Plethysmographic Lung Volume Measurements

Please note that there are 88 slides in this presentation. Most of them will not be covered in detail during the lecture. They are included for self-study or reference.

Important Rules:

The Golden Rule of Lung Volume Measurements:

The Golden Rule of Pulmonary Diagnostic Measurements:

How to learn plethysmography:

Do studies on yourself, or have someone perform them on you.
• Understand:
  - what you're measuring
  - how you're measuring it
  - the conditions the measurements are performed under

• **How to learn plethysmography:**

• **How to learn plethysmography:**

• **How to learn plethysmography:**

• **Vtg - What's Measured?**

• VTG (thoracic gas volume)

• switch-in error

• VC

• IC

• ERV
TLC, RV and FRC are calculated from these measurements.

**How’s Vtg Measured?**
A modern whole-body plethysmograph collects data from three sources:

**What are the Measurement Conditions?**
*Functional Residual Capacity:* the volume of air remaining in the lung at the end of a normal, relaxed expiration, or more technically, the lung volume at which the elastic recoil force of the lung is equal and opposite in sign to the outward expansive force of the chest wall.

*FRC* is condition-dependent

We need to realize the variability of FRC, and do our best to minimize its variability.

Most of the time, FRC can be reproducibly measured, *IF* the maneuver is instructed and performed correctly.

Patient instructions on “normal breathing” are *very* important.

However...

TLC measurement reproducibility is far easier to obtain than FRC reproducibility.

After VC, TLC is the most diagnostically important lung volume.
VTG Measurement Steps:

Boyle's Law:
\[ P_1 \times V_1 \times T_1 = P_2 \times V_2 \times T_2 \]

If the temperature of a given mass of gas remains constant, the volume and pressure of that gas are inversely related.

Boyle's Law is used twice, first to calculate the lung volume at the end of an inspiratory effort, and then to calculate the resting lung volume.

Boyle's Law
To calculate end-inspiratory effort lung volume:

- \( P_1 \) is the initial pressure in the box at rest –

- \( V_1 \) is the initial volume of the box at rest –

- \( P_2 \) is the pressure in box at the end of chest expansion –

- \( V_2 \) is the volume in box at the end of chest expansion –

Boyle's Law
To calculate end-inspiratory effort lung volume:

\[
\begin{align*}
P_1 \times V_1 &= P_2 \times V_2 \\
P_{\text{box init}} \times V_{\text{box init}} &= P_{\text{box end-insp}} \times V_{\text{box end-insp}}
\end{align*}
\]

\( known \) \hspace{1cm} \( known \) \hspace{1cm} \( known \) \hspace{1cm} \( unknown \)
Boyle's Law
To calculate the resting volume of the chest:

- $P_1$ is the initial pressure of the mouth/alveoli at rest –

- $V_1$ is the initial (resting) volume of the chest –

- $P_2$ is the pressure in mouth/alveoli during inspiration -

- $V_2$ is the volume in chest at the end of chest expansion –

\[
P_1 \times V_1 = P_2 \times V_2
\]
\[
P_{box\ init} \times V_{box\ init} = P_{box\ end-insp} \times V_{box\ end-insp}
\]
\[
known \quad unknown \quad known \quad known
\]
\[
(from \ first \ calculation)
\]

Plethysmographic Assumptions:
There is no gas flow during the ventilatory efforts against an occluded airway.

Therefore, there are no flow-resistive losses of pressure in the airways and PAIRWAYoccluded is therefore equal to PA.

*The FRC would be overstated if there were any flow. This can be a problem with obstructive airways; panting slower may reduce but not completely eliminate this error.*
Plethysmographic Assumptions:
The pulmonary parenchyma is either sufficiently elastic, or gas-containing spaces are freely in communication with each other, so that changes in pressure are uniform throughout all the gas-containing areas of the lung.

*This assumption may not be true when FRCpleth is measured at low lung volumes. This might be due to airway closure or to non-uniform pleural pressures.*

Plethysmographic Assumptions:
Only gas in the thorax undergoes rarefaction and compression.

*This assumes that the volume of gas in the gastrointestinal tract is insignificant, not compressed or both.*

- **Thermal Equilibration -**

Is essential!!! Temperature **MUST** remain constant for Boyle's Law to work.

The greater the difference between room and box temperature, the longer the time needed for thermal equilibration.

Vendors frequently understate the amount of time actually needed for equilibration.

Plethysmographs never become completely equilibrated.

- **Thermal Equilibration -**
All modern plethysmographs use a metered leak, which is large enough to allow the increasing pressure to be slowly vented from the
box, but small enough to not have a significant effect on measurements. The metered leak also ensures that box pressure measurements are referenced to the current atmospheric pressure. This leak is compensated for during box pressure transducer calibration.

- Thermal Equilibration -

- Tidal Breathing -

It must be instructed, demonstrated and observed, and if necessary, critiqued and corrected.

- Tidal Breathing -

think of something other than your breathing (daydream)

concentrate on relaxing your stomach, chest and shoulders at the end of each expiration

- Tidal Breathing -

a normal ventilatory rate (< 18)

a reproducible, consistent end-expiratory level
• at least a slowing of flow towards end-expiration

• ideally, a short end-expiratory plateau

- Tidal Breathing -

• If a patient isn't breathing tidally at FRC, don't be afraid to correct them.

• A few sighs may help "reset" their breathing.

• DON'T RUSH! Remember, the volume you switch them in at is the volume you measure.

• Tidal breathing can be measured during thermal equilibration.

- Tidal Breathing -

ERS(2003): Relaxation Volume (Vrel):

The static equilibrium volume of the relaxed ventilatory system, or the volume at which the elastic recoil pressures of the lung and the relaxed chest wall are equal and opposite in sign. FRC in healthy humans approximates the Vrel.

- Tidal Breathing -

- Tidal Breathing -

• Explain equipment and maneuver.
• Patient should be seated "comfortably erect".

• Hands must support cheeks only during VTG measurement, but not during tidal breathing and SVC measurements. When supporting their cheeks, the patient should try to keep their upper body relaxed.

• **The VTG Maneuver**

  Two methods of measuring VTG:

• **Panting:** may be more difficult to perform, but more data are collected (better measurement reliability).

• **Non-panting:** is easier to perform, but only one inspiratory loop is collected per trial (less data = less measurement reliability).

• **The VTG Maneuver**

  Many patients will breathe too hard and fast, and move up and down when instructed to pant. For this reason, I tend not to use the word "pant"; I say "a gentle breathing effort, in and out". The breathing effort should be gentle, smooth and synchronous.

• **The VTG Maneuver**

  Helpful instructions include:

• Continue a *gentle breathing effort* in and out, back and forth, against the closed valve.

• Gently suck and blow against the valve.

• Pant like a puppy.

• Stress that there is **no** air movement; we are measuring pressures, not speed or volume.
The VTG Maneuver

Mental images I use when performing VTG's on myself include:

• A pressure gauge: I try to make the needle smoothly and evenly move back and forth, like a metronome.

• A piston, smoothly pushing and pulling air. Sometimes it's helpful to relate things like this to the patient.

The VTG Maneuver

Demonstration Techniques:

• Stretch an exam glove lightly over a cardboard mouthpiece; perform the panting maneuver with this so the patient can see the glove move in and out.

• A syringe with the plunger halfway out and the end blocked with your finger; move the plunger in and out slightly. The plunger represents the diaphragm.

• Have patient put mouthpiece/filter into their mouth, support their cheeks and have them breathe tidally. Hold your hand 1" in front of filter. After a few breaths, occlude end of filter, simulating the valve.

The VTG Maneuver

Panting Maneuver:

• Gently continue ventilatory effort against the valve, rate = 30 - 60 per minute

• The loop should be a straight line, possibly a little open in the middle, and not moving across screen
• The number of loops collected can be determined either by the software or the technologist, but generally the valve should not be closed for more than five seconds.

**The VTG Maneuver**

**Non-panting Maneuver:**

• Close valve at end-expiration, and the patient inhales against the valve with just enough force to open the valve, measuring just one inspiratory loop.

• The loop should be straight, not curved.

• Always attempt the panting maneuver first.

**IC, VC and ERV Measurement**

• After valve opens, the patient can return to normal breathing and remove their hand from their cheeks. *When they are ready:*

• The patient is instructed to inhale to TLC.

• From TLC, smoothly exhale to RV.

• From RV, inhale again to TLC.

• Return to tidal breathing and then end maneuver.

**IC, VC and ERV Measurement**

A frequent problem in slow vital capacity measurement is that more effort is put into the forced (FVC) measurement than the slow. There is no physiological reason for a SVC to be smaller than a FVC. The only reason this happens is from suboptimal instructions from the technologist and/or suboptimal effort by the patient.
IC, VC and ERV Measurement

A few points to remember about VC measurement:

• Errors of VC measurement are only errors of understatement.

• If patient exhales for ten seconds on FVC, they'll have to exhale longer than that on SVC, since they're exhaling more slowly.

• Some patients may coordinate a forced maneuver better than a slow one. If this appears to be the case, as long as the tidal breathing baseline was correctly measured, it is acceptable to perform it in this manner.

IC, VC and ERV Measurement

If FRC and IC are correctly measured, but ERV is not, what measurements are reliable?

• FRC, IC and TLC are good, ERV, RV and VC are not.

If FRC and ERV are correctly measured, but IC is not, what measurements are reliable?

• FRC, ERV and RV are good, IC, VC and TLC are not.

IC, VC and ERV Measurement

• The entire procedure (VT – VTG – VC) should be repeated until three reproducible trials have been obtained.

• Tell the patient, “We’ll repeat this measurement when you are ready.” This is important, don’t rush them. If they would perform better after resting a few moments, then wait until they say they’re ready.
Maneuver Errors and Correction

During VTG measurement, you're looking at a graph of two signals, mouth pressure and box pressure.

- Mouth pressure is plotted on the Y (ordinate, or vertical) axis
- Box pressure is plotted against the X (abscissa, or horizontal) axis
- Positive mouth pressure (an expiratory effort) will result in an upward deflection of the tracing
- Negative mouth pressure (an inspiratory effort) will produce a downward deflection.

**Maneuver Errors and Correction**

The key to identifying VTG loop artifacts is to understand which transducer makes the tracing go which way.

This will tell you what the patient is doing correctly or incorrectly, so that reinforcement or corrective reinstruction can be given.

**Maneuver Errors and Correction**

\[
\begin{align*}
+PM & \uparrow \\
- PB & \leftrightarrow +PB \\
& \downarrow \\
- PM & 
\end{align*}
\]
Maneuver Errors and Correction

Ideal VTG loops will be a straight line going from the upper-left to lower-right quadrants.

They may be slightly open in the middle; the more open they are, the more difficult it is to determine the tangent line.

Generally, as long as both sides of an open loop are symmetrical, the tangent will be reliable.

Asymmetrical VTG loops usually have poor reproducibility and reliability.

Maneuver Errors and Correction
Technologists often forget to look at the patient when trying to identify the cause of incorrect VTG performance.

Is there excessive body movement?

Is there mouthpiece or noseclip leakage?

Is the mouthpiece moving in their mouth?

Are their cheeks bulging in and out?

It's often easier to discern what's wrong by looking at the patient rather than at their VTG loops.

Maneuver Errors and Correction
• It’s helpful to first demonstrate to the patient what they are doing wrong, and then demonstrate the correct performance.

• There is frequently more than one problem.

• Remember that it is equally important to reinforce proper maneuver performance.

Again, look at both the graph and the patient during VTG performance to identify where the problems are, and then the improper performance can be corrected.

• Maneuver Errors and Correction

• Maneuver Errors and Correction

• Open Loops: there are many reason these can occur:
  • unsupported cheeks
  • inadequate thermal equilibration
  • high airway compliance
  • panting too hard
  • mouthpiece moving in and out of mouth
  • excessive body movement
  • cabin or valve leak

• Maneuver Errors and Correction
• **Vertical Loops:**
  - a tracing that goes straight up and down represents just a mouth pressure signal, but no box pressure signal
  - the patient is breathing with their buccal (mouth) muscles, not with their diaphragm
  - reinstruct the patient, stressing that this should be a breathing effort from their chest and abdomen
  - the breathing effort is to come from their stomach (diaphragm), not their mouth muscles

• **Maneuver Errors and Correction**

• **Straight, Open Loops:**
  - straight, open loops represent a patient panting too hard, causing over-ranging of the mouth pressure transducer
  - the tracings should not exceed +/- 10 cm/H₂O
  - soft and gentle are the operative words; instruct the patient to pant more lightly

• **Maneuver Errors and Correction**

• On the previous slide, note the change in angle between the first loop and the third and fourth loops, with the second loop open and having two different angles. There are two sets of two reproducible VTG's, each over 0.5 liter apart. What's correct?

• **Maneuver Errors and Correction**
• Changing Slope:
  • a tracing that changes its slope is caused by mouthseal leakage; the volume being measured is changing.
  • a gradual change in slope is caused by a small leak, while a sudden shift in the slope is caused by a sudden, larger leak.

• Maneuver Errors and Correction

• Horizontal Loops:
  • a tracing that goes back and forth represents just a box pressure signal, but no mouth pressure signal
  • the patient is breathing against either a closed glottis or against their tongue, which is blocking the mouthpiece
  • reinstruct the patient

• Maneuver Errors and Correction

• Multiple Errors:
  • usually caused by a combination of all of the above, and is often accompanied by anxiety
  • correction entails identifying what the patient is doing incorrectly and reinstructing and/or demonstrating correct performance

• Maneuver Errors and Correction

• Loops Open at One End:
• on the lower (inspiratory) end are usually caused by incomplete thermal equilibration

• these loops will also usually move from left to right

**Maneuver Errors and Correction**

**Loops Drifting Left or Right:**

• A tracing that moves steadily to the right represents a changing or drifting box pressure, which is likely caused by incomplete thermal equilibration.
  
  — Allow more equilibration time. Also, ensure that the system is recording box temperature correctly.

• A tracing that steadily moves towards the left (a reverse “N”) is likely caused by a leak in the plethysmograph cabin - must be remedied before reliable measurements can be obtained.

**Maneuver Errors and Correction**

**Loops Above or Below the X-Axis:**

• a tracing oscillating above the zero pressure baseline will occur when a patient is exhaling, but not inhaling, against the valve

• a tracing oscillating below the zero pressure baseline will occur when a patient is inhaling, but not exhaling, against the valve

• reinstruct the patient

• the VTG *may* still be accurate
Maneuver Errors and Correction

A linear Loops (curving at one end):

- An a linear tracing is usually caused by a changing volume, which may be caused by:
  - Mouthpiece movement or unsupported cheeks
  - Excessive body movement during either expiration (upper-half of loop) or inspiration (lower-half of loop)
  - Use of buccal muscles during either the inspiratory or expiratory phase will cause that phase to curve vertically
  - Decreasing or no change in mouth pressure will cause the tracing to curve horizontally, either from the tongue blocking the mouthpiece or from glottic closure.

ATS/ERS: Standardization of the Measurement of Lung Volumes

In 2005, the American Thoracic Society (ATS) and the European Respiratory Society (ERS) issued five joint statements on pulmonary function testing. The third one was the Standardization of the Measurement of Lung Volumes. Two different recommendations for subdivision measurements were offered.

ATS/ERS: Standardization of the Measurement of Lung Volumes

The first (and preferred) lung volume measurement method is:

- Measure VT → measure VTG → back to VT →
- Measure ERV → measure IVC → back to Vt

- Reported FRC: mean of acceptable efforts
- Reported ERV: mean of acceptable efforts
- Reported RV: reported FRC minus reported ERV
• Reported TLC: reported RV plus largest acceptable IVC

• **ATS/ERS: Standardization of the Measurement of Lung Volumes**
  The second recommended lung volume measurement method is:
  
  measure VT → measure VTG → back to VT →
  measure IC → measure EVC → back to VT

• Reported FRC: mean of acceptable efforts
• Reported IC: mean of acceptable efforts
• Reported TLC: reported FRC plus reported IC
• Reported RV: reported TLC minus largest acceptable EVC

• **ATS/ERS: Standardization of the Measurement of Lung Volumes**

  • Both methods should be performed as “linked” maneuvers (without patient coming off the mouthpiece).
  
  • European convention is the first method, while the second method predominates in the United States.
  
  • The second method may be better for extremely dyspneic patients. If necessary, it can be unlinked (measure a linked FRC and IC, then add separately-performed VC).

• **ATS/ERS: Standardization of the Measurement of Lung Volumes**
  **ATS/ERS Reproducibility Recommendations:**

  • **VC:**
    same as for spirometry; at least three acceptable trials performed, with the difference between the largest and second-largest trials no greater than 150 mL.

  • **FRC:**
at least three acceptable trials performed that are all within 5% (the difference between the highest and lowest trials divided by the mean)

- **ATS/ERS: Standardization of the Measurement of Lung Volumes**
  - **ATS/ERS Reproducibility Recommendations:**

- IC and ERV: ATS/ERS found little consensus on IC and ERV reproducibility. Their recommendations are to report:
  - the largest VC
  - the mean IC from all acceptable trials
  - the mean ERV from all acceptable trials.

- **ATS/ERS: Standardization of the Measurement of Lung Volumes**
  - **ATS/ERS Data Reporting Recommendations:**

  - at least three measurements should be obtained,
  - the VTG loops should be straight and closed (a straight line) angling from the left upper to right lower quadrants of the screen,
  - the pressures should not exceed +10 cm/H2O to -10 cm/H2O in pressure,
  - FRCPLETH should be within +/- 5% of the mean value, and the two largest VC's should be within 150 mL of each other.

- **ATS/ERS: Standardization of the Measurement of Lung Volumes**
  - **ATS/ERS Data Reporting Recommendations:**

  - the average of all acceptably performed FRCPLETH, IC and ERV measurements are reported,
• the largest VC should be reported; this VC can be from a SEVC, SIVC, FEVC or FIVC,

• All data are reported in BTPS.

• Plethysmograph Quality Assurance

• Plethysmograph Quality Assurance

• **Important Rules:**

*The Golden Rule of Lung Volume Measurements:*

*The Golden Rule of Pulmonary Diagnostic Measurements:*