MEASUREMENTS OF LUNG VOLUME & AIRWAY RESISTANCE

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INTRODUCTION

- lung volumes measured by spirometry are useful for detecting, characterising & quantifying the severity of lung disease

- Measurements of absolute lung volumes, RV, FRC & TLC are technically more challenging → limiting use in clinical practice

- Precise role of lung volume measurements in the assessment of disease severity, functional disability, course of disease and response to treatment remains to be determined

- Lung volume are necessary for a correct physiological diagnosis in certain clinical conditions

- Contrast to the relative simplicity of spirometric volumes variety of disparate techniques have been developed for the measurement of absolute lung volumes

- Various methodologies of body plethysmography, nitrogen washout, gas dilution, and radiographic imaging methods

Eur Respir J 2005; 26: 511–522

- “lung volume” usually refers to the volume of gas within the lungs, as measured by body plethysmography, gas dilution or washout

- Lung volumes derived from conventional chest radiographs are usually based on the volumes within the outlines of the thoracic cage & include
  - volume of tissue (normal and abnormal)
  - lung gas volume

- Lung volumes derived from CT scans can also include estimates of abnormal lung tissue volumes

LUNG VOLUMES

- There are four volume subdivisions which
  - do not overlap
  - can not be further divided
  - when added together equal total lung capacity

- Lung capacities are subdivisions of total volume that include <u>two or more</u> of the 4 basic lung volumes

BASIC LUNG VOLUMES

- Tidal Volume
- Inspiratory Reserve Volume
- Expiratory Reserve Volume
- Residual Volume

- Tidal volume
  - The amount of gas inspired or expired with each breath
- Inspiratory Reserve Volume
  - Maximum amount of additional air that can be inspired from the end of a normal inspiration
- Expiratory Reserve Volume
  - The maximum volume of additional air that can be expired from the end of a normal expiration

- Residual Volume
  - The volume of air remaining in the lung after a maximal expiration
  - This is the only lung volume which cannot be measured with a spirometer

BASIC LUNG CAPACITIES

- Total Lung Capacity
- Vital Capacity
- Functional Residual Capacity
- Inspiratory Capacity

- **Total Lung Capacity**
  - volume of air contained in the lungs at the end of a maximal inspiration
  - Sum of all four basic lung volumes
  - TLC = RV + IRV + TV + ERV

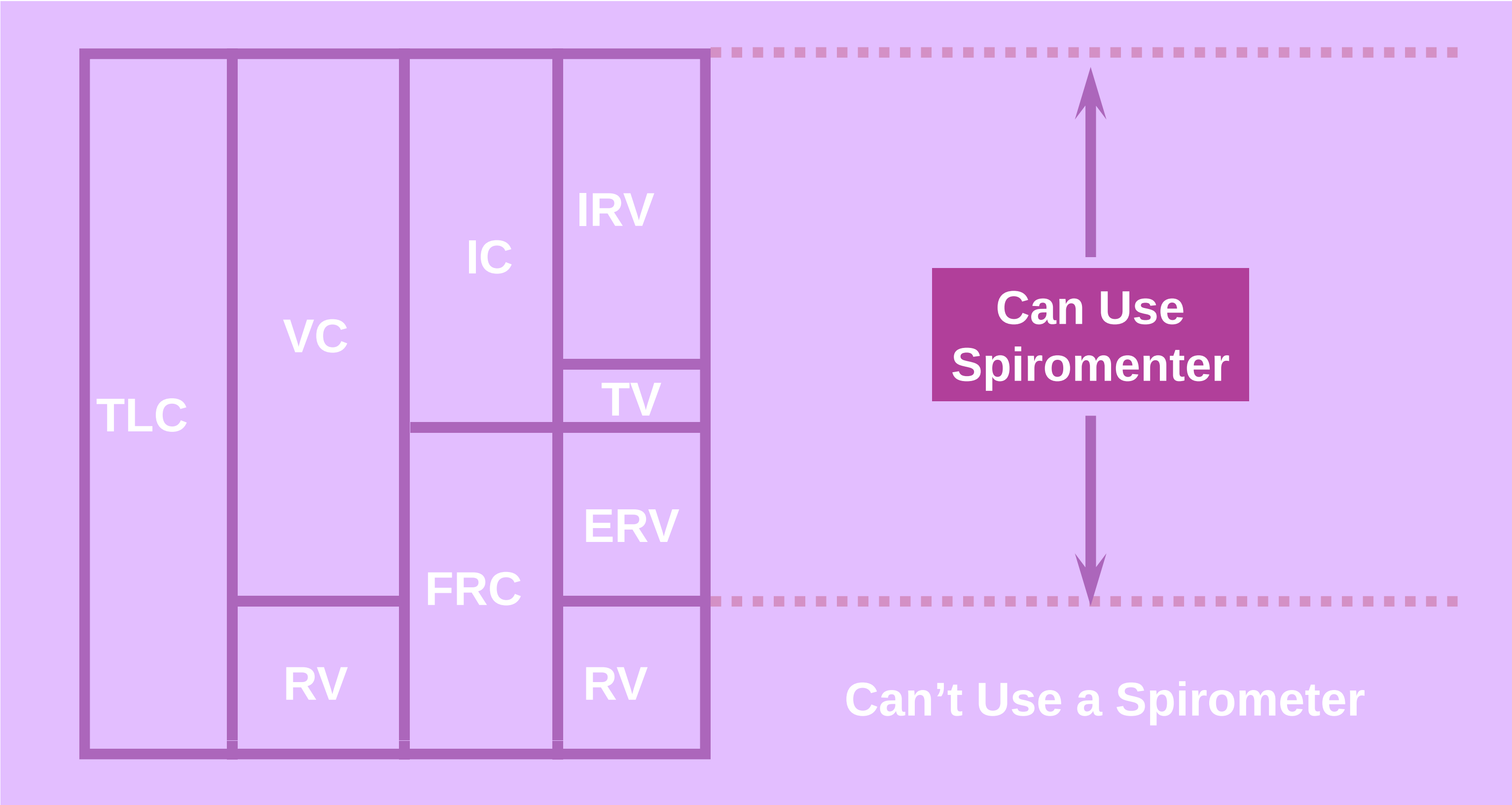
- **Vital Capacity**
  - The maximum volume of air that can be forcefully expelled from the lungs following a maximal inspiration
  - Largest volume that can be measured with a spirometer
  - VC = IRV + TV + ERV = TLC - RV

- Functional Residual Capacity
  - The volume of air remaining in the lung at the end of a normal expiration
  - FRC = RV + ERV

- Inspiratory Capacity
  - Maximum volume of air that can be inspired from end expiratory position
  - This capacity is of less clinical significance than the other three
  - IC = TV + IRV

MEASURING VITAL CAPACITY AND ITS SUBCOMPONENTS

- Use a spirometer



MEASURING RESIDUAL VOLUME

- Cannot use spirometry

- Measure FRC, then use:

  $$RV = FRC - ERV$$

- Residual Volume is determined by one of 3 techniques
  - Gas Dilution Techniques
    - Nitrogen washout
    - Helium dilution
  - Whole Body Plethysmography
  - Radiography

- Two most commonly used gas dilution methods for measuring lung volume
  - open circuit nitrogen (N_2) method
  - closed-circuit helium (He) method
- Both methods take advantage of
  - physiologically inert gas that is poorly soluble in alveolar blood and lung tissues
  - both are most often used to measure functional residual capacity

- In the *open-circuit* method, all exhaled gas is collected while the subject inhales pure oxygen
- Initial concentration of nitrogen in the lungs is assumed to be about 0.81
- rate of nitrogen elimination from blood and tissues about 30 mL/min
- measurement of the total amount of nitrogen washed out from the lungs permits the calculation of the volume of nitrogen-containing gas present at the beginning of the manoeuvre

Mass Balance:

$$\frac{0.80\ FRC}{\text{N2 Start}} = \frac{V_{spirometer} \times F_{N_2}}{\text{N2 Finish}}$$

$$FRC = \frac{V_{Spirometer} \bullet F_{N_2}\ (\text{spiometer})}{F_{N_2}\ (\text{lung})} = \frac{40{,}000\,ml \bullet 0.05}{0.8}$$

An advantage of the open-circuit method is that

- permits an assessment of the uniformity of ventilation of the lungs by
  - analyzing the slope of the change in nitrogen concentration over consecutive exhalations
  - measuring the end-expiratory concentration of nitrogen after 7 minutes of washout
  - by measuring the total ventilation required to reduce end-expiratory nitrogen to less than 2%

Am Rev Respir Dis 1980; 121:789-794

- The open-circuit method is sensitive to
  - Leaks anywhere in the system – mouthpiece
  - Errors in measurement of nitrogen concentration & exhaled volume

- If a pneumotachygraph is used attention must be paid to the effects of the change in viscosity of the gas exhaled, because it contains a progressively decreasing concentration of nitrogen

Disadvantages

- Does not measure the volume of gas in poor communication with the airways e.g. lung bullae
- Assumes that the volume at which the measurement was made corresponds to the end-expiratory point
- requires a long period of reequilibration with room air before the test can be repeated

Measuring spirometric volumes immediately before measuring FRC can eliminate the assumption of a constant or reproducible end-expiratory volume

CLOSED-CIRCUIT HELIUM DILUTION METHOD

- Subject rebreathe a gas mixture containing helium in a closed system until equilibibriation is achieved

- Volume and concentration of helium in the gas mixture rebreathed are measured

- Final equilibrium concentration of helium permits calculation of the volume of gas in the lungs at the start of the manoeuvre

Start: known ml of 10% He in Spirometer

Rebreath for 10 min (until He evenly distributed)

$$F_{He_{initial}} \bullet V_{Spirometer} = F_{He_{final}} \bullet (V_{Spirometer} + FRC)$$

$$FVC = \frac{(F_{He_{initial}} - F_{He_{final}}) \cdot V_{Spirometer}}{F_{He_{final}}}$$

- Thermal-conductivity meter measures the helium concentration continuously, permitting return of the sampled gas to the system

- Because the meter is sensitive to carbon dioxide it is removed from the system by adding carbon dioxide absorber

- Removal of CO_2 & O_2 consumption results in a constant fall in the volume of gas in the closed circuit

- An equivalent amount of oxygen is to be introduced as an initial bolus or as a continuous flow

- Closed-circuit method is sensitive to errors from leakage of gas and alinearity of the gas analyzer
- Fails to measure the volume of gas in lung bullae & cannot be repeated at short intervals
- Test results are reproducible

Scand J Clin Lab Invest 1973; 32:271-277

BODY PLETHYSMOGRAPHY

- Three types of plethysmograph
  - pressure
  - Volume
  - pressure-volume/flow

PRESSURE (CLOSED-TYPE)

- Has a closed chamber with a fixed volume in which the subject breathes
- Volume changes associated with compression or expansion of gas within the thorax are measured as pressure changes in gas surrounding the subject within the box
- Volume exchange between lung and box does not directly cause pressure changes
- Thermal, humidity, & CO_2- O_2 exchange differences between inspired and expired gas do cause pressure changes

- Thoracic gas volume and resistance are measured during rapid manoeuvres
- Small leaks are tolerated or are introduced to vent to slow thermal-pressure drift
- Best suited for measuring small volume changes because of its high sensitivity & excellent frequency response
- Measurements are usually brief and are used to study rapid events it need not be leak-free, absolutely rigid, or refrigerated

VOLUME (OPEN-TYPE)

- Has constant pressure and variable volume
- When thoracic volume changes, gas is displaced through a hole in the box wall and is measured
  - spirometer or
  - integrating the flow through a pneumotachygraph
- Suitable for measuring small or large volume changes

- To attain good frequency response, the impedance to gas displacement must be very small

- Requires a
  - low-resistance pneumotachygraph
  - sensitive transducer
  - fast, drift-free integrator, or
  - meticulous utilization of special spirometers

- Difficult to be used for routine studies

PRESSURE-VOLUME PLETHYSMOGRAPH

- Combines features of both types
- As the subject breathes from the room, changes in thoracic gas volume compress or expand the air around the subject in the box and also displace it through a hole in the box wall
- Compression or decompression of gas is measured as a pressure change
- displacement of gas is measured
  - spirometer connected to the box or
  - integrating airflow through a pneumotachygraph in the opening

- All of the change in thoracic gas volume is accounted for by adding the two components (pressure change and volume displacement)

- This combined approach has
  - wide range of sensitivities
  - permitting all types of measurements to be made with the same instrument (i.e., thoracic gas volume and airway resistance, spirometry, and flow-volume curves)

- Box has excellent frequency response and relatively modest requirements for the spirometer

- The integrated-flow version dispenses with water-filled spirometers and is tolerant of leaks

THORACIC GAS VOLUME

- Compressible gas in the thorax, whether or not it is in free communication with airways
- By Boyle's law, pressure times the volume of the gas in the thorax is constant if its temperature remains constant ($PV = P'V'$)
- At end-expiration, alveolar pressure (Palv) equals atmospheric pressure (P) because there is no airflow & V (thoracic gas volume) is unknown
- Airway is occluded and the subject makes small inspiratory and expiratory efforts against the occluded airway

- During inspiratory efforts, the thorax enlarge (ΔV) and decompresses intrathoracic gas, creating a new thoracic gas volume (V' = V + ΔV) and a new pressure (P' = P + ΔP)

- A pressure transducer between the subject's mouth and the occluded airway measures the new pressure (P')

- Assumed - $P_{mouth} = P_{alv}$ during compressional changes while there is no airflow at the mouth →pressure changes are equal throughout a static fluid system (Pascal's principle)

- Boyle –Mariotte's Law : P x V = constant under isothermal conditions

$$P_A \times TGV = (P_A - \Delta PA)(TGV + \Delta V)$$

Expanding and rearranging equation

$$TGV = (\Delta V / \Delta P_A)(P_A - \Delta P_A)$$

Since ΔP_A is very small compared to P_A (<2%) it is usually omitted in the differential term

$$TGV \sim (\Delta V / \Delta P_A) \times P_A \text{ with } P_A = P_{bar} - P_{H2O},sat$$

$$TGV \sim (\Delta V / \Delta P_A) \times (P_{bar} - P_{H2O},sat)$$

- The measured TGV additionally includes any apparatus dead spaces (Vd,app) as well as any volume inspired above resting end-expiratory lung volume at the moment of occlusion (Vt,occ)

- FRC_{pleth} can be derived from TGV by subtraction of these two volume components

$$FRC_{pleth} = TGV - V_{d,app} - V_{t,occ}$$

- The thoracic gas volume usually measured is slightly larger than FRC unless the shutter is closed precisely after a normal tidal volume is exhaled
- Connecting
  - the mouth-piece assembly to a valve and spirometer (or pneumotachygraph and integrator)
  - using a pressure-volume plethysmograph

  makes it possible to measure TLC and all its subdivisions in conjunction with the measurement of thoracic gas volume

Problems

- Effects of Heat, Humidity, and Respiratory Gas Exchange Ratio
- Changes in Outside Pressure
- Cooling
- Underestimation of Mouth Pressure
- Compression Volume

IMAGING TECHNIQUES

- In uncooperative subjects radiographic lung volumes may be more feasible than physiological measurements
- The definition of the position of lung inflation at the time of image acquisition is clearly essential
- Volumes measured carry their own assumptions and limitations, and cannot be directly compared with volumes measured by the other techniques

CONVENTIONAL RADIOGRAPHS

- The principle is to outline the lungs in both A-P & lateral chest radiographs, and determine the outlined areas
  - assuming a given geometry or
  - using planimeters in order to derive the confined volume
- Adjustments are made for
  - magnification factors
  - volumes of the heart
  - intrathoracic tissue and blood
  - infradiaphragmatic spaces
- In the determination of TLC, 6–25% of subjects differed by >10% from plethysmographic measurements in adult subjects

Academic Press Inc., New York, 1982; pp. 155–163

COMPUTED TOMOGRAPHY

- In addition to thoracic cage volumes, CTs can provide estimates of
  - lung tissue and air volumes
  - volume of lung occupied by
    - Increased density (e.g. In patchy infiltrates) or
    - Decreased density (e.g. in emphysema or bullae)

- In a study of children, comparable correlations were observed for CT and radiographic measurements as compared with plethysmographic TLC

Am J Respir Crit Care Med 1997; 155: 1649– 1656

- Disadvantage → high radiation dose

MAGNETIC RESONANCE IMAGING

- MRI offers the advantage of a large number of images within a short period of time, so that volumes can be measured within a single breath
- Potential for scanning specific regions of the lung, as well as the ability to adjust for lung water and tissue
- despite the advantages of an absence of radiation exposure its use for measuring thoracic gas volume is limited by its considerable cost

Resistive Forces

- Inertia of the respiratory system (negligible)
- Friction
  - lung & chest wall tissue surfaces gliding past each other
  - lung tissue past itself during expansion
  - frictional resistance to flow of air through the airways (80%)

Airflow in the Airways Exists in Three Patterns

- **Laminar**
- **Turbulent**
- **Transitional [distributed laminar]**

- Reynolds number $= \frac{\rho \times Ve \times D}{\eta}$

  ρ= density
  Ve= linear velocity of fluid
  D = diameter of tube
  η = viscosity of fluid

- Turbulent flow tends to take place when gas density, linear velocity & tube radius are large
- Linear velocity (cm/sec) of gas in the tube is calculated by dividing the flow rate (L/sec) by tube area (cm^2)
- Tube area refers to total cross sectional area of the airways of a given generation

- Airflow is transitional throughout most of tracheobronchial tree
- Energy required to produce this flow is intermediate between laminar and turbulent
- Many bifurcations in tracheobronchial tree, flow becomes laminar at very low Reynolds number in small airways distal to the terminal bronchioles
- Flow is turbulent only in the trachea where the radius is large and linear velocities reach high values [during exercise, during a cough]

- Airway resistance is easy to measure repeatedly & is always related to the lung volume at which it is measured

- Measurements of RAW useful in differential diagnosis of
  - type of airflow obstruction
  - localization of the major site of obstruction

- Measured during airflow & represents the ratio of the driving pressure and instantaneous airflow

- RAW is determined by measuring the slope (β) of a curve of plethysmograph pressure (x-axis) displayed against airflow (y-axis) on an oscilloscope during rapid, shallow breathing through a pneumotachygraph within the plethysmograph

- Shutter is closed across the mouth-piece, and the slope (α) of plethysmographic pressure (x-axis) displayed against mouth pressure (y-axis) is measured during panting under static conditions

- Because P_{mouth} equals P_{alv} in a static system it serves two purposes
  - Relates changes in plethysmographic pressure to changes in P_{alv} in each subject
  - Relates RAW to a particular thoracic gas volume

Physiologic factors affecting plethysmographic measurement of RAW

Airflow

- RAW pertains to a particular flow rate during continuous pressure-flow curves, so the slope may be read at any desired airflow rate
- RAW is measured at low flows, at which transmural compressive pressures across the airways are small and the relation to Palv is linear
- Airway dynamics measured during forced respiratory maneuvers is associated with
  - large transmural compressive pressures across the airways
  - maximal dynamic airway compression limiting airflow rates and
  - possible alterations in airway smooth muscle tone

  under such circumstances, RAW may be increased markedly

Volume

- Near TLC, resistance is small, but near RV, resistance is large
- Lung volume may be changed voluntarily to evaluate RAW at larger or smaller volumes in health and disease
- As a first approximation, airway conductance (GAW), the reciprocal of RAW, is proportional to lung volume

Transpulmonary Pressure

- RAW is related more directly to lung elastic recoil pressure than to lung volume
- Subjects with increased lung elastic recoil have a higher GAW at a given lung volume because of increased tissue tension pulling outward on airway walls
- Loss of elastic recoil results in loss of tissue tension and decreased traction on airway walls, so GAW is decreased
- This relationship may be used to analyze the mechanism of airflow limitation in various obstructive ventilatory defects (e.g., bullous lung disease)

Airway Smooth Muscle Tone.

- Airways affected markedly by smooth muscle tone, depending on the state of inflation and volume history

- Relationships are relevant to diseases in which
  - smooth muscle tone is increased (e.g., asthma)
  - low lung volumes are encountered (e.g., during cough, when pneumothorax is present)

- Bronchoconstriction is not demonstrable temporarily after a deep breath or at TLC in healthy subjects

- RAW in healthy subjects may be greater when a given lung volume is reached from RV than from TLC

Panting

- Panting minimizes changes in the plethysmograph caused by thermal, water saturation, and carbon dioxide-oxygen exchange differences during inspiration and expiration

- Improves the signal-to-drift ratio, because each respiratory cycle is completed in a fraction of a second

- gradual thermal changes and small leaks in the box become insignificant compared with volume changes attributable to compression and decompression of alveolar gas

- Glottis stays open, rather than partly closing and varying position, as it does during tidal breathing

IMPULSE OSCILLOMETRY AND FORCED OSCILLATION METHODS

- DuBois and colleagues described an oscillatory method to measure the mechanical properties of the lung and thorax

Eur Respir J 1996; 9:1747-1750

- Use an external loudspeaker or similar device to generate and impose flow oscillations on spontaneous breathing

- Impulse oscillometry measures RAW and lung compliance independently of respiratory muscle strength and patient cooperation

- Sound waves at various frequencies (3 - 20 Hz) are applied to the entire respiratory system
- piston pump can be used to apply pressure waves around the body in a whole-body respirator
- Slow frequency changes in pressure, flow, and volume generated by the respiratory muscles during normal breathing are subtracted from the Raw data
- permitting analysis of the pressure-flow-volume relationships imposed by the oscillation device

- The elastic forces of the lungs and chest wall oppose the volume changes induced by the applied pressure & decrease as the frequency of oscillation increases

- The total force or pressure that opposes the driving pressure applied by the loudspeaker can be measured as peak-to-peak pressure difference divided by peak-to-peak flow → combination of the resistance and *reactance*

- This resistance is proportional to the RAW in healthy subjects and patients, although it does include a small component of lung tissue and chest wall resistance as well as the resistance of the airways

OSCILLATING AIR FLOW

- High frequency oscillating air flow is applied to the airways
- Resultant pressure & airflow changes are measured
- Applying a/c theory Raw can be measured contineously

J Appl Physol 1970; 28: 113-16

- Measures total respiratory resistance through out the vital capacity – displaying resistance as function of lung volume