Pulmonary Function Testing Part I

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This Presentation is Approved for
1.5 CRCE Credit Hours

Learning Objectives

- Describe the devices & methods for direct / indirect spirometry & body plethysmography, for lung volume & compliance measurement
- Interpret lung volumes & compliance
- Describe the devices & methods for measuring inspiratory & expiratory pressures
- Interpret inspiratory & expiratory pressures
- Describe the physiologic basis & indications for spirometric flow measurements
- Describe the devices & methods for spirometric flow measurements
- Interpret results from spirometric flow measurements
- Describe body plethysmographic measurement of airway resistance

Introduction to Pulmonary Function Testing

Purposes of PFTs

- Suggest a diagnosis by identifying the pattern of disease, e.g.
  - Restrictive
  - Obstructive
  - Neuromuscular
  - Combined defects
- Assess the severity & progression of disease

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

Types of PFTs

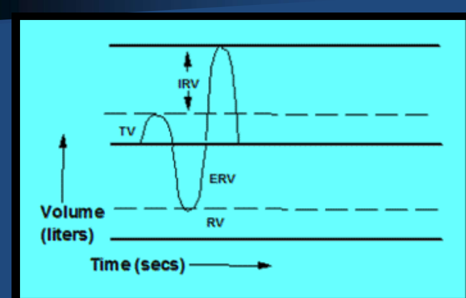
- Bronchodilator response
- Bronchoprovocation
- Exercise testing
- Metabolic testing

Lung Measurement Volume

Lung Compartments

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

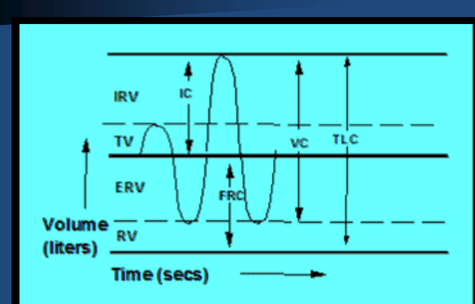
Lung Compartments



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

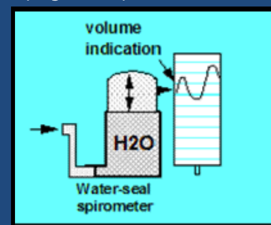


Direct Spirometry

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

Direct Spirometry Devices

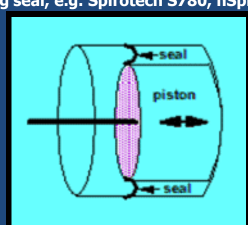
- Volume displacement spirometers
  - Water seal, e.g. Collins, Tissot



FYI see links below to view vintage water seal spirometer

Direct Spirometry

- Volume displacement spirometers
  - Dry rolling seal, e.g. Spirotech S780, nSpire HD CPL



See links below to view dry rolling seal spirometer

Direct Spirometry

- Volume displacement spirometers
  - Water seal
  - Dry rolling seal
  - Bellows - Vitalograph Gold Standard™

See links below to View wedge bellows spirometer & Vitalograph Gold Standard™

Direct Spirometry

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

Direct Spirometry

- Volume displacement spirometers
- Mechanical respirometers
- Electronic spirometers - flow sensors
  - Pneumotachometers
  - Heated wire sensors
  - Pitot tube sensors
  - Ultrasonic flow sensors

FYI see links below for info & images of pneumotachometers

Gas Dilution Methods

- Indirect spirometry to measure capacities that contain RV
- Principle

  C1V1 = C2V2 →

  $$V1(FRC) = \frac{C2V2}{C1}$$

Gas Dilution Methods

- Methods
  - Helium dilution
  - Nitrogen washout

Nitrogen Washout

- Open circuit method
- Patient breathes 100% O_2, starting at FRC
- Exhaled gas is collected in Tissot spirometer or Douglas bag
- N_2 concentration measured
- When minimal N_2 % (1%) is reached, volume & % N_2 in Tissot are measured

See links below to view Douglas bag collection

Nitrogen Washout

- Tissot water seal spirometer

Image courtesy of Mr. Kevin Hogben, International Sales & Product Specialist Manager for Medisoft

Nitrogen Washout

- Calculation includes correction factors

  $$FRC = \frac{(Vexh)\ (\%N_2exh)}{\%N_2alv\ (0.75)}$$

Helium Dilution Method

- Closed circuit method
- Patient rebreathes HeO_2 mixture with known volume of He at FRC until equilibration between lung & spirometer
- O_2 is added during the test
- CO_2 is absorbed during the test

Helium Dilution Method

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

  FRC = (%Heinitial - %Hefinal) x system volume / %Hefinal

FYI see links below for descriptions of both FRC methods

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

See links below to view interactive animation of He dilution test

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

- 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)

Whole Body Plethysmography

- Advantages
  - Measures all thoracic gas
  - Rapid measurement
  - Better cooperation
  - Also measures R_{AW}

Whole Body Plethysmography

- Disadvantages
  - Claustrophobia
  - Equipment expense
  - Equipment space requirement
  - Extensive operator training
  - May overestimate FRC

Alternative Methods for Lung Volumes

- Imaging techniques
  - Standard radiographs
  - Computed tomography
  - Magnetic resonance imaging
- Oxygen washout - during mechanical ventilation

FYI see links below for article on lung volume measurement standardization

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 - decreased compliance of lung and thorax (C_{LT})
  - Extrinsic restrictive disease
    - Morbid obesity
    - Pleural disease
    - Thoracic deformity, e.g. kyphoscoliosis

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)

Abnormal Volumes - Implications

- Reduced volumes
  - Additional tests may be indicated to differentiate
    - Lung compliance
    - Maximal inspiratory & expiratory pressure
  - Neuromuscular conditions
    - Normal compliance
    - Decreased PI_{MAX} , PE_{MAX}

Abnormal Volumes - Implications

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

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

See links below to view esophageal balloon

Lung Compliance

- Normals
  - C_L = 200 mL/cm H_2O
  - C_{TH} = 200 mL/cm H_2O
  - C_{LT} = 100 mL/cm H_2O
- $1/C_{LT} = 1/C_L + 1/C_{TH} \rightarrow$
  $1/100 = 1/200 + 1/200$

See links below to view compliance curve

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 H_2O)
  - Mouthpiece (flanged) or mask
  - Nose clip
  - Controlled leak - 2 mm diameter, 20 - 30 mm length

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)

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

Sniff Nasal Inspiratory Pressure (SNIP)

- Description
  - Manometer connected via tube to one nostril
  - Other nostril remains open
  - Patient instructed to sniff maximally

See links below to view sniff measurement (scroll down)

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

FYI see links below for article with predicted SNIP

Pathophysiologic Basis for Spirometry

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
  - Unit of measurement - cm H_2O/L/sec
  - Alternate unit - reciprocal of R_{AW} is airway conductance (G_{AW})
  - Measured directly with whole body plethysmography

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

- 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

- R_{AW} is non-constant during ventilatory cycles because the airway diameters change
  - High volumes - larger airways & lesser R_{AW}
  - Low volumes - smaller airways & greater R_{AW}

Physiology of Air Flow

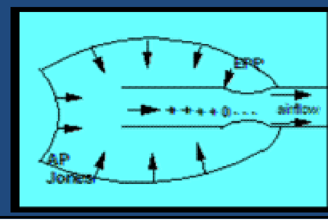
- Pathologic factors that affect R_{AW}
  - Bronchospasm - smooth muscle contraction
  - Bronchiolitis - narrows lumens
  - Airway edema
  - Smooth muscle hypertrophy
  - Connective tissue remodeling
  - Increased numbers of mucus glands & goblet cells
  - Luminal secretions

Physiology of Air Flow

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

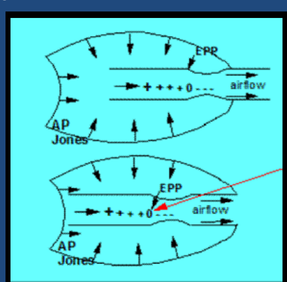
Physiology of Air Flow

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



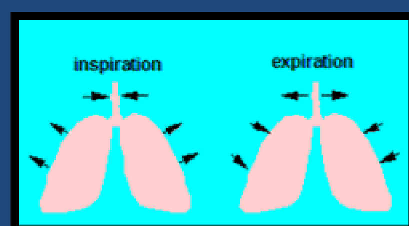
Physiology of Air Flow

- Migration of EPP



Physiology of Air Flow

- Inspiration vs. expiration
  - During inspiration intrathoracic airways tend to expand & extrathoracic airways tend to collapse



Physiology of Air Flow

- Fixed vs. variable obstruction
  - Fixed obstructions limit both inspiratory & expiratory flow, e.g.
    - Tumors
    - Congenital or acquired airway defects
  - Variable obstructions change with intrathoracic pressure changes & vary with
    - Location of obstruction
    - Airway collapsibility

Spirometry Methods & Devices

Spirometry

- Description - measurement of inhaled &/or exhaled air flow
- Purpose - to diagnose & evaluate airway obstructive disease
- Types
  - Volume-time curves
  - Flow-volume curves

Spirometry Indications

- Patients presenting with undiagnosed respiratory symptoms, e.g.
  - Dyspnea
  - Wheeze
  - Cough

Spirometry Indications

- Patients with suspected COPD, in particular those with a positive smoking history &
  - Increasing age
  - Chronic cough
  - Breathlessness on exertion, &
  - Daily wheezing

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 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 Devices

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

Spirometry Devices

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

Spirometry Procedures

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

FYI see links below for complete description of procedure

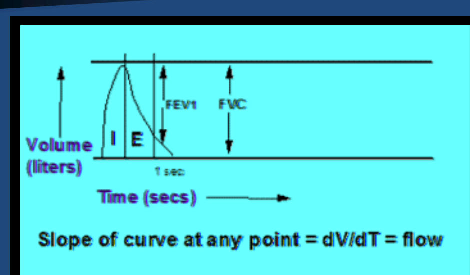
Spirometry Procedures

- 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, & repeat FVC maneuvers

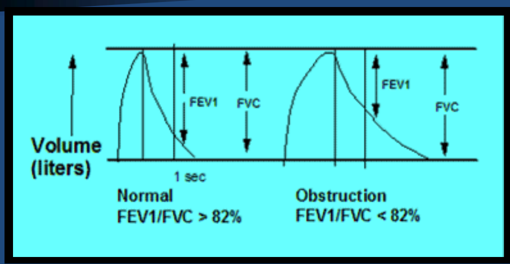
Up next: Video of spirometry

Spirometry Interpretation

Timed Forced Vital Capacity (FVC)



Timed Forced Vital Capacity (FVC)



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

FVC Parameters

$FEV_{0.5}$ - forced exhaled volume in 0.5 s (liters)

FEV_6 - forced exhaled volume in 6 s (liters)

FEV_6 / FVC %

FVC Parameters

$FEV_{0.5}$ - forced exhaled volume in 0.5 s (liters)

FEV_6 - forced exhaled volume in 6 s (liters)

FEV_6 / FVC %

$FEF_{25\text{-}75\%}$ - forced expiratory flow between 25% & 75% expiration

PEF - peak expiratory flow

$V_{MAX50\%}$, $V_{MAX75\%}$ - flows at 50% & 75% expiration respectively (flow-volume study)

Interpretation

- Assumed preconditions
  - Test is properly done by skilled operator
  - Testing equipment is mechanically operational & calibrated
  - Patient is capable, properly instructed, & motivated

Interpretation

FEV_1 / FVC is most reliable indicator for expiratory airway obstruction

$FEF_{25\text{-}75\%}$ - its utility is controversial

FEV_6 / FVC - informing patients of lung age purported to aid smoking cessation? (controversial)

FYI see links below to view Vitalograph spirometers

Interpretation

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

FYI see links below for ATS standards for spirometry

Flow-Volume Studies

Interpretation

- Plot inspiratory & expiratory flows versus lung volumes
- Advantages
  - Display instantaneous flows at all points of FEVC & FIVC
  - Graphic display of volume vs. flow for qualitative analysis
  - Evaluates inspiratory & expiratory obstruction
  - Capability to superimpose curves

Devices

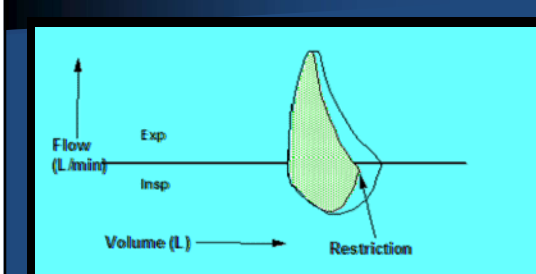
- Flow measuring device
- Microprocessor, to
  - Process signals
  - Generate display
  - Store & recall data

FYI see links below to view various portable spirometers

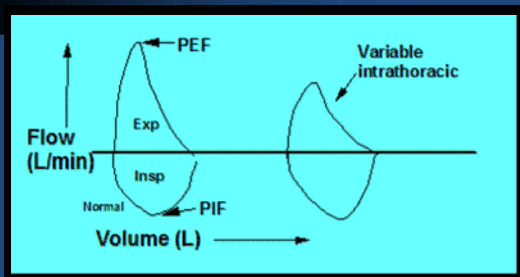
Technique

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

Flow-Volume Loops

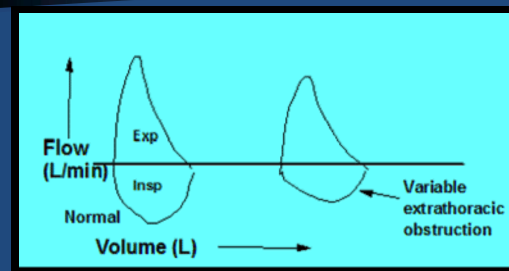


Flow-Volume Loops

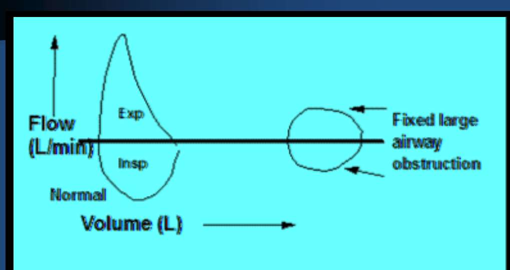


Variable obstruction will change with pressure
Fixed obstruction remains constant

Flow-Volume Loops



Flow-Volume Loops



FYI see links below for info & images on F-V loops

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

Plethysmographic Measurement

- Advantages
  - Effort independence
  - Feasible with infants
  - Rapid test completion
- Disadvantages
  - Equipment expense
  - Equipment space
  - Extensive operator training

FYI see links below to view infant PFT chamber

Measurement

- Whole body plethysmographic measurement of
  - Alveolar pressure
  - Gas flow
- Patient pants or breathes at TV
- Pressure-flow tracings generated

Parameters

- R_{AW} - airways resistance (cm H_2O/L/sec)
- $R_{AW0.5}$ - airways resistance at flow = 0.5 L/sec
- sR_{AW} - specific airways resistance (cm H_2O/L/sec/L)

Parameters

- R_{AW} - airways resistance (cm H_2O/L/sec)
- $R_{AW0.5}$ - airways resistance at flow = 0.5 L/sec
- sR_{AW} - specific airways resistance (cm H_2O/L/sec/L)
- G_{AW} - conductance (L/sec/cm H_2O)
- sG_{AW} - specific conductance (L/sec/cm H_2O/L)
- Shapes of loops

Normal Values

- $R_{AW0.5}$ - 0.6 - 2.4 cm H_2O/L/sec
- sR_{AW} > 0.15 L/sec/cm H_2O/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

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

Summary & Review

- Pathophysiologic basis for spirometry - factors that affect airflow
  - Muscle strength
  - Airway resistance
  - Elastic recoil of lung
  - Airway collapsibility

Citation: Hayes D Jr, Kraman SS. The physiologic basis of spriometry. Respir Care. 2009 Dec;54(12):1717-26.

Summary & Review

- Spirometry methods & devices
  - Indications & contraindications for spirometry
  - Spirometry devices
  - Procedures
- Spirometry interpretation
  - FVC curves
  - FVC parameters
  - Values for FEV_1 / FVC

Summary & Review

- Flow-volume loops
  - Restriction
  - Variable intrathoracic obstruction
  - Variable extrathoracic obstruction
  - Fixed large airway obstruction
- Airway resistance studies - gold standard
  - Indications
  - Procedure
  - Parameters & interpretation

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