thus, for the pneumothorax, the two volumes are 8% (lungs) and 65% thorax.

In the other three panels, the system is intact and the pleural space is indicated by the box between the lung and thorax springs. The arrows to the right of each of these boxes indicate the degree of displacement of each spring from its resting volume. Notice that in the last panel, one spring is lengthened (lungs) and the other (thorax) is compressed.