



# **Lung Volumes**

# **Pulmonary Function Test**

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## Introduction

Lung volumes are among the most clinically important measurements in respiratory physiology. They characterize the mechanical behavior of the respiratory system and provide objective, quantifiable data that guide diagnosis, prognosis, and management across a broad spectrum of pulmonary and critical care conditions. From the bedside assessment of a ventilated patient in intensive care to the outpatient spirometry of a patient with suspected COPD, lung volume measurements form the cornerstone of respiratory evaluation.

John Hutchinson's introduction of the spirometer in 1846 established vital capacity (VC) as a measurable quantity. Subsequent developments in body plethysmography and gas dilution techniques expanded our ability to measure previously inaccessible volumes such as the residual volume (RV) and functional residual capacity (FRC). Assessment of respiratory muscle strength through Maximum Inspiratory Pressure (MIP/P<sub>I</sub>max) and Maximum Expiratory Pressure (MEP/P<sub>E</sub>max) further extended the clinical toolkit.

This chapter reviews the four primary lung volumes (TV, IRV, ERV, RV) and four derived capacities (TLC, VC, FRC, IC). Measurement techniques including spirometry, body plethysmography, gas dilution, CT volumetry, MIP, and MEP are detailed with device schematics. Clinical interpretation of abnormal lung volumes in obstructive and restrictive disease is presented with corrected, physiologically accurate flow-volume loops. A detailed section covers lung volumes in mechanical ventilation: lung-protective strategies, PEEP optimization, auto-PEEP management, pressure-volume relationships, and VILI mechanisms. Reference values are based on GLI-2012 equations with ATS/ERS 2022 standardization guidance.

Today, international standards from the American Thoracic Society (ATS) and European Respiratory Society (ERS), most recently updated in 2022, govern all these measurements.

## Definitions and Classification

Pulmonary function is characterized by four primary lung volumes and four derived lung capacities. A capacity is the sum of two or more volumes. None of the four volumes overlap; together they sum to the Total Lung Capacity (TLC).

### The Four Primary Lung Volumes

Table 1. The Four Primary Lung Volumes. Values for healthy adult male (~175 cm, 25 years). Female values ~20-25% lower. PBW = Predicted Body Weight.

Volume	Abbrev.	Definition	Normal (Male)	Clinical Significance
Tidal Volume	TV	Volume inhaled or exhaled during normal quiet breathing	~500 mL	Basis for ventilator settings (6 mL/kg PBW in ARDS)
Inspiratory Reserve Volume	IRV	Max additional volume above normal tidal inspiration	~3,000 mL	Reduced in restriction and hyperinflation
Expiratory Reserve Volume	ERV	Max additional volume expelled beyond normal tidal expiration	~1,200 mL	Markedly reduced in obesity and supine position
Residual Volume	RV	Volume remaining after maximum forced exhalation; cannot be measured by spirometry alone	~1,200 mL	Elevated in gas trapping (COPD); requires plethysmography/gas dilution

## The Four Lung Capacities

Table 2: The Four Derived Lung Capacities. LLN = Lower Limit of Normal (5th percentile)

Capacity	Abbrev.	Components	Normal	Clinical Use
Total Lung Capacity	TLC	TV + IRV + ERV + RV	~6.0 L	Gold standard for restriction (TLC < LLN)
Vital Capacity	VC	TV + IRV + ERV	~4.7 L	Reflects muscle strength and lung/chest wall mechanics
Inspiratory Capacity	IC	TV + IRV	~3.5 L	Dynamic hyperinflation marker; IC/TLC < 0.25 predicts COPD mortality
Functional Residual Capacity	FRC	ERV + RV	~2.4 L	Equilibrium point of respiratory system; O <sub>2</sub> reservoir during apnea

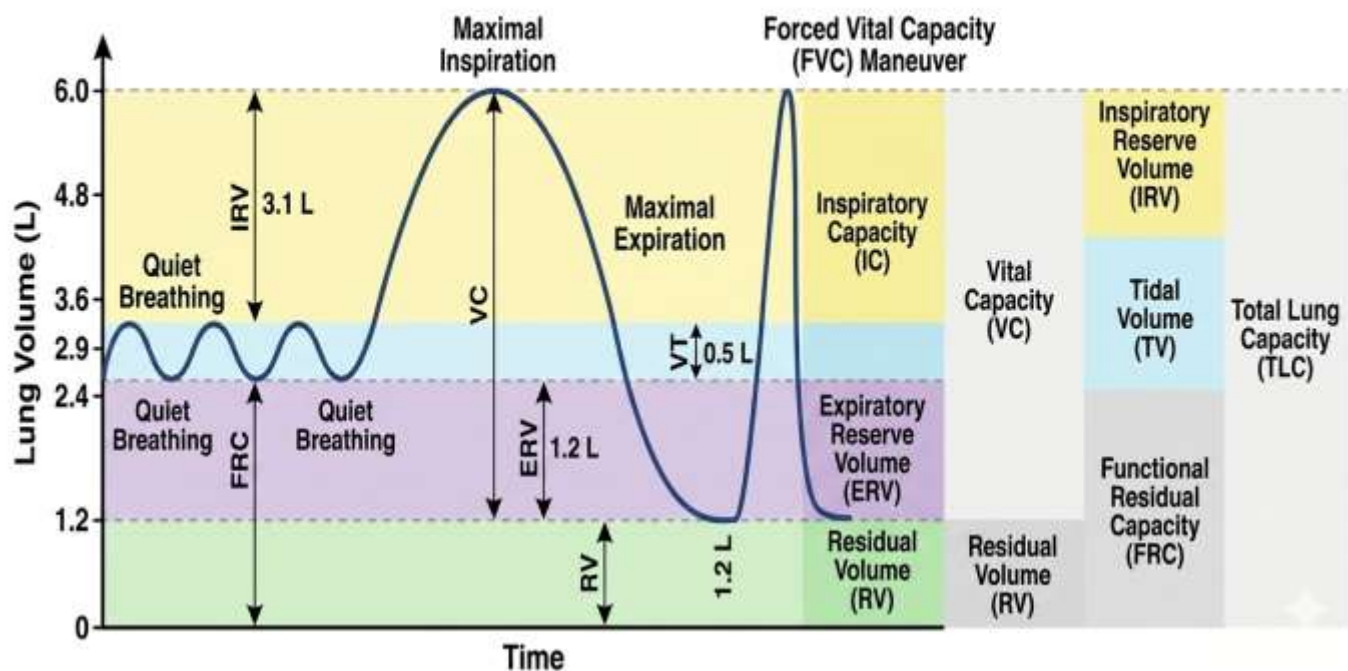


Figure 1: Spirogram showing all four primary lung volumes and capacities. Quiet breathing, maximal maneuvers, and forced VC maneuver illustrated. RV cannot be measured by spirometry.

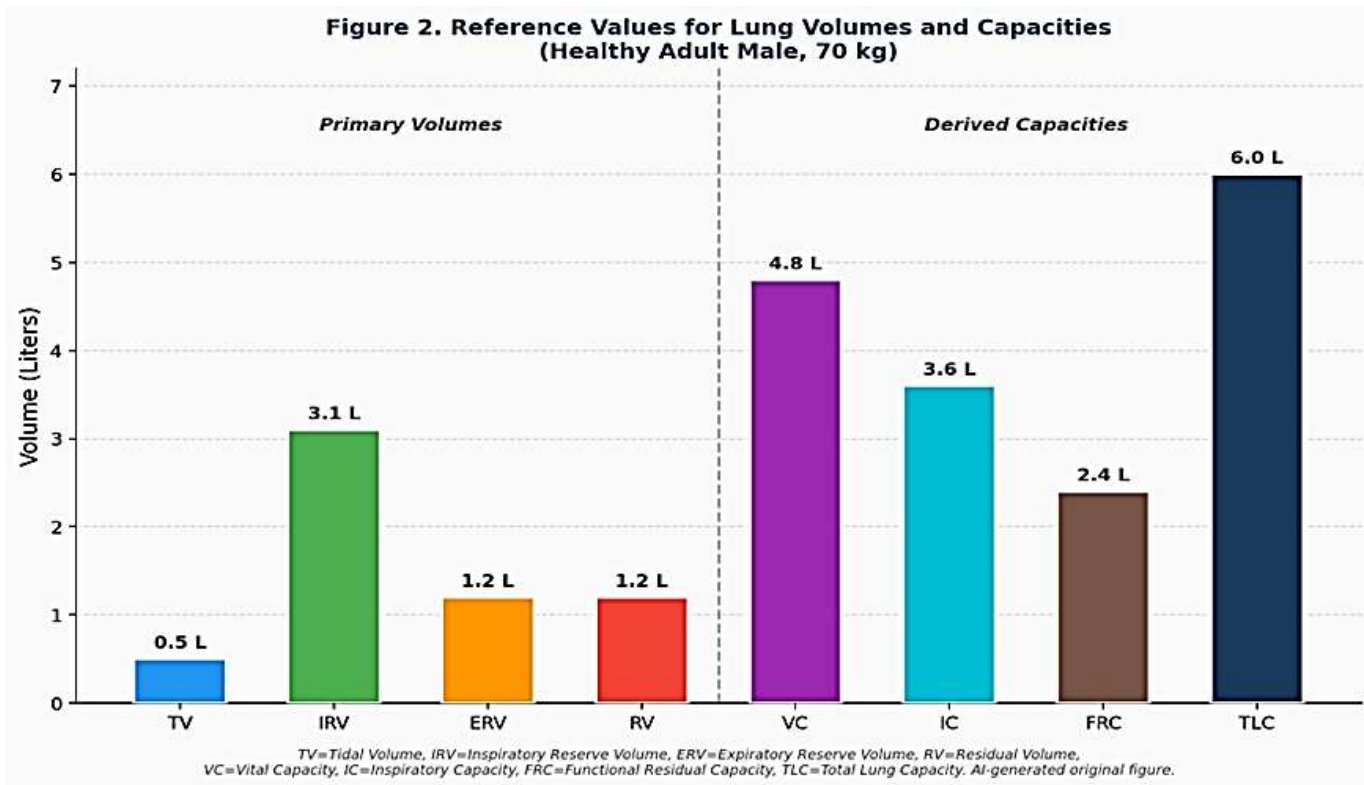


Figure 2: Reference values for the four primary volumes and four derived capacities (healthy adult male).

## Physiological Basis of Lung Volumes

### Static Mechanics and the Balance of Forces

At FRC, the respiratory system is in mechanical equilibrium, the inward elastic recoil of the lungs exactly balances the outward recoil of the chest wall.

Lung compliance ( $C_L = \Delta V/\Delta P$ ) is  $\sim 200$  mL/cmH<sub>2</sub>O for the lungs alone, Chest wall compliance ( $C_{CW}$ )  $\sim 200$  mL/cmH<sub>2</sub>O resulting in  $\sim 100$  mL/cmH<sub>2</sub>O for the total respiratory system. Conditions that stiffen the lungs (fibrosis, ARDS, pulmonary edema) decrease compliance, reducing FRC and TLC. Emphysema destroys elastic tissue, increasing compliance and elevating FRC.

### Residual Volume and Airway Closure

RV cannot be directly measured because airways in dependent lung regions close before the chest wall reaches its minimum volume. This is called airway closure and occurs at the closing capacity. When closing capacity exceeds FRC (with aging, obesity, or supine positioning), airways close during normal tidal breathing, causing V/Q mismatch and hypoxemia. The RV/TLC ratio  $>35-40\%$  indicates gas trapping characteristic of obstructive disease.

### FRC as an Oxygen Reservoir

FRC serves as the oxygen reservoir during apnea. Pre-oxygenation with 100% FiO<sub>2</sub> for 3-5 minutes replaces nitrogen in the FRC with oxygen, extending safe apnea time from  $\sim 1-2$  minutes to 8-10 minutes in healthy individuals. Obese and critically ill patients have reduced FRC, shortening this window.

#### Clinical Pearl: FRC and Airway Management

- ✓ Pre-oxygenate  $\geq 3$  minutes with 100% O<sub>2</sub> before intubation to maximize O<sub>2</sub> reserve
- ✓ Obese patients: FRC reduced  $\leq 30\%$  supine, use ramped or semi-recumbent position
- ✓ HFNO or NIV during pre-oxygenation further increases FRC oxygen content
- ✓ Children desaturate faster than adults (smaller FRC relative to metabolic rate)

## Factors Affecting Lung Volumes

### Age, Sex, Height, Ethnicity

Lung volumes peak around age 25 then decline progressively. FVC declines ~25-30 mL/year (men) and ~20-25 mL/year (women). TLC is relatively preserved with aging while RV increases. Males have ~20-25% larger lung volumes than females of the same height. Height is the strongest single predictor of lung volumes. The GLI-2012 multi-ethnic equations are the current international standard providing continuous predictions and Lower Limits of Normal (LLN = 5th percentile, Z-score  $\leq -1.645$ ).

A 2023 ATS statement highlighted that applying fixed race corrections may perpetuate health disparities by systematically lowering expected values for minority patients. The field is moving toward race-neutral reference equations.

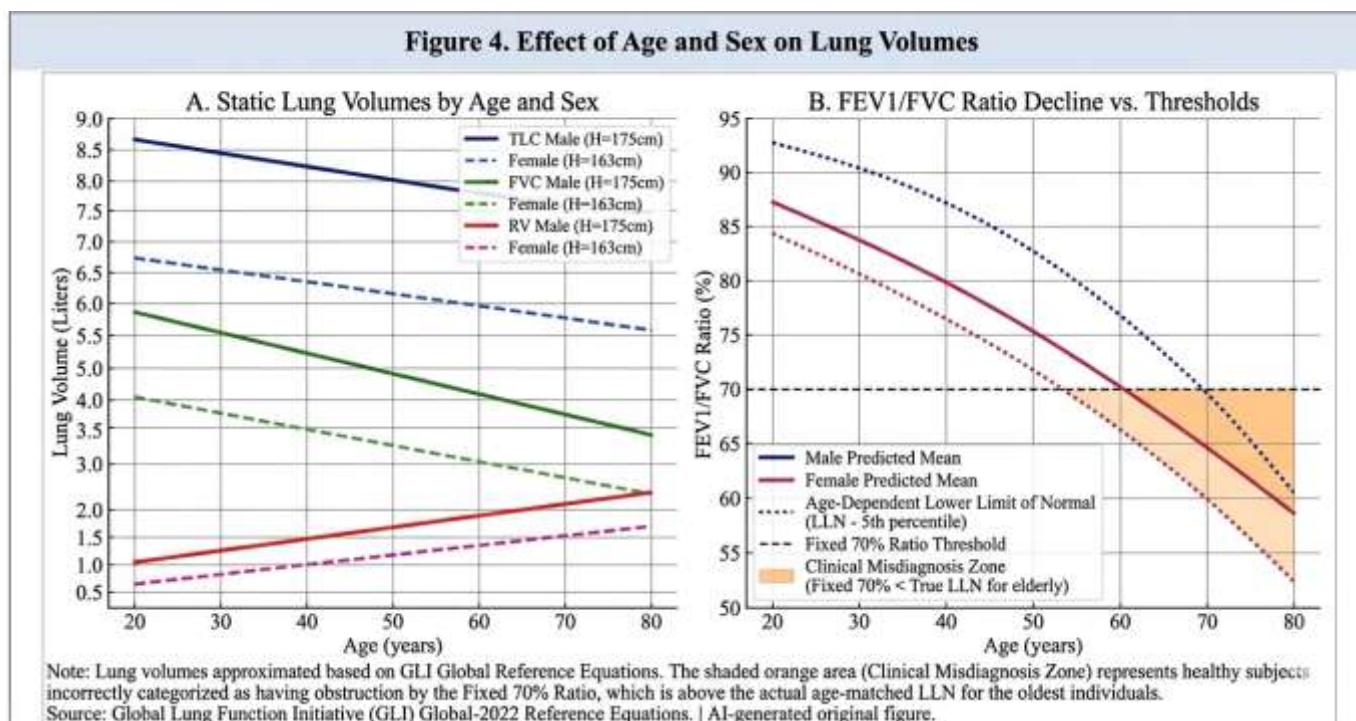


Figure 4: Left: Age-related changes in TLC, FVC, and RV by sex. Right: Age-related FEV<sub>1</sub>/FVC ratio decline. Fixed 70% threshold may over-diagnose obstruction in elderly. Based on approximate GLI-2012 equations.

**Body Position**

Table 3: Effect of Body Position on FRC. PFT = Pulmonary Function Test; ICU = Intensive Care Unit.

Position	FRC Change	Clinical Implication
Upright (sitting/standing)	Baseline	Optimal for PFT; maximizes FRC and gas exchange
Semi-recumbent (30-45°)	-0.3 to -0.5 L	Standard ICU positioning; reduces aspiration risk
Supine	-0.5 to -1.0 L	Increased shunt; airway closure more likely in obesity
Prone	Variable; FRC improves in ARDS	Redistributes ventilation; reduces dorsal atelectasis (PROSEVA)
Trendelenburg	-1.0 to -1.5 L	Significant FRC reduction; avoid in respiratory failure
Obesity supine	-30 to -50% of upright FRC	Closing capacity may exceed FRC; higher PEEP required

## Measurement of Lung Volumes

### Spirometry

Spirometry is the most widely available standardized pulmonary function test. It directly measures FVC, FEV<sub>1</sub>, FEF<sub>25-75</sub>, PEF, TV, IRV, ERV, and slow VC. Critically, spirometry cannot measure RV, FRC, or TLC. ATS/ERS 2022 criteria require  $\geq 3$  acceptable maneuvers with the best two FVC and FEV<sub>1</sub> values agreeing within 150 mL.



Figure 5A: Spirometer schematic diagram. Measures dynamic lung volumes and flows. Cannot measure RV, FRC, or TLC. ATS/ERS 2022 standardized.

### Body Plethysmography

Body plethysmography is the gold standard for measuring absolute lung volumes including FRC, RV, and TLC. The patient sits in a sealed booth and pants against a closed shutter.

Boyle's Law ( $P_1V_1 = P_2V_2$ ) allows calculation of thoracic gas volume (TGV) from changes in box pressure ( $P_b$ ) and mouth pressure ( $P_m$ ). Key advantage: it measures all intrathoracic gas including trapped air, making it superior to gas dilution in obstructive disease.



Figure 5B: Body plethysmograph schematic. Patient in sealed booth pants against closed shutter. Boyle's Law calculates TGV. Gold standard for TLC, FRC, RV.

## Gas Dilution Methods

In helium dilution (closed circuit), a known helium concentration equilibrates with the FRC; its dilution yields the lung volume ( $FRC = V_1 \times (C_1 - C_2) / C_2$ ).

In nitrogen washout (open circuit), the patient breathes 100% O<sub>2</sub> until end-tidal N<sub>2</sub> falls below 1%; total expired N<sub>2</sub> volume yields FRC.

Both measure only communicating airspaces and may underestimate TLC in obstructive disease.

Multiple-breath nitrogen washout (MBNW) additionally provides the Lung Clearance Index (LCI), sensitive to early small airway disease.



Figure 5C: Helium dilution (left) and nitrogen washout (right) systems. Both measure FRC, RV, and TLC in communicating airways only. N<sub>2</sub> washout provides Lung Clearance Index (LCI).

### **MIP and MEP (Respiratory Muscle Pressure)**

Maximum Inspiratory Pressure (MIP / P<sub>I</sub>max) and Maximum Expiratory Pressure (MEP / P<sub>E</sub>max) are volitional measures of respiratory muscle strength. They are essential for assessing neuromuscular disease, ventilator weaning readiness, and cough effectiveness, and are directly linked to lung volumes because respiratory muscle force-generating capacity depends on the length-tension relationship at the measurement lung volume.

MIP / P<sub>I</sub>max: Measured from Residual Volume

The patient exhales to RV, then inhales maximally against a completely occluded airway for  $\geq 1$  second. At RV, the diaphragm and inspiratory muscles are at their optimal length for force generation. The most negative pressure generated is recorded.

- Normal values: Males -75 to -100 cmH<sub>2</sub>O; Females -50 to -75 cmH<sub>2</sub>O
- Weaning failure threshold: MIP less negative than -20 to -30 cmH<sub>2</sub>O
- High risk for respiratory failure: MIP less negative than -15 cmH<sub>2</sub>O
- Trend over days is more predictive of weaning success than a single value

MEP / PEmax: Measured from Total Lung Capacity

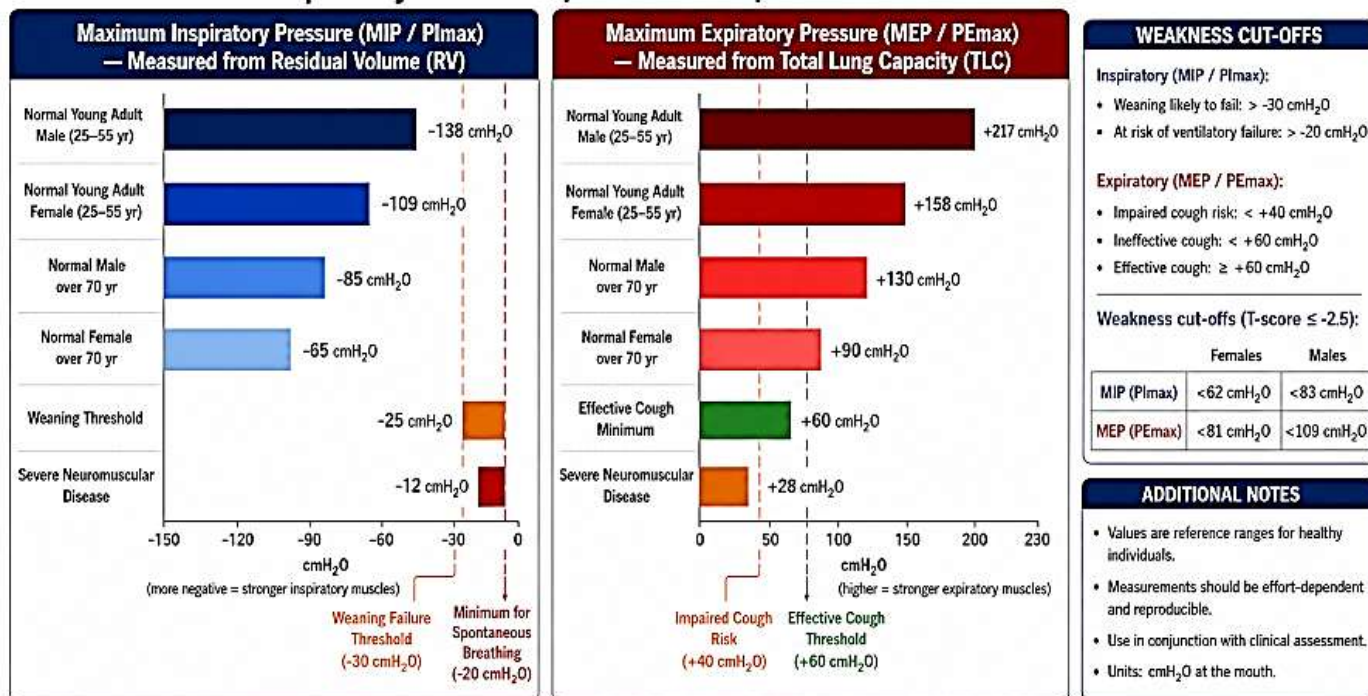
The patient inhales to TLC, then exhales forcefully against a completely occluded airway for  $\geq 1$  second. At TLC, the expiratory muscles (abdominals, internal intercostals) are at optimal length.

- Normal values: Males +100 to +140 cmH<sub>2</sub>O; Females +70 to +100 cmH<sub>2</sub>O
- Effective cough threshold: MEP  $\geq 60$  cmH<sub>2</sub>O
- Impaired cough / aspiration risk: MEP < 45 cmH<sub>2</sub>O
- Used to monitor disease progression in ALS, GBS, myasthenia gravis



Figure 5D: MIP (left) and MEP (right) manometer schematic diagrams. MIP measured from RV (optimal diaphragm length); MEP from TLC (optimal expiratory muscle length). Report best of  $\geq 3$  efforts within 20 cmH<sub>2</sub>O.

### Maximum Respiratory Pressures (MIP and MEP): Reference Values and Clinical Thresholds



Reference: Lista-Paz et al. (2023) large European cohort + ATS/ERS Statement on Respiratory Muscle Testing (2002).  
 Values should be interpreted using laboratory-specific reference equations when possible.  
 These values support clinical decision-making in the context of the individual patient.

Figure 5E: MIP and MEP reference values and clinical thresholds. Based on Black & Hyatt 1969; ATS/ERS Respiratory Muscle Testing Statement 2002.

Table 4: MIP and MEP Reference Values and Clinical Thresholds. NM = Neuromuscular; RV = Residual Volume; TLC = Total Lung Capacity. ATS/ERS: best of ≥ 3 reproducible efforts within 20 cmH<sub>2</sub>O.

Parameter	Measured From	Normal Male	Normal Female	Key Threshold	Indications
MIP / PImax	Residual Volume (RV)	-75 to -100 cmH <sub>2</sub> O	-50 to -75 cmH <sub>2</sub> O	Weaning fail if < -20 to -30 High risk if < -15	Ventilator weaning; NM disease; ICU
MEP / PEmax	Total Lung Capacity (TLC)	+100 to +140 cmH <sub>2</sub> O	+70 to +100 cmH <sub>2</sub> O	Cough: ≥60 cmH <sub>2</sub> O Impaired: <45	Cough assessment; NM disease; secretion clearance

## Lung Volumes in Pulmonary Disease

### Obstructive Pattern

Obstructive disease (COPD, asthma, bronchiectasis) is defined by  $FEV_1/FVC$  below the LLN. Full lung volumes demonstrate:

- Increased TLC (hyperinflation from air trapping and loss of elastic recoil in COPD)
- Markedly increased RV (gas trapping); RV/TLC ratio > 40-55% in severe COPD
- Increased FRC (shifted equilibrium point due to reduced elastic recoil)
- Reduced VC and FVC (from gas trapping reducing the exhaled volume)
- Scooped (deeply concave) expiratory limb on flow-volume loop — the hallmark
- IC/TLC ratio < 0.25 strongly predicts mortality in COPD (Casanova et al., 2005)

### Restrictive Pattern

Restriction is defined by TLC below the LLN. Causes: intrinsic (IPF, sarcoidosis) or extrinsic (chest wall, NM disease, obesity). Pattern:

- Reduced TLC (the defining criterion requires plethysmography or gas dilution)
- Reduced FVC and VC proportionally
- Preserved or elevated  $FEV_1/FVC$  ratio (> 80%) no airflow limitation
- Near-normal or high peak expiratory flow relative to FVC
- Nearly linear (non-scooped) expiratory limb on flow-volume loop

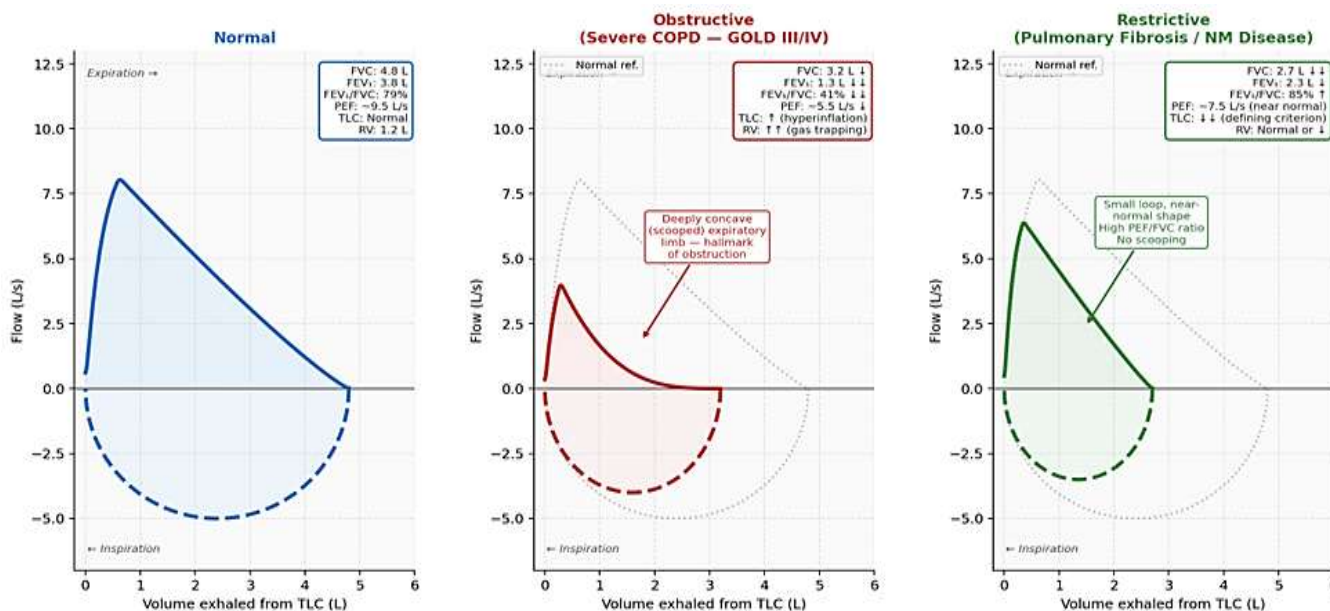
#### Warning: FVC Reduction Does NOT Equal Restriction

- ✓ A reduced FVC alone is insufficient to diagnose restriction
- ✓ Severe COPD with gas trapping produces pseudo-restriction (low FVC with elevated  $FEV_1/FVC$ )
- ✓ True restriction requires  $TLC < LLN$  by plethysmography or gas dilution
- ✓ Always measure TLC before diagnosing a restrictive defect

**Interpretation Table**

Table 5: Lung volume interpretation patterns. LLN = Lower Limit of Normal; TLC = Total Lung Capacity; FRC = Functional Residual Capacity; RV = Residual Volume.

Parameter	Normal	Obstructive	Restrictive	Mixed
FEV <sub>1</sub> /FVC	≥LLN (~79%)	↓ (<LLN)	Normal or ↑ (>80%)	↓ (<LLN)
FVC	≥LLN	Normal or ↓	↓	↓
TLC	≥LLN	Normal or ↑	↓ (<LLN)	↓ (<LLN)
RV	Normal	↑↑ (gas trapping)	Normal or ↓	Variable
RV/TLC	<35%	↑ (> 40-55%)	Normal	Variable
FRC	Normal	↑ (hyperinflation)	↓	Variable
Flow-volume loop	Normal shape	Scooped/concave	Small, non-scooped, high PEF/FVC	Scooped + small



Key: Obstructive = deeply concave/scooped expiratory limb, reduced FEV<sub>1</sub>/FVC, elevated TLC. Restrictive = small loop, near-normal loop shape, PRESERVED or elevated FEV<sub>1</sub>/FVC ratio, no scooping. Reference: Pellegrino R et al. ERSATS Standardisation of Spirometry. Eur Respir J 2005; Miller MR et al. Standardisation of spirometry. Eur Respir J 2005. AI-generated original figure. CC BY-NC.

Figure 6: Flow-Volume loops in Normal (left), Obstructive (middle), Restrictive (right). Obstructive: deeply concave expiratory limb, reduced FEV<sub>1</sub>/FVC, elevated TLC. Restrictive: smaller loop, near-normal shape, elevated FEV<sub>1</sub>/FVC, no scooping. Gray dotted = normal reference.

## Reference Values

Table 6: Reference values based on GLI-2012 equations

Parameter	Male 25y, 175cm	Female 25y, 163cm	LLN / Threshold
FVC (L)	5.00	3.60	Z-score < -1.645
FEV <sub>1</sub> (L)	4.10	3.00	Z-score < -1.645
FEV <sub>1</sub> /FVC (%)	82%	83%	Z-score < -1.645 (≥ 70% historically)
TLC (L)	6.60	4.90	Z-score < -1.645 = restriction
FRC (L)	3.30	2.50	Context-dependent
RV (L)	1.70	1.30	Z-score > +1.645 = elevated
RV/TLC (%)	26%	27%	>35-40% = gas trapping
MIP / P <sub>I</sub> max	-75 to -100 cmH <sub>2</sub> O	-50 to -75 cmH <sub>2</sub> O	Weaning fail: > -20 to -30
MEP / P <sub>E</sub> max	+100 to +140 cmH <sub>2</sub> O	+70 to +100 cmH <sub>2</sub> O	Effective cough: ≥ 60

## Lung Volumes in Mechanical Ventilation

### Tidal Volume and Lung-Protective Ventilation

The ARDSNet ARMA trial (2000) demonstrated that TV of 6 mL/kg predicted body weight (PBW) reduced 28-day ARDS mortality from 39.8% to 31.0% vs. 12 mL/kg PBW (ARR 8.8%, P = 0.007).

Current guidelines target TV 4-8 mL/kg PBW, plateau pressure  $\leq 30$  cmH<sub>2</sub>O, and driving pressure ( $\Delta P = P_{plat} - PEEP$ )  $\leq 15$  cmH<sub>2</sub>O.

#### PBW Formula

✓ Males:  $PBW (kg) = 50 + 0.91 \times [\text{height (cm)} - 152.4]$

✓ Females:  $PBW (kg) = 45.5 + 0.91 \times [\text{height (cm)} - 152.4]$

✓ Lung size correlates with height/sex NOT actual body weight

✓ Using actual weight in obese patients delivers dangerously excessive TV and causes VILI

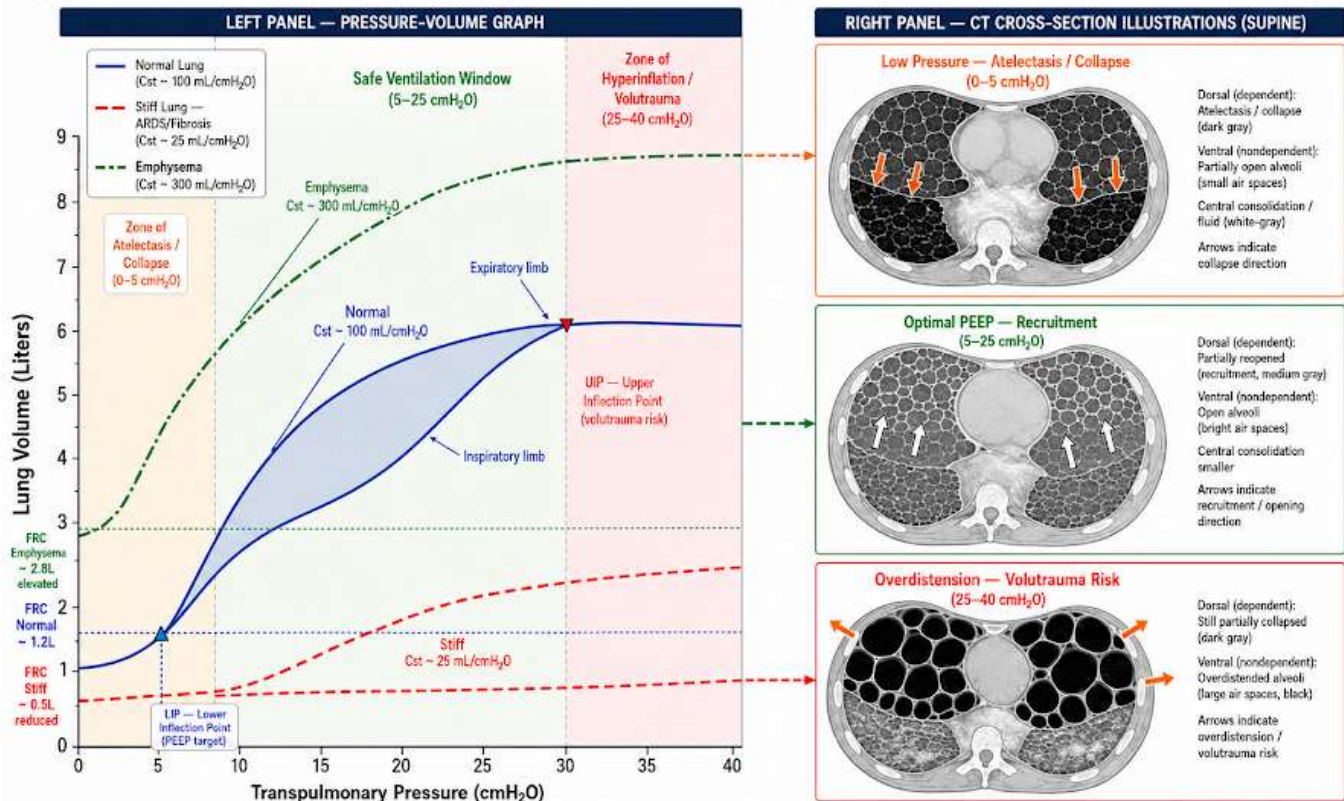
### FRC, PEEP, and End-Expiratory Lung Volume

PEEP maintains positive airway pressure at end-expiration, increasing end-expiratory lung volume (EELV) above the patient's intrinsic FRC. Each cmH<sub>2</sub>O of PEEP increases EELV by ~30-50 mL in healthy lungs. Benefits include alveolar recruitment, improved V/Q matching, reduced shunt, and reduced work of breathing in auto-PEEP patients.

Table 7: PEEP Titration Strategies. LIP = Lower Inflection Point;  $\Delta P$  = Driving Pressure; Ptp = Transpulmonary Pressure; EIT = Electrical Impedance Tomography.

PEEP Strategy	Method	Target	Evidence
ARDSNet FiO <sub>2</sub> /PEEP tables	Step-up PEEP based on required FiO <sub>2</sub>	SpO <sub>2</sub> 88-95%; PaO <sub>2</sub> $\geq 55$ mmHg	High (RCT)
Driving pressure minimization	Titrate PEEP to minimize $\Delta P$ at fixed TV	$\Delta P \leq 15$ cmH <sub>2</sub> O	Moderate
P-V curve / LIP method	Set PEEP 2 cmH <sub>2</sub> O above LIP	Above alveolar closing pressure	Moderate
Esophageal manometry	Maintain positive end-expiratory transpulmonary pressure	Ptp(ce) $\geq 0$ cmH <sub>2</sub> O	Moderate
Electrical Impedance Tomography (EIT)	Real-time regional ventilation monitoring	Minimize ventilation heterogeneity	Emerging

Figure 7. Pressure-Volume (P-V) Curves: Lung Compliance, Recruitment, and Regional Lung Behavior in Normal, ARDS/Fibrosis, and Emphysema



Reference: Gattinoni L et al. *Am Rev Respir Dis* 1987; Harris RS. *Respir Care* 2005; Gattinoni L et al. *N Engl J Med* 2006.  
 Cst = Static Compliance; LIP = Lower Inflection Point; UIP = Upper Inflection Point; FRC = Functional Residual Capacity; PEEP = Positive End-Expiratory Pressure.

Figure 7: Corrected Pressure-Volume (P-V) Curves. Stiff lung (ARDS/fibrosis): flat curve, low Cst (~25-30 mL/cmH<sub>2</sub>O), requiring high pressure for small volume gain. Normal: sigmoid curve, Cst ~200 mL/cmH<sub>2</sub>O. Emphysema: steep curve, high Cst (~380 mL/cmH<sub>2</sub>O), elevated FRC and TLC

### Respiratory System Compliance

$$CRS = \text{Tidal Volume} / (\text{Plateau Pressure} - \text{PEEP}) = TV / (P_{\text{plat}} - \text{PEEP})$$

Normal CRS ≈ 50-100 mL/cmH<sub>2</sub>O in mechanically ventilated patients (lower than spontaneously breathing due to supine position). In ARDS: typically, 20-40 mL/cmH<sub>2</sub>O.

Driving pressure ( $\Delta P = TV/CRS$ ) indirectly reflects mechanical stress on the aerated lung and is the strongest predictor of ARDS mortality.

### Lung Compliance

CL = Tidal Volume / Transpulmonary pressure (PTP) directly reflects mechanical stress on the lung

### **Auto-PEEP and Dynamic Hyperinflation**

Auto-PEEP (intrinsic PEEP, PEEPi) is the positive alveolar pressure at end-expiration exceeding set extrinsic PEEP, resulting from incomplete lung emptying before the next breath. It causes progressive gas stacking (dynamic hyperinflation), particularly dangerous in ventilated COPD and severe asthma.

#### Causes

- High respiratory rate (insufficient expiratory time)
- Short I:E ratio (prolonged inspiration, shortened expiration)
- High tidal volume (more volume to exhale per breath)
- High airway resistance: bronchospasm, secretions, small/kinked ETT
- Reduced expiratory flow from obstructive lung disease (most common ICU cause)

#### Detection

Quantitative: End-Expiratory Hold (EEH) maneuver, occlude expiratory valve for 3-5 seconds while patient is apneic. Total PEEP = set PEEP + auto-PEEP.

Qualitative: on the volume-time waveform, a rising end-expiratory baseline indicates progressive gas stacking. On flow-time waveform, expiratory flow does not return to zero before the next breath.

Figure 8. Lung Volume and Flow Waveforms During Volume-Controlled Ventilation (VCV)

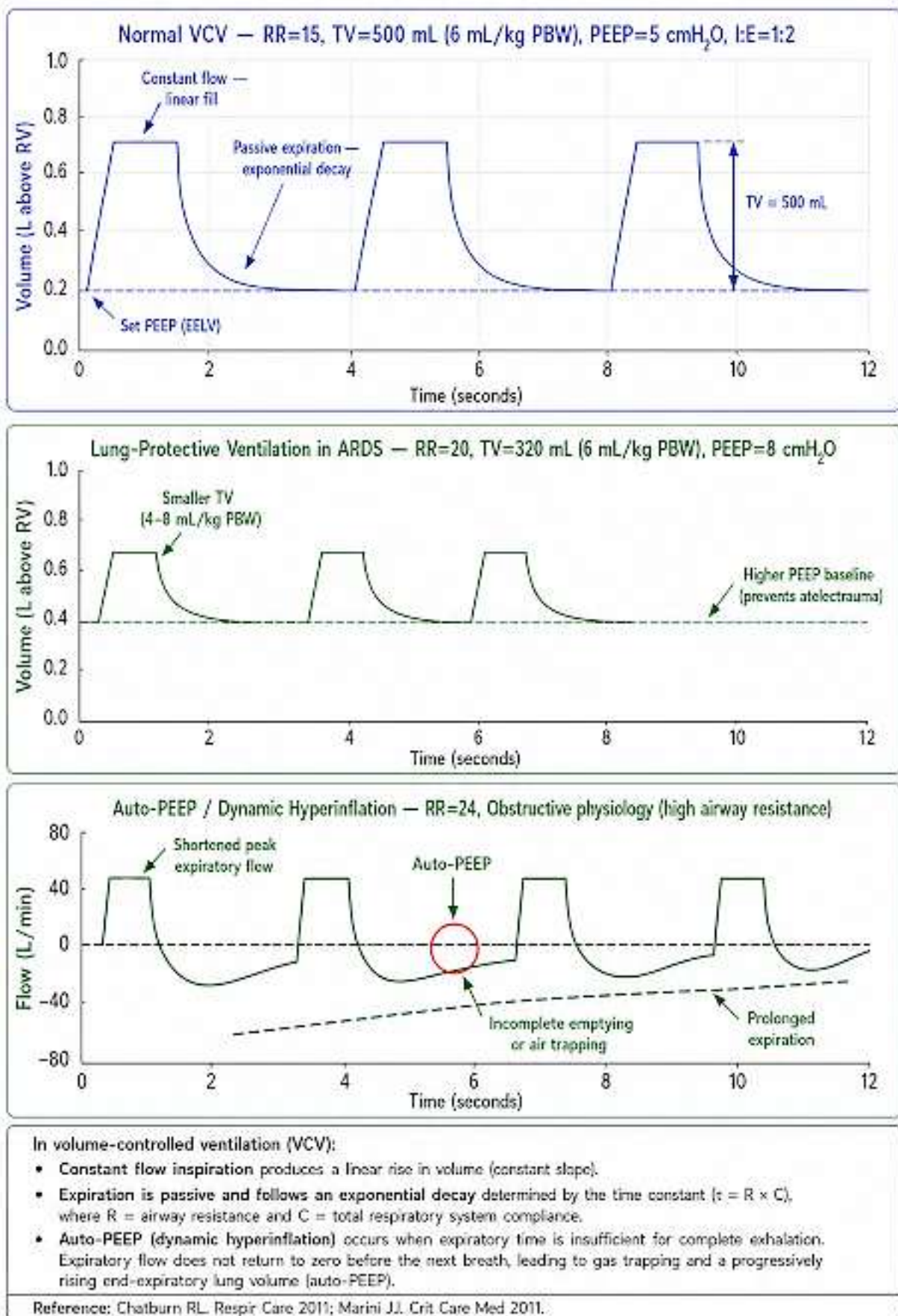


Figure 8: Volume-time waveforms during VCV. Top (blue): normal — linear fill, exponential decay, stable EELV. Middle (green): lung-protective ARDS — smaller TV, higher PEEP baseline. Bottom (red): auto-PEEP/dynamic hyperinflation — rising end-expiratory volume (red triangles) = progressive gas stacking above set PEEP

#### Management of Auto-PEEP

Table 8: Management Strategies for Auto-PEEP. PEEP<sub>i</sub> = Intrinsic PEEP; T<sub>i</sub> = Inspiratory Time; T<sub>e</sub> = Expiratory Time; SABA = Short-Acting Beta Agonist; ETT = Endotracheal Tube.

Strategy	Mechanism	Implementation
Reduce respiratory rate	Prolongs expiratory time (T <sub>e</sub> )	Decrease rate 2-4 breaths/min; accept permissive hypercapnia (pH >7.20)
Reduce tidal volume	Less volume to exhale per breath	Target 4-6 mL/kg PBW; monitor PaCO <sub>2</sub>
Shorten T <sub>i</sub> / increase flow	Maximizes T <sub>e</sub>	I:E 1:3 to 1:5; inspiratory flow 80-100 L/min
Treat bronchospasm	Reduces airway resistance, improves expiratory flow	SABA nebulization; systemic corticosteroids; IV Mg <sup>2+</sup>
Apply extrinsic PEEP (50-80% of PEEP <sub>i</sub> )	Reduces inspiratory threshold load without worsening hyperinflation	Measure PEEP <sub>i</sub> first; apply 50-80% of measured PEEP <sub>i</sub>
Emergency disconnect (hemodynamic collapse)	Decompresses trapped gas	Disconnect ETT for 10-30 sec; expect dramatic BP improvement

**VILI Mechanisms**

Table 9: Mechanisms of Ventilator-Induced Lung Injury (VILI). TV = Tidal Volume; PBW = Predicted Body Weight; Pplat = Plateau Pressure; EELV = End-Expiratory Lung Volume; NMB = Neuromuscular Blockade.

Mechanism	Definition	Prevention
Volutrauma	Overdistension injury from excessive TV; the dominant VILI mechanism	TV $\leq$ 6 mL/kg PBW; Pplat $\leq$ 30; driving pressure $\leq$ 15
Barotrauma	Gross air leak (pneumothorax) from excessive pressure	Limit Pplat; treat auto-PEEP; avoid excessive PEEP
Atelectrauma	Cyclic alveolar collapse and re-expansion generating shear stress	Adequate PEEP to maintain EELV above closing capacity
Biotrauma	Mechanical stress triggers cytokine release (IL-6, IL-8, TNF- $\alpha$ ) and systemic organ injury	Lung-protective ventilation; prone positioning; NMB in severe ARDS
Rheotrauma	Injury from high inspiratory flow rates and shear stress	Control inspiratory flow; avoid turbulent high-flow delivery

**Key Principles of Lung-Protective Ventilation**

- ✓ TV 4-8 mL/kg PBW (start at 6 mL/kg) based on predicted, NOT actual body weight
- ✓ Plateau pressure (Pplat)  $\leq$  30 cmH<sub>2</sub>O
- ✓ Driving pressure ( $\Delta P = P_{plat} - PEEP$ )  $\leq$  15 cmH<sub>2</sub>O — strongest mortality predictor
- ✓ Adequate PEEP to prevent cyclic atelectasis (atelectrauma)
- ✓ Accept permissive hypercapnia (pH > 7.20) rather than increasing TV
- ✓ Prone positioning  $\geq$  16 hr/day for P/F < 150 (PROSEVA trial, Guérin 2013)
- ✓ Consider early NMB (cisatracurium) for P/F < 150 in first 48 hours

## **Conclusion**

Lung volumes are the structural and functional currency of respiratory physiology. The four primary volumes and four capacities, measured by spirometry, body plethysmography, gas dilution, and respiratory muscle pressure testing (MIP/MEP), provide complementary and essential information for diagnosing and monitoring pulmonary and neuromuscular disease. Accurate interpretation requires appropriate GLI-2012 reference equations, understanding of measurement limitations, and awareness of clinical context.

In mechanical ventilation, lung volume concepts directly translate into life-saving interventions: PBW-based tidal volume selection, driving pressure optimization, PEEP titration to maintain EELV above closing capacity, and recognition and management of auto-PEEP and dynamic hyperinflation. For respiratory therapy specialists at Dr. Sulaiman Al Habib Medical Group and across the region, mastery of these principles is foundational to delivering evidence-based, patient-centered respiratory care.

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