Pulmonary Function Testing Part I

Arthur Jones, EdD, RRT

Introduction to Pulmonary Function Testing

Learning Objectives:

- Describe the devices and methods for direct/ indirect spirometry and body plethysmography, for lung volume and compliance measurement.
- Interpret lung volumes and compliance
- Describe the devices and methods for measuring inspiratory and expiratory pressures.
- Interpret inspiratory and expiratory pressures.

Purposes of PFTs:

- Suggest a diagnosis by identifying the pattern of disease; e.g.,
  - restrictive
  - obstructive
  - neuromuscular
  - combined defects
- Assess the severity and progression of disease

Learning Objectives:

- Describe the physiologic basis and indications for spirometric flow measurements.
- Describe the devices and methods for spirometric flow measurements.
- Interpret results from spirometric flow measurements.
- Describe body plethysmographic measurement of airway resistance.

Purposes of PFTs:

- Evaluate therapeutic & rehabilitation regimens
- Evaluate surgical risk
- Determine disability
- Estimate prognosis

Types of PFTs:

- Lung volumes
  - direct spirometry
  - dilution methods
  - plethysmography
- Lung mechanics
  - airway flow
  - airway resistance
  - lung compliance
- Diffusing capacity

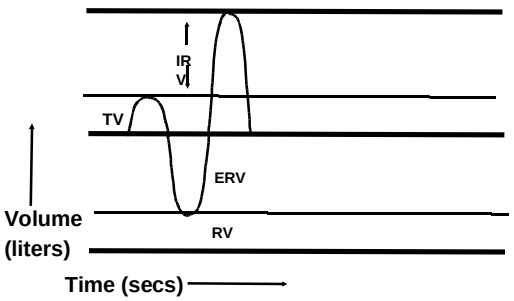
Lung compartments

- Lung volumes
  - Tidal volume (TV)
  - Inspiratory reserve volume (IRV)
  - Expiratory reserve volume (ERV)
  - Residual volume (RV)

Types of PFTs:

- Bronchodilator response
- Bronchoprovocation
- Exercise testing
- Metabolic testing

Lung compartments



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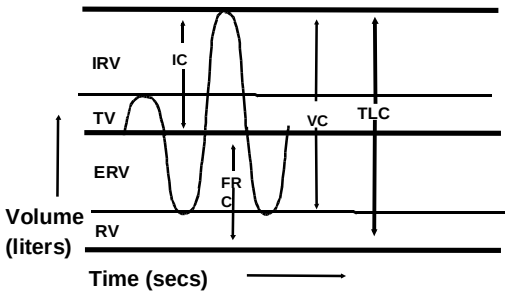
Lung Volume Measurement

Lung compartments

- Lung capacities two or more volumes
  - Inspiratory capacity (IC) = TV + IRV
  - Functional residual capacity (FRC) = ERV + RV
  - Vital capacity (VC) = IRV + TV + ERV
  - Total lung capacity (TLC) = TV + IRV + ERV + RV

Lung compartments



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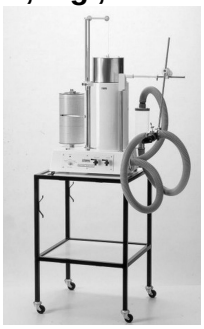
Direct spirometry devices

- volume displacement spirometers:
  - water seal; e.g., Collins, Tissot

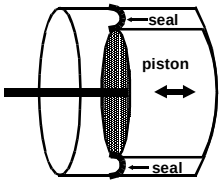


Direct spirometry

- Measures all volumes and capacities that do NOT include the RV; i.e., FRC & TLC

Direct spirometry

- volume displacement spirometers
  - dry rolling seal; e.g., Spirotech S780, nSpire HD CPL



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Direct spirometry devices

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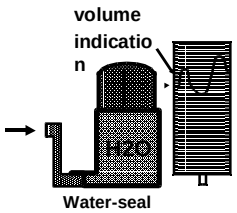

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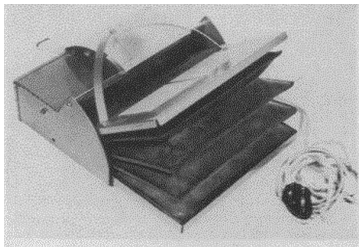
Direct spirometry

- volume displacement spirometers
  - dry rolling seal; e.g., Spirotech S780

Direct spirometry

- volume displacement spirometers
  - bellows



Direct spirometry

- volume displacement spirometers
- mechanical respirometers
- electronic spirometers - flow sensors
  - pneumotachometers
  - heated wire sensors
  - pitot tube sensors
  - ultrasonic flow sensors

Direct spirometry

- volume displacement spirometers
  - bellows - Vitalograph Gold Standard™

Indirect spirometry

- Gas dilution methods
  - measure capacities that contain RV
  - Principle:

    C1V1 = C2V2 ==>
    - V1(FRC) = C2V2/C1

Direct spirometry

- Volume displacement spirometers
- Turbines - flow sensors; e.g., Wright respirometer

Gas dilution methods

- Methods
  - Helium dilution
  - Nitrogen washout

Nitrogen washout

- Open circuit method
- Patient breathes 100% O2, starting at FRC
- Exhaled gas is collected in Tissot spirometer or Douglas bag
- N2 concentration measured
- When minimal N2% (1%) is reached, volume & %N2 in Tissot are measured

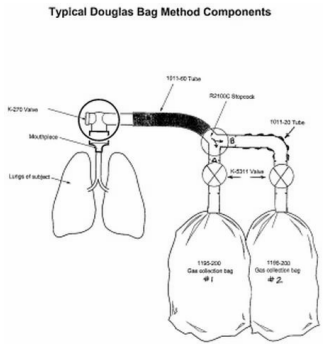
Nitrogen washout

- Calculation includes correction factors

$$FRC = \frac{(Vexh)(\%N_2exh)}{\%N_2alv\ (.75)}$$

Nitrogen washout

- Douglas collection bag



Helium dilution method

- Closed circuit method
- Patient rebreathes HeO2 mixture with known volume of He at FRC until equilibration between lung and spirometer
- O2 is added during the test
- CO2 is absorbed during the test

Nitrogen washout

- Tissot water seal spirometer

Helium dilution method

- Total volume for circuit and spirometer calculated (with correction factors)

$$FRC = \frac{(\%Heinitial - \%Hefinal)}{\%Hefinal} \times \text{system volume}$$

Helium dilution method

- Sources of error
  - patient intolerance - long procedure
  - leaks in system
  - leaks in patient; e.g., eardrums
  - slow, or non-communicating lung units
    - slow units increase equilibration time
    - closed units cause underestimation of FRC

Whole body plethysmography

- Advantages
  - measures all thoracic gas
  - rapid measurement
  - better cooperation
  - also measures R_{AW}

Whole body plethysmography

- Measures thoracic gas volume (TGV, V_{TG}) - includes all gas in the thorax
- Trapped gas can be estimated:

$Volume_{trapped} = TGV_{pleth} - FRC_{He\ dilution}$

- Principle - Boyle's law
  - P1V1 = P2V2

Whole body plethysmography

- Disadvantages
  - claustrophobia
  - equipment expense
  - equipment space requirement
  - extensive operator training
  - may overestimate FRC

Whole body plethysmography

- Patient sits in sealed chamber
- Pants at FRC against closed shutter
- Mouth pressure change is measured
- Chamber volume change is measured
- Oscilloscope displays relationship of changes in pressure & volume (tangent)
  - $TGV\ (V_{TG}) = (dV/dP_A)\ (P_A - dP_A)$

Alternate methods for lung volumes

- Imaging techniques
  - standard radiographs
  - computed tomography
  - magnetic resonance imaging
- Oxygen washout - during mechanical ventilation

Abnormal volumes - implications

- Reduced volumes with decreased lung compliance (C_L) ==> restriction
  - intrinsic pulmonary restrictive disease
    - fibrotic processes; e.g., silicosis, idiopathic pulmonary fibrosis
    - pulmonary edema
    - space occupying lesions; e.g., tumors
    - surfactant deficiency

Abnormal volumes - implications

- Reduced volumes
  - additional tests may be indicated to differentiate
    - lung compliance
    - maximal inspiratory and expiratory pressure
  - neuromuscular conditions
    - normal compliance
    - decreased PI_{MAX}, PE_{MAX}

Abnormal volumes - implications

- Reduced volumes - decreased compliance of lung and thorax (C_{LT})
  - extrinsic restrictive disease
    - morbid obesity
    - pleural disease
    - thoracic deformity; e.g., kyphoscoliosis

Abnormal volumes - implications

- Increased volumes - RV, FRC, TLC
  - emphysema - loss of lung elasticity
  - asthma (severe) - airway obstruction causing gas trapping

Abnormal volumes - implications

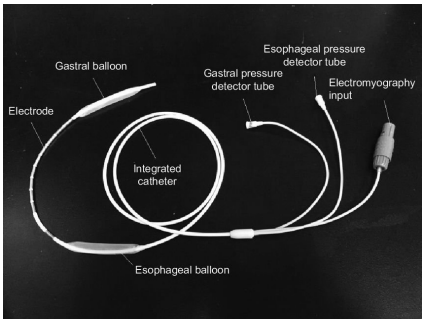
- Reduced volumes
  - reduced effort - normal compliance (C_{LT})
    - neuromuscular weakness; e.g., myasthenia gravis, muscular dystrophy may progress to extrinsic restrictive disease
    - purposeful - malingering (will not affect RV)

Lung compliance

- Purpose - to determine restriction
- Measurement requires
  - static volumes (zero flow)
  - pleural pressure (esophageal pressure)
  - alveolar pressure (mouth pressure)
  - shutter for flow interruption
- Volume-pressure curve generated from data

Lung compliance

- pleural pressure (esophageal pressure)



Lung compliance

- Normals
  - C_L = 200 mL/cm H2O
  - C_{TH} = 200 mL/cmH2O
  - C_{LT} = 100 mL/cm H2O

- $1/C_{LT}$ = $1/CL + 1/C_{TH}$ ==>

1/100 = 1/200 + 1/200

Lung compliance

- Implications of abnormal compliance
  - decreased C_L - intrinsic restrictive disease
  - decreased C_{TH} - extrinsic restrictive disease
  - increased C_L - emphysema

Inspiratory/expiratory pressures

- PI_{MAX} (NIF - NOT)
  - maximal sustained pressure to generate inspiration
  - measures strength of inspiratory muscles
- PE_{MAX}
  - maximal sustained expiratory pressure
  - reflects coughing capability

Inspiratory/expiratory pressures

- Measurement devices
  - pressure transducer OR
  - aneroid manometer (±200 cm H2O)
  - mouthpiece (flanged) or mask
  - nose clip

Inspiratory/expiratory pressures

- Measurement technique
  - PI_{MAX}
    - patient exhales to RV
    - airway occluded
    - maintain maximal pressure 2-3 s
  - PE_{MAX}
    - patient inhales to TLC
    - airway occluded
    - maintain maximal pressure 2-3 s

Inspiratory/expiratory pressures

- Sources of error
  - non-standardization of technique among operators
  - inadequate cooperation
  - leaks
  - pressure generated by cheek muscles (mouthpiece measurement)

Sniff nasal inspiratory pressure (SNIP)

- Advantages
  - natural maneuver - easy to do
  - eliminates cheek muscle pressure
  - reliability better than PI_{MAX}
  - validated for all age groups

Normal values*

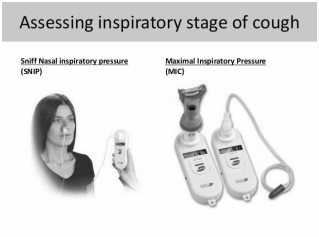
Females	Mean (cm H2O)	SD (cm H2O)
PI_{MAX}	79	± 19
PE_{MAX}	111	± 25
Males		
PI_{MAX}	117	± 25
PE_{MAX}	192	± 42

*Charfi MR, et al. 1991

Pathophysiologic Basis For Spirometry

Sniff nasal inspiratory pressure (SNIP)

- Description
  - manometer connected via tube to one nostril
  - other nostril remains open
  - patient instructed to sniff maximally



Physiology of air flow

- Factors affecting the magnitude of airflow
  - ventilatory muscle strength
  - airway resistance
  - elastic recoil of lung
  - airway collapsibility

Physiology of air flow

- Ventilatory muscle strength
  - inspiratory strength - determines maximal inspired lung volume
    - greater volume ==> greater elastic recoil
    - greater volume ==> larger airways at beginning of expiration
  - expiratory strength - determines drive pressure for forced expiration

Physiology of air flow

- Airway resistance (R_{AW}) - pressure required to produce flow
  - predominant factor in R_{AW} - the radius of the airway
  - R_{AW} :: $1/r^4$ ==>
  - decreasing radius by 1/2 increases R_{AW} by $2^4 = 16$ times ==>
  - pressure required to produce flow must increase by factor of 16 OR
  - the same pressure will produce 1/16 flow

Physiology of air flow

- Airway resistance (R_{AW}) - pressure required to produce flow
  - unit of measurement - cm H2O/L/sec
  - alternate unit - reciprocal of R_{AW} is airway conductance (G_{AW})
  - measured directly with whole body plethysmography

Physiology of air flow

- R_{AW} is non-constant during ventilatory cycles because the airway diameters change
  - high volumes - larger airways and lesser R_{AW}
  - low volumes - smaller airways and greater R_{AW}

Physiology of air flow

- Airway resistance (R_{AW}) - pressure required to produce flow
  - predominant factor in R_{AW} - the radius of the airway
  - R_{AW} :: $1/r^4$ ==>
  - decreasing radius by 1/2 increases R_{AW} by $2^4 = 16$ times ==>

Physiology of air flow

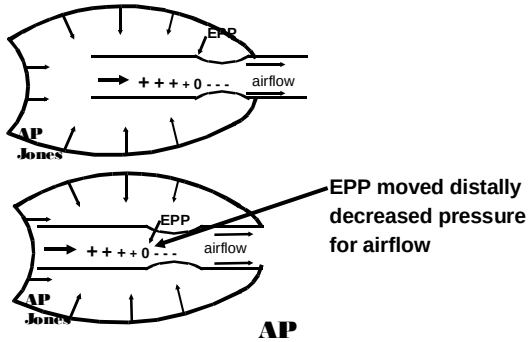
- Pathologic factors that affect R_{AW}
  - bronchospasm - smooth muscle contraction
  - bronchiolitis - narrows lumens
  - airway edema
  - smooth muscle hypertrophy

Physiology of air flow

- Pathologic factors that affect R_{AW}
  - bronchospasm - smooth muscle contraction
  - bronchiolitis - narrows lumens
  - airway edema
  - smooth muscle hypertrophy
  - connective tissue remodeling
  - increased numbers of mucus glands and goblet cells
  - luminal secretions

Physiology of air flow

- Migration of EPP



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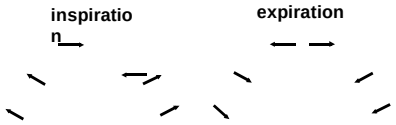
Physiology of air flow

- Factors affecting expiratory airflow
  - elastic recoil of lung - produces expiratory drive pressure during quiet breathing
  - when elastic recoil is decreased and time for expiration is decreased, gas trapping occurs

Physiology of air flow

- Inspiration vs. expiration
  - during inspiration intrathoracic airways tend to expand and extrathoracic airways tend to collapse



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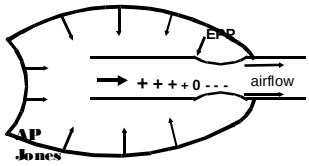
Physiology of air flow

- Airway collapsibility - migration of equal pressure point (EPP)
- EPP - point where intra-airway (drive) pressure equals surrounding pressure



Physiology of air flow

- Fixed, vs. variable obstruction
  - Fixed obstructions limit both inspiratory and expiratory flow; e.g,:
    - tumors
    - congenital or acquired airway defects

Physiology of air flow

- Fixed, vs. variable obstruction
  - Fixed obstructions limit both inspiratory and expiratory flow; e.g,:
    - tumors
    - congenital or acquired airway defects
  - Variable obstructions change with intrathoracic pressure changes and vary with:
    - location of obstruction
    - airway collapsibility

Spirometry indications

- Patients presenting with undiagnosed respiratory symptoms; e.g.,
  - dyspnea
  - wheeze
  - cough

Spirometry Methods and Devices

Spirometry indications

- Patients with suspected COPD, in particular those with a positive smoking history and:
  - increasing age
  - chronic cough
  - breathlessness on exertion, and
  - daily wheezing

Spirometry

- Description - measurement of inhaled and/or exhaled air flow
- Purpose - to diagnose and evaluate airway obstructive disease
- Types:
  - volume-time curves
  - flow-voume curves

Spirometry indications

- History of recurrent winter chest infections
- Diagnosis of COPD
- Monitoring patients with established obstructive disease
- Diagnosis of asthma - normal spirometry results do NOT rule out asthma

Spirometry relative contraindications

- Known or suspected respiratory infection
- Hemoptysis of unknown origin
- Pneumothorax
- Uncontrolled hypertension or history of hemorrhagic CVA

Spirometry devices

- Displays - screen, paper
- Data recording - paper, digital
- Data reporting - printout, digital file
- Data storage - preferably digital

Spirometry relative contraindications

- Known or suspected respiratory infection
- Hemoptysis of unknown origin
- Pneumothorax
- Uncontrolled hypertension or history of hemorrhagic CVA
- Recent thoracic, abdominal or eye surgery
- Nausea, vomiting, pain
- Confusion, dementia

Spirometry procedures

- Pre-testing history and physical examination
- Ask time of most recent bronchodilator
- Measure height, weight

Spirometry devices

- Volume displacement - laboratories
- Turbine spirometers
- Pneumotachographs
- Ultrasonic types
- Heated wire type
- Pitot tube type

Spirometry procedures

- Rapid inspiration, then forced expiration
- Repeat three times
- Two largest FVC, FEV_1 must be within 150 mL
- Report greatest FVC, FEV_1
- Administer bronchodilator, if ordered and repeat FVC maneuvers

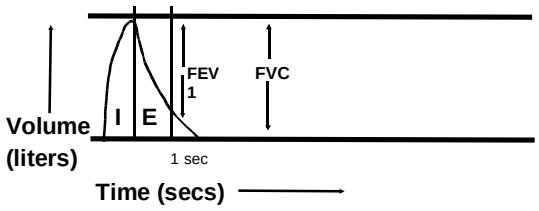
Spirometry Interpretation

FVC parameters

- FVC* - forced vital capacity (liters)
- FEV_1* - forced exhaled volume in 1 s (liters)
- FEV_1/FVC%* (FEV_1/FVC) * 100

*denotes undisputed utility

Timed forced vital capacity (FVC)



Slope of curve at any point = dV/dT = flow

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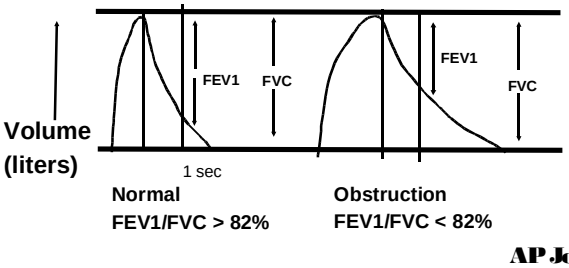
FVC parameters

- $FEV_{0.5}$ - forced exhaled volume in 0.5s (liters)
- FEV_6 - forced exhaled volume in 6s (liters)
- FEV_6/FVC%

Timed forced vital capacity (FVC)



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FVC parameters

- $FEV_{0.5}$ - forced exhaled volume in 0.5s (liters)
- FEV_6 - forced exhaled volume in 6s (liters)
- FEV_6/FVC%
- $FEF_{25-75\%}$ - forced expiratory flow between 25% and 75% expiration
- PEF - peak expiratory flow
- $V_{MAX50\%}$, $V_{MAX75\%}$ - flows at 50% and 75% expiration respectively (flow-volume study)

Interpretation

- Assumed preconditions:
  - test is properly done by skilled operator
  - testing equipment is mechanically operational and calibrated
  - patient is capable, properly instructed and motivated

Flow-Volume Studies

Interpretation

- FEV_1/FVC is most reliable indicator for expiratory airway obstruction
- $FEF_{25-75\%}$ - its utility is controversial
- FEV_6/FVC - informing patients of lung age purported to aid smoking cessation??? (controversial)

Flow-volume studies

- Plot inspiratory and expiratory flows, versus lung volumes
- Advantages:
  - display instantaneous flows at all points of FEVC and FIVC
  - graphic display of volume vs. flow for qualitative analysis
  - evaluates inspiratory and expiratory obstruction
  - capability to superimpose curves

Interpretation

Degree of severity	FEV1% pred.
Mild	>80
Moderate	50-79
Severe	30-49
Very severe	<30

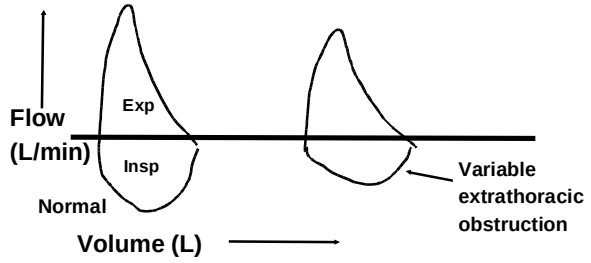
Devices

- Flow measuring device
- Microprocessor, to:
  - process signals
  - generate display
  - store and recall data

Technique

- Prepare patient
- Calibrate sensor
- Maximal inspiration, then,
- Forced expiration (FEVC), then,
- Forced inspiration (FIVC)

Flow-volume loops



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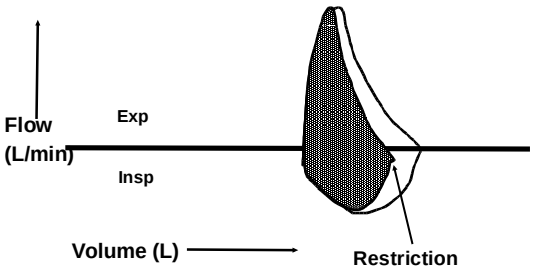
Flow-volume loops



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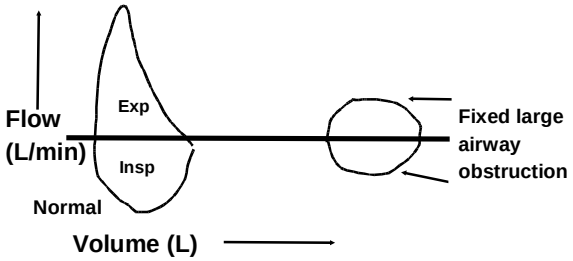

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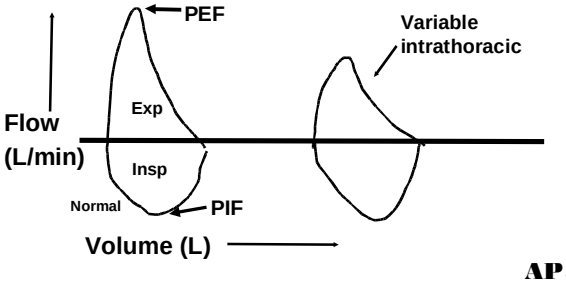
Flow-volume loops



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Variable obstruction will changes with pressure
Fixed obstruction remains constant

Airways Resistance Studies

Airways resistance studies

- The gold standard for evaluating airway function
- Purposes:
  - asthma diagnosis
  - bronchodilator response
  - evaluate obstruction for patients who are unable or unwilling to generate FVC
  - bronchodilator response in patients who show a clinical response; but unchanged spirometry

Parameters

- R_{AW} - airways resistance (cm H2O/l/sec)
- $R_{AW0.5}$ - airways resistance at flow = 0.5 L/sec
- sR_{AW} - specific airways resistance (cm H2O/L/sec/L)

Plethysmographic measurement

- Advantages
  - effort independence
  - feasible with infants
  - rapid test completion
- Disadvantages
  - equipment expense
  - equipment space
  - extensive operator training

Parameters

- R_{AW} - airways resistance (cm H2O/l/sec)
- $R_{AW0.5}$ - airways resistance at flow = 0.5 L/sec
- sR_{AW} - specific airways resistance (cm H2O/L/sec/L)
- G_{AW} - conductance (L/sec/cm H2O)
- sG_{AW} - specific conductance (L/sec/cm H2O/L)
- Shapes of loops

Measurement

- Whole body plethysmographic measurement of:
  - alveolar pressure
  - gas flow
- Patient pants or breathes at TV
- Pressure-flow tracings generated

Normal values

- $R_{AW0.5}$ - 0.6 - 2.4 cm H2O/L/sec
- sG_{AW} - > 0.15 L/sec/cm H2O/L

Summary & Review

- Purposes (indications) for PFTs
- Types of tests
- Lung volume measurements
  - volumes & capacities
  - direct spirometry
  - direct spirometry devices
  - gas dilution methods for FRC
  - whole body plethysmography for TGV
  - alternative methods for volumes

Summary & Review

- Spirometry methods and devices
  - indications and contraindications for spirometry
  - spirometry devices
  - procedures
- Spirometry interpretation
  - FVC curves
  - FVC parameters
  - Values for FEV_1/FVC

Summary & Review

- Implications for abnormal volumes
- Laboratory lung compliance measurement
- Inspiratory and expiratory pressures

Summary & Review

- Flow-volume loops
  - restriction
  - variable intrathoracic obstruction
  - variable extrathoracic obstruction
  - fixed large airway obstruction
- Airway resistance studies - gold standard
  - indications
  - procedure
  - parameters and interpretation

Summary & Review

- Pathophysiologic basis for spirometry - factors that affect airflow
  - muscle strength
  - airway resistance
  - elastic recoil of lung
  - airway collapsibility

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