Plethysmography Test Performance Raw and Lung Volumes
A Review

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Lung Volume by Plethysmography
Clinical Indications

- The measurement of TLC to distinguish between restrictive and obstructive processes.
- The evaluation of the pathophysiology of obstructive lung diseases that may produce artifactual results when measured by dilution methods.
- Measurements requiring repeated trials.

AARC Clinical Practice Guideline
Airway Resistance Clinical Indications

- Bronchodilator response
- Bronchial provocation testing
- Pre- and post- surgical intervention for UAO
**Plethysmography Terminology**

- **Thoracic Gas Volume (TGV)** – also known as $V_{pant}$
  - A non-specific term. Volume of air in thorax at time shutter closure.
  - Measured during lung volume measurements to obtain $FRC_{pleth}$
  - Measured at the end of airway resistance measurements to correct the resistance measurement to the lung volume at which it was measured
Plethysmography Terminology

- Functional Residual Capacity (FRC\textsubscript{pleth})
  - Volume of air contained within the thoracic cage measured by plethysmography and corrected to the average end-expiratory lung volume that preceded the shutter closure that measured TGV
Airway resistance and lung volume

- $sR_{\text{aw}}$
  - $sR_{\text{aw}} = R_{\text{aw}} \times V_{\text{pant}}$
  - Inverse, linear relationship to lung volume

- $sG_{\text{aw}}$ ($G_{\text{aw}}$ relative to measured lung volume)
  - $sG_{\text{aw}} = 1/sR_{\text{aw}}$ or $1/(R_{\text{aw}} \times V_{\text{pant}})$
  - $sG_{\text{aw}}$ is not volume-dependent; can be used to assess change in airway resistance even if lung volume changes.
TGV ($V_{pant}$)

Shutter closure at end-expiration

Shutter closure during panting
Lung volumes requires stable resting EELV
- Shutter closed after stable EELV established, then:
  - FRC to RV to TLC (preferred) or
  - FRC to TLC to RV

Rapid panting of Raw raises EELV
- Shutter closed at end of collection to measure TGV for correcting Raw to sGaw
Considerations Prior to Testing

- Calibration

- Quality Aspects
  - Test Performance
    - Instrument
    - Patient
  - Test Review
  - Error Recognition
  - Troubleshooting
  - Data Reduction
Calibration

- Environmental parameters MUST be checked for accuracy including barometric pressure, temperature, and box volume.

- Devices to calibrate daily:
  - Flow Sensor
  - Mouth pressure Transducer
  - Box pressure Transducer
  - Box leak test (time constant)
Changes in mouth pressure and box pressure are the primary signals in closed shutter maneuver.

During expiratory phase, the cheeks can bow outwards if not supported:
- Mouth pressure signal diminished
- Can produce unusable TGV loops

ATS says ‘support with fingertips’ but flat of palm works better.
Mouthpiece

- Whenever possible, dentures remain

- Rigid round or oval filter mouthpiece works for some, not all patients

- **Flanged mouthpiece** helps maintain air-tight seal during closed shutter maneuver
Pre-test

- Smoking, eating and physical activity
  - Avoid for 1 hour

- Discontinue IV*

- Discontinue supplemental oxygen*

- Withhold bronchodilators*
Pre-test

- Open-door phase
- Closed door phase
- Performance criteria
- Coaching/reassurance
- Performance assessment
- Data selection/reporting
Patient Management
Reassurance

- Reassure the patient to relieve anxiety associated with the test or sitting within the cabinet
- The test will take 3-4 minutes
- The door can be released at any time from the inside (manufacturer-specific)
Patient Management Explanation

- **Open-door phase**
  - Thoroughly explain the procedure
    - Open shutter-”like a small piston”
    - Closed shutter- brief, gentle efforts
      - ‘try panting with your hand over your mouth’
      - Cheeks **must** be supported by hands
  - Demonstrate the maneuver
  - Practice with the patient
  - Emphasize relaxing and breathing normally between measurements

- **Door Closed Phase**
  - Practice while waiting for thermal stability
    - 30-45s minimum
Patient Management
Closed Shutter Explanation

- Patient performance criteria
  - Emphasize consistent, brief, gentle efforts between 0.5-1.0 efforts/sec (30 to 60/minute)
  - Relax between efforts
  - Emphasize this is NOT an MVV or MIP/MEP
  - Provide continuous feedback on performance
Patient Management Coaching

- Provide Real time feedback
- Practice Maneuver Prior Door Closure
- Practice Maneuver After Door Closure
- Evaluate and Correct during Testing
Test Procedure Preparation

- Instrument warmed up, then calibrated
- LEAVE THE DENTURES IN! (unless they interfere)
- Seat in box – proceed to open door phase
  - Get patient to relax – talk to them
  - Explain procedure; practice pant with hand over mouth
  - Adjust mouthpiece height, shouldn’t be too low or high
  - Practice mouthpiece and nose clip placement
  - Practice cheek support
- Close door – wait for thermal equilibration (30-60s)
3 Phases of Lung Volume by Plethysmography Measurement

1. Establish FRC - resting tidal breathing, establish stable baseline (EELV) for 3-10 Breaths.

2. Measure TGV - close shutter at end-expiratory lung volume; brief, gentle pant efforts for 2-3 s.

3. Measure VC - open Shutter, exhale to RV then inhale to TLC or inhale to TLC and exhale to RV (minimal effort).
Metronome vs. Coaching Cadence during closed shutter

- Shutter typically closed for 2-3s
- Any coaching of cadence (including metronome) before shutter will typically increase respiratory rate
- Increasing respiratory rate when obstruction is present will increase EELV
- Control cadence only after shutter closes
After first lung volume measurement...

- Often good to allow patient to remove noseclips and come off mouthpiece to rest
  - Opening door can reduce stress, allow nasal O₂

- Talk to/assess patient

- Review results
  - Look at stability of EELV prior to shutter
    - Assess line of best fit of 3-5 breaths; adjust if needed
  - Examine TGV loop
    - too small, too large, unidirectional, slope correct?

- Reinstruct and resume – goal is 3-5 repeatable, linked LVs
Lung Volume by Plethysmography

Common Errors

- Starting the measurement before thermal equilibration achieved
- No stable resting end-expiratory lung volume (EELV) during tidal breathing
- Pant effort unidirectional
- Pant frequency too fast
- Pant frequency too slow
- Pant effort too large
- Pant effort too small
- Glottis closing during effort
- Improper vital capacity maneuver after shutter opens
- Unlinked lung volumes
- One shutter closure for both lung volumes and airway resistance
Starting the measurement before thermal equilibration achieved

Typically 30–120s after door sealed

Temperature

Box Pressure

Time

wide loops
Wide loops caused by starting measurement too soon, same loop can result from panting too slowly.
Common Lung Volume Errors
unstable resting EELV during tidal breathing

- Causes:
  - Anxiety
  - Dyspnea
  - Confusion

- Correction
  - Relaxed tone of voice
  - Guided imagery
  - Minimize time
  - Thorough explanation
  - Good coaching
Common Lung Volume Errors

Pant effort unidirectional

- Causes:
  - Poor understanding
  - Expectation of airflow
  - Loss of attention to coaching

- Correction
  - Thorough explanation
  - Practice
  - Good coaching
Common Lung Volume Errors

Pant frequency too fast

- The assumption that mouth pressure = alveolar pressure no longer valid at pant frequencies above 90/minute.
- Mouth pressure will underestimate alveolar pressure resulting in an overestimation of FRCₚleth.

Causes:
- Improper coaching
- Anxiety
- Dyspnea
- Confusion
- Airway resistance measurement

Correction
- Relaxed tone of voice
- Thorough explanation
- Practice hand over mouth with coaching of cadence
Pant frequency too fast
0.5L increase in EELV before shutter

Try to keep tidal end-expiratory baseline and shutter volume within 200mL
Common Lung Volume Errors

Pant frequency too slow

Thermal drift causes wider TGV loops making slope assignment more difficult

- **Causes:**
  - Failure to follow cadence
    - too slow (< 30/minute)
  - Confusion
- **Correction**
  - Relaxed tone of voice
  - Thorough explanation
  - Practice with coaching of cadence
Wide loops caused by panting too slowly
same loop can result from starting measurement too soon
Common Lung Volume Errors

Pant effort too small (<5cmH2O or 0.5kPa)
Difficult to assign TGV slope.

- Causes:
  - Confusion
  - Anxiety
  - Weakness

- Correction
  - Coaching at time of testing
  - Between-effort discussion
Common Lung Volume Errors

Pant effort too large (>20cmH2O or 2kPa)

Difficult to assign TGV slope.

- **Causes:**
  - Confusion/poor understanding
  - Anxiety

- **Correction**
  - Coaching at time of testing
  - Between-effort discussion
Pant effort too large
Same patient after reinstructing
Common Lung Volume Errors
Improper Vital Capacity Maneuver

Examples:
- Unlinked to baseline and shutter maneuvers
- Forcing the exhalation
- Poor ERV maneuver (too short)
- Poor IC maneuver (no plateau)

Correction
- Instruct and Coach
- Demonstrate
‘Linked’ Lung Volumes

- Lung volume measurement – 3 phases
  - Stable EELV established
  - Lung volume at or near EELV measured
  - Vital capacity measured
    - ERV to TLC (ATS preferred) or IC to RV

- ‘Linked’ means 3 phase are tied to each other
  - (patient doesn’t come off mouthpiece until all 3 events have been completed)
Patient Performance
Lung Volume Acceptability Criteria

- Stable resting EELV (minimum of 3 breaths)
  - No evidence of leaks or drift
- Panting Frequency should be ~ 1.0 br/sec
  - 30-60/min - no higher than 90/min!
- Linear, appropriately sized loops
- 3-5 repeatable efforts
  - \((FRC_{pleth} \text{ range/mean} < 5\%)\)
Editing Lung Volumes

- Delete (deactivate) unacceptable efforts
- Adjust lines representing EELV, if necessary
  - At least 3 breaths
  - Can ignore last breath if patient reacted to imminent shutter closing
- Adjust TLC and RV points
- Adjust slopes on TGV loops, if necessary
- Check FRC (and RV, TLC) variability
Lung Volume Variability

- > 3 acceptable FRC\textsubscript{pleth} within 5\% of the mean

\[
\frac{\text{Largest FRC}_{\text{pleth}} - \text{smallest FRC}_{\text{pleth}}}{\text{mean FRC}_{\text{pleth}}} \leq 0.05
\]

- Linked VCs show \(\leq 0.15\text{L}\) variability
Evaluating Tidal Breathing

Unstable Tidal Breathing

Stable Tidal Breathing
12 breaths in 10s = 72 b/min.
Resting tidal breathing?
VC = 87% of predicted

tidal volume \approx 0.2 \text{L}
Why is tidal EELV sloping upward?
Calibrate/Verify using 3 flows
Consider low-flow range agreement

Consider that Inspiratory and Expiratory errors are cumulative and sum with each tidal breath.

Example:
Low flow range expiratory error: -2%
Low flow range inspiratory error: +2%

Each tidal breath will show 4% discrepancy in volume

*inspiratory volume ~ 4% larger than expiratory volume
Reviewing the Acceptable Trials

- TGV measurements:
  - The TGV loop should always be linear.
  - The source of error in computerized line fitting is usually electronic noise.
  - The line-of-best-fit should lie along the longitudinal axis of the loop.
CLOSED SHUTTER

\[ TGV = \frac{\text{Delta Mouth Pressure}}{\text{Delta Volume}} \]
Review Repeatability and Switch-in Points
Reporting Lung Volumes

- $FRC_{\text{pleth}}$ is mean of all acceptable efforts
  - $\leq 5\%$ variability, $(\text{highest} - \text{lowest})/\text{mean} \times 100$
- ERV is mean of ERVs from acceptable linked* vital capacity (ERV then TLC or IC to RV)
- VC is largest acceptable linked VC

* Mean ERV should be close to largest ERV
Result Reporting

- $RV = \text{mean } FRC_{\text{pleth}} - \text{mean } ERV$

- $TLC = RV + \text{largest VC}$

- alternate TLC calculation:
  - $FRC_{\text{pleth}}$ and IC still linked but patient can’t perform sustained exhalation
  - $TLC = \text{mean of 3 largest } FRC_{\text{pleth}} + \text{IC sums}$
  - $RV = \text{mean } TLC \text{ minus largest VC}$
Data Review

Lung Volumes:

- Perform 3 – 5 acceptable trials

- Variability of $\text{FRC}_{\text{pleth}}$ should be within 5% of the mean.

- Compare with other methods of volume determination when available
Volume Acceptability:

- Compare the VC volume with the FVC volume

Alternative Method:
- IC to TLC after shutter opens
- TLC = mean of 3 largest FRC_{pleth} + IC sums
- Use the IC and ERV measurements from the largest acceptable VC maneuver to calculate derived values

- Compare TLC from different methods

- Compare VA from DLco and TLC from plethysmography
  - VA should never be higher
Performance Standard
Test Quality Review
Lung Volumes

- Was the pre-shutter EELV stable for 3-10 breaths?
  - Respiratory rate reasonable for patient?
  - EELV (FRC) correctly assigned?
- Was the shutter closed at the correct level?
  - Start of tidal inspiration (target: within 0.20L of FRC)
  - Effort correct (> 5 cm H20 and < 20 cmH20)?
- Was the TGV loop bidirectional (inspiratory and expiratory) and closed?
- Is assigned TGV slope correct?
- Parallel to TGV loop?
- RV and TLC points correctly assigned?
Performance Standard Test Quality Review

Airway Resistance/Conductance

➢ Was the volume small (i.e. 50-100ml)
➢ Was the Pant frequency ~ 1Hz (30-60/m) for TGV
➢ Was the Pant frequency ~1.5 -2 Hz (90-120/m) for Raw?
➢ Is there minimal hysteresis in the open shutter loop?
➢ Is the Raw loop measured in the +0.5 to - 0.5 L/sec range?
➢ Is the Raw slope parallel with the Raw loop?
➢ Are there at least 3 acceptable trials?
➢ Has repeatability criteria been met?
➢ Is the TGV slope parallel with the TGV loop?
Variability and Repeatability

- Is the FRC$_{pleth}$ variability less than 5%?
  - Variability = \frac{(\text{max} - \text{min})}{\text{mean}} \times 100

- Is the variability of SVC within 0.15L of the largest SVC?

- Is the variability for sGaw $\pm$ .01 of mean when below .17 or $\pm$ .02 of mean when .18 or greater?
Airway Resistance
Airway Resistance Performance and Patient Management
Reassure the patient continually to relieve anxiety associated with the test or sitting within the cabinet

- The test will take 3–4 minutes
- The door can be released at any time from the inside (manufacturer specific)
Patient Management Explanation

- Open-Door Phase
  - Thoroughly explain the procedure
    - Open shutter-”like a small piston”
    - Closed shutter-”try panting with your hand over your mouth”
      - Brief, gentle efforts
    - Cheeks **must** be supported by hands
  - Demonstrate the maneuver
  - Practice with the patient
  - Emphasize relaxing and breathing normally between measurements

- Closed-Door Phase
  - Practice while waiting for thermal stability
Patient Management
Explanation

- Patient performance criteria
  - Small breaths (~50-100ml)
  - Emphasize consistent, gentle efforts between 1.5 - 2 efforts/sec (90 to 120)
  - Relax between efforts
  - Emphasize this is NOT an MVV or MIP/MEP
  - Provide continuous feedback on performance
Patient Management Coaching

- Provide real-time feedback
- Practice maneuver prior to door closure
- Practice maneuver after door closure
- Evaluate and correct during testing
Open Shutter Panting Too Big

Ends of Loops are Off Screen
Open Shutter Panting Still too Big

Loop is also too wide
Open Shutter Panting Too Small

Expiratory flow less than 0.5LPS
Airway Resistance and Conductance Correctly Performed
Data Review

Airway Mechanics: $R_{aw}$ loop

- The measurement is generally made a loop intersection with $+0.5$ and $-0.5$ L/sec horizontal markers.

- When the loop appears aberrational in the $+0.5$ and $-0.5$ L/sec segment, measure through the larger linear portion of the loop.

- Most importantly, STANDARDIZE the method of measurement in your lab.
$R_{aw}$ Acceptability Criteria

- Panting frequency should be $\sim 90 \text{–} 120$ breaths/minute
- Open–shutter loops are linear, non–elliptical and closed (or nearly so)
- Intersection of loops with $+0.5\text{LPS}$ and $-0.5\text{LPS}$ used to construct slope
- Average of 4–5 acceptable trials
- $\text{sGaw}$ variability is $\pm 0.01$ of mean when below 0.17 or $\pm 0.02$ of mean when 0.18 or greater
Airways Mechanics
Open - Shutter Loop Morphology

Inspiration

Expiration

"Fixed Extrathoracic Lesion"
Open–Shutter Loop Morphology

Inspiration

+ 0.5 L/s
0.0 L/s
-0.5 L/s

"TOO FAST"

Expiration
Open–Shutter Loop Morphology

Inspiration

+ 0.5 L/s

0.0 L/s

-0.5 L/s

Expiration
Airway Collapse Pattern

Airway Collapse Patterns may be better represented by separating Rinspiratory and Repspiratory.