Pathophysiology of Respiratory Failure and Use of Mechanical Ventilation

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Definition

- Respiratory failure is a syndrome of inadequate gas exchange due to dysfunction of one or more essential components of the respiratory system:
  - Chest wall (including pleura and diaphragm)
  - Airways
  - Alveolar–capillary units
  - Pulmonary circulation
  - Nerves
  - CNS or Brain Stem

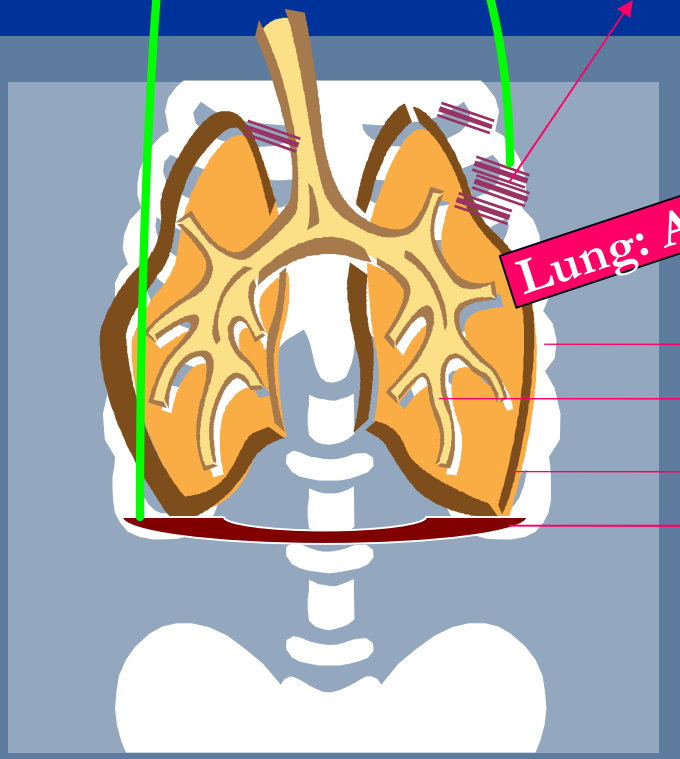
Respiratory System

Brain

Spinal cord

Nerves

Intercostal muscles



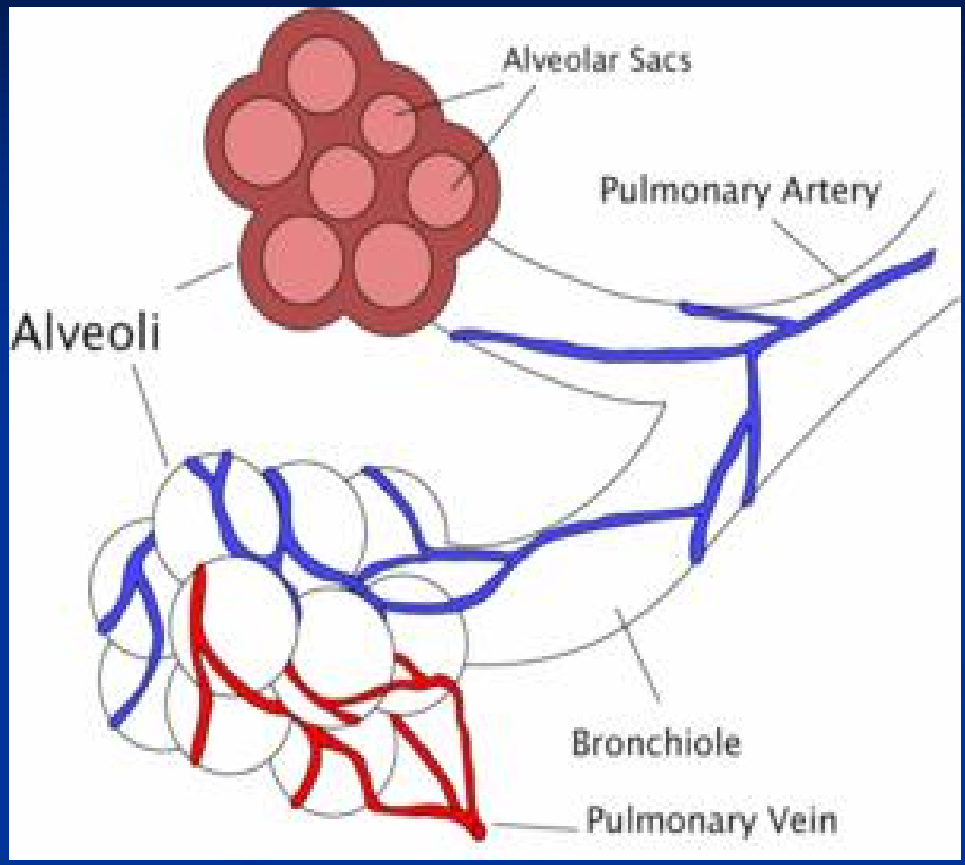
Lung: Alveolar Unit

Chest wall

Airway

Pleura

Diaphragm



Epidemiology

- Incidence: about 360,000 cases per year in the United States
- 36% die during hospitalization
- Morbidity and mortality rates increase with age and presence of comorbidities

Classification

- Type I or Hypoxemic (PaO2 <60 at sea level): *Failure of oxygen exchange*
  - Increased shunt fraction (Q_S/Q_T)
    - Due to alveolar flooding
    - Hypoxemia refractory to supplemental oxygen
- Type II or Hypercapnic (PaCO2 >45): *Failure to exchange or remove carbon dioxide*
  - Decreased alveolar minute ventilation (V_A)
  - Often accompanied by hypoxemia that corrects with supplemental oxygen

Classification

- Type III Respiratory Failure: *Perioperative respiratory failure*
  - Increased atelectasis due to low functional residual capacity (FRC) in the setting of abnormal abdominal wall mechanics
    - Often results in type I or type II respiratory failure
    - Can be ameliorated by anesthetic or operative technique, posture, incentive spirometry, post-operative analgesia, attempts to lower intra-abdominal pressure
- Type IV Respiratory Failure: S*hock*
  - Type IV describes patients who are intubated and ventilated in the process of resuscitation for shock
    - Goal of ventilation is to stabilize gas exchange and to unload the respiratory muscles, lowering their oxygen consumption

Classification

- Respiratory failure may be
  - Acute
  - Chronic
  - Acute on chronic
    - E.g.: acute exacerbation of advanced COPD

Pathophysiology: Mechanisms

- Hypoxemic failure
  - Ventilation/Perfusion (V/Q) mismatch
  - Shunt
  - Exacerbated by low mixed venous O2 (SvO2)
- Hypercapnic failure
  - Decreased minute ventilation (MV) relative to demand
  - Increased dead space ventilation

Pathophysiology: Etiologic Categories

- Nervous system failure (Type II)
  - Central hypoventilation
  - Neuropathies
- Muscle (pump) failure (Type II)
  - Muscular dystrophies
  - Myopathies
- Neuromuscular transmission failure (Type II)
  - Myasthenia gravis
- Airway failure (Type II)
  - Obstruction
  - Dysfunction

Pathophysiology: Etiologic Categories

- Chest wall and pleural space failure (Type II)
  - Kyphoscoliosis
  - Morbid obesity
  - Pneumothorax
  - Hydrothorax
  - Hemothorax
- Alveolar unit failure (Type I)
  - Collapse
  - Flooding: edema, blood, pus, aspiration
  - Fibrosis
- Pulmonary vasculature failure (Type I)
  - Pulmonary embolism
  - Pulmonary hypertension

Causes

- Type I respiratory failure
  - Pneumonia
  - Cardiogenic pulmonary edema
    - Pulmonary edema due to increased hydrostatic pressure
  - Non-cardiogenic pulmonary edema
    - Pulmonary edema due to increased permeability
    - Acute lung injury (ALI)
    - Acute respiratory distress syndrome (ARDS)
  - Pulmonary embolism (see also type IV respiratory failure)
  - Atelectasis (see also type III respiratory failure)
  - Pulmonary fibrosis

Causes

- Type II respiratory failure
  - Central hypoventilation
  - Asthma
  - Chronic obstructive pulmonary disease (COPD)
    - Hypoxemia and hypercapnia often occur together
- *Neuromuscular and chest wall disorders
    - Myopathies
    - Neuropathies
    - Kyphoscoliosis
    - Myasthenia gravis
  - Obesity Hypoventilation Syndrome

Causes

- Type III respiratory failure
  - Inadequate post-operative analgesia, upper abdominal incision
  - Obesity, ascites
  - Pre-operative tobacco smoking
  - Excessive airway secretions
- Type IV respiratory failure
  - Cardiogenic shock
  - Septic shock
  - Hypovolemic shock

Diagnosis: History

- Sepsis suggested by fever, chills
- Pneumonia suggested by cough, sputum production, chest pain
- Pulmonary embolus suggested by sudden onset of shortness of breath or chest pain
- COPD exacerbation suggested by history of heavy smoking, cough, sputum production
- Cardiogenic pulmonary edema suggested by chest pain, paroxysmal nocturnal dyspnea, and orthopnea

Diagnosis: History

- Noncardiogenic edema suggested by the presence of risk factors including sepsis, trauma, aspiration, and blood transfusions
- Accompanying sensory abnormalities or symptoms of weakness may suggest neuromuscular respiratory failure; as would the history of an ingestion or administration of drugs or toxins.
- Additional exposure history may help diagnose asthma, aspiration, inhalational injury and some interstitial lung diseases

Diagnosis: Physical Findings

- Hypotension usually with signs of poor perfusion suggests severe sepsis or massive pulmonary embolus
- Hypertension usually with signs of poor perfusion suggests cardiogenic pulmonary edema
- Wheezing suggests airway obstruction:
  - Bronchospasm
  - Fixed upper or lower airway pathology
  - Secretions
  - Pulmonary edema (“cardiac asthma”)

Diagnosis: Physical Findings

- Stridor suggests upper airway obstruction
- Elevated jugular venous pressure suggests right ventricular dysfunction due to accompanying pulmonary hypertension
- Tachycardia and arrhythmias may be the cause of cardiogenic pulmonary edema

Diagnosis: Laboratory Workup

- ABG
  - Quantifies magnitude of gas exchange abnormality
  - Identifies type and chronicity of respiratory failure
- Complete blood count
  - Anemia may cause cardiogenic pulmonary edema
  - Polycythemia suggests may chronic hypoxemia
  - Leukocytosis, a left shift, or leukopenia suggestive of infection
  - Thrombocytopenia may suggest sepsis as a cause

Diagnosis: Laboratory Workup

- Cardiac serologic markers
  - Troponin, Creatine kinase- MB fraction (CK-MB)
  - B-type natriuretic peptide (BNP)
- Microbiology
  - Respiratory cultures: sputum/tracheal aspirate/broncheoalveolar lavage (BAL)
  - Blood, urine and body fluid (e.g. pleural) cultures

Diagnostic Investigations

- Chest radiography
  - Identify chest wall, pleural and lung parenchymal pathology; and distinguish disorders that cause primarily V/Q mismatch (clear lungs) vs. Shunt (intra-pulmonary shunt; with opacities present)
- Electrocardiogram
  - Identify arrhythmias, ischemia, ventricular dysfunction
- Echocardiography
  - Identify right and/or left ventricular dysfunction

Diagnostic Investigations

- Pulmonary function tests/bedside spirometry
  - Identify obstruction, restriction, gas diffusion abnormalities
  - May be difficult to perform if critically ill
- Bronchoscopy
  - Obtain biopsies, brushings and BAL for histology, cytology and microbiology
  - Results may not be available quickly enough to avert respiratory failure
  - Bronchoscopy may not be safe in the if critically ill

Respiratory Failure: Management

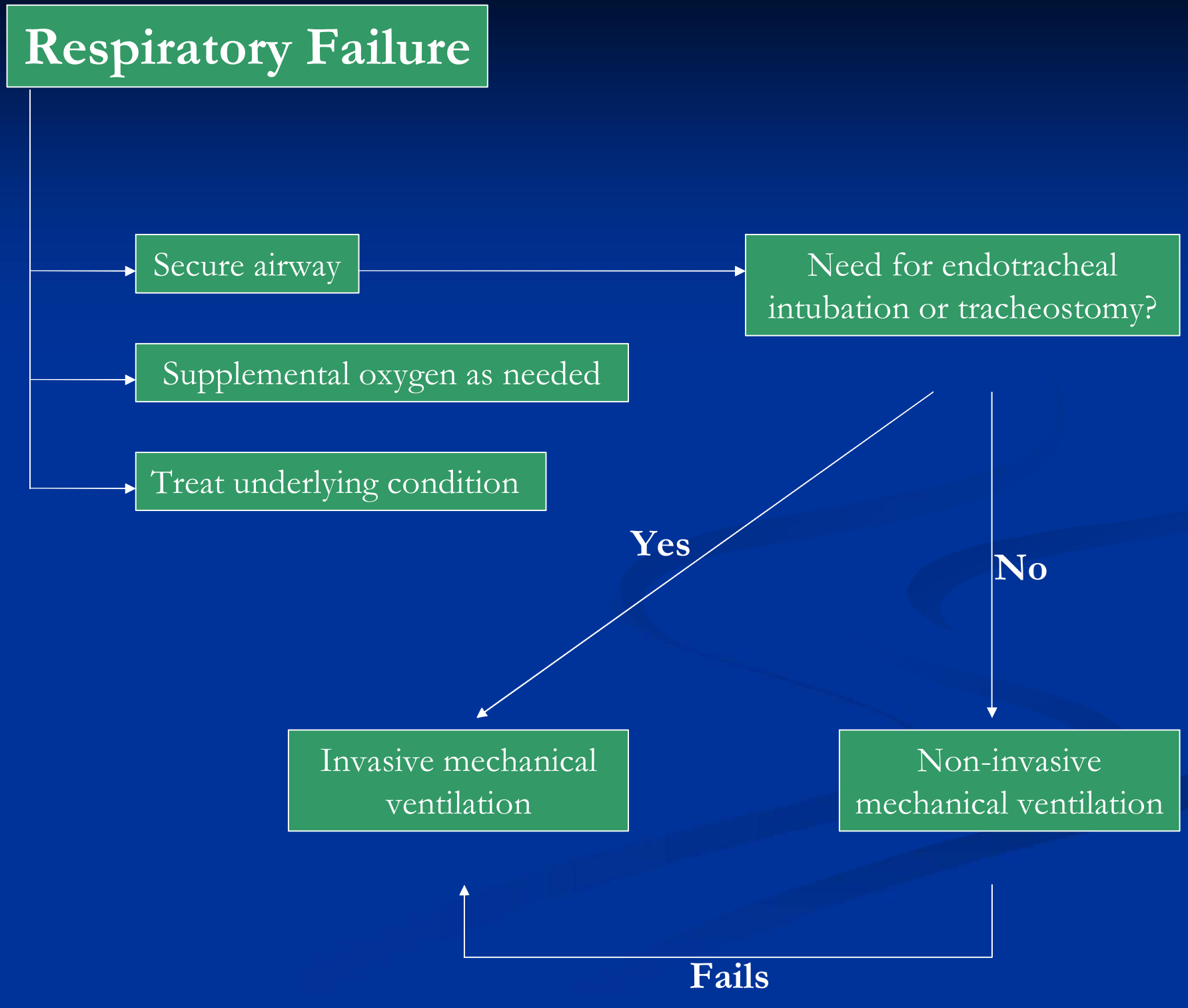
- ABC's
  - Ensure airway is adequate
  - Ensure adequate supplemental oxygen and assisted ventilation, if indicated
  - Support circulation as needed

Respiratory Failure: Management

- Treatment of a specific cause when possible
  - Infection
    - Antimicrobials, source control
  - Airway obstruction
    - Bronchodilators, glucocorticoids
  - Improve cardiac function
    - Positive airway pressure, diuretics, vasodilators, morphine, inotropy, revascularization

Respiratory Failure: Management

- Mechanical ventilation
  - Non-invasive (if patient can protect airway and is hemodynamically stable)
    - Mask: usually orofacial to start
  - Invasive
    - Endotracheal tube (ETT)
    - Tracheostomy – if upper airway is obstructed


Respiratory Failure
Secure airway
Supplemental oxygen as needed
Treat underlying condition
Need for endotracheal intubation or tracheostomy?
Yes
No
Invasive mechanical ventilation
Non-invasive mechanical ventilation
Fails

Indications for Mechanical Ventilation

- Cardiac or respiratory arrest
- Tachypnea or bradypnea with respiratory fatigue or impending arrest
- Acute respiratory acidosis
- Refractory hypoxemia (when the P_aO_2 could not be maintained above 60 mm Hg with inspired O_2 fraction (F_IO_2)>1.0)
- Inability to protect the airway associated with depressed levels of consciousness

Indications for Mechanical Ventilation

- Shock associated with excessive respiratory work
- Inability to clear secretions with impaired gas exchange or excessive respiratory work
- Newly diagnosed neuromuscular disease with a vital capacity <10-15 mL/kg
- Short term adjunct in management of acutely increased intracranial pressure (ICP)

Invasive vs. Non-invasive Ventilation

- Consider non-invasive ventilation particularly in the following settings:
  - COPD exacerbation
  - Cardiogenic pulmonary edema
  - Obesity hypoventilation syndrome
  - Noninvasive ventilation may be tried in selected patients with asthma or non-cardiogenic hypoxemic respiratory failure

Goals of Mechanical Ventilation

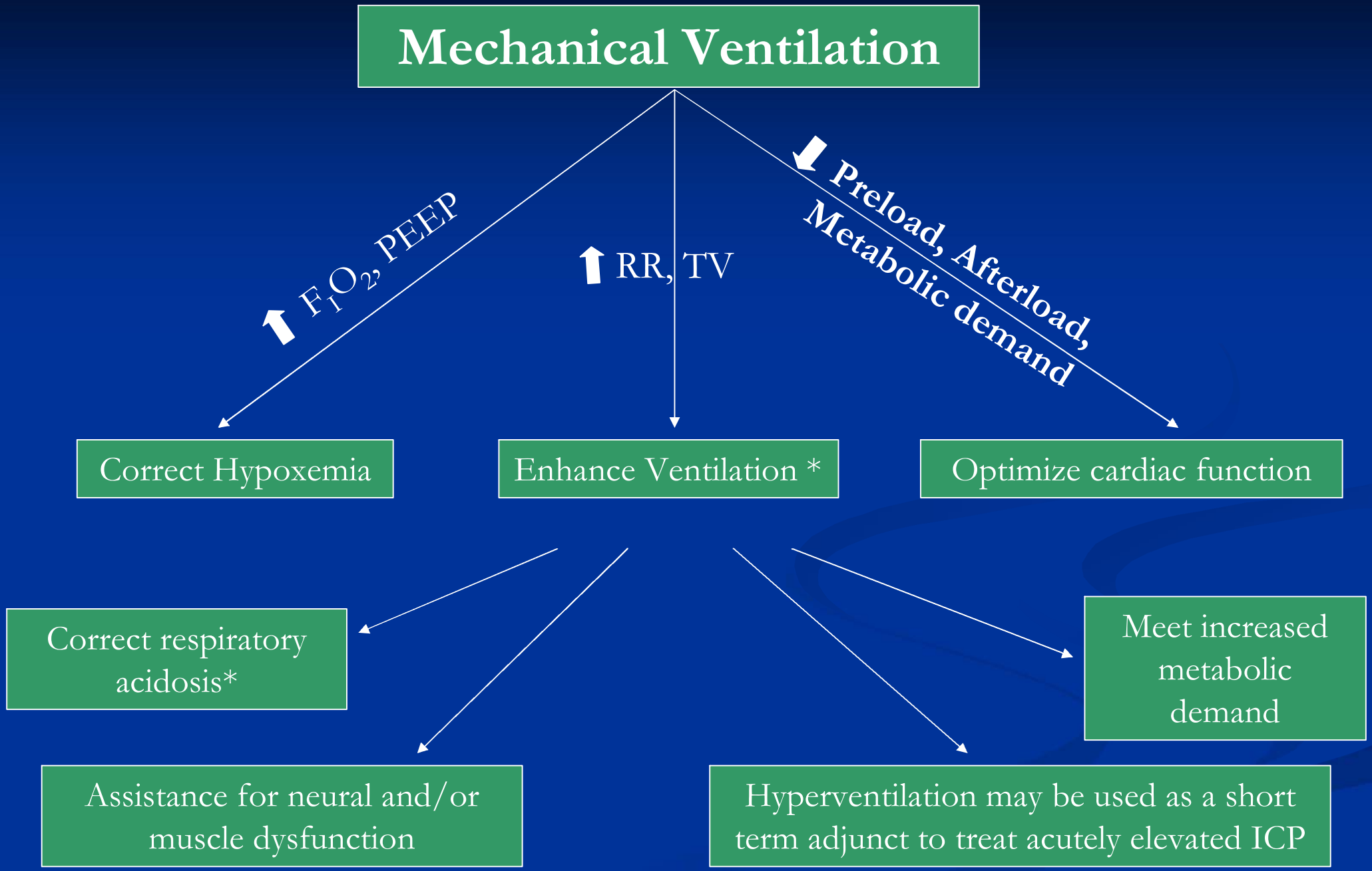
- Improve ventilation by augmenting respiratory rate and tidal volume
  - Assistance for neural or muscle dysfunction
    - Sedated, comatose or paralyzed patient
    - Neuropathy, myopathy or muscular dystrophy
    - Intra-operative ventilation
  - Correct respiratory acidosis, providing goals of lung-protective ventilation are met
  - Match metabolic demand
  - Rest respiratory muscles

Goals of Mechanical Ventilation

- Correct hypoxemia
  - High F_IO_2
  - Positive end expiratory pressure (PEEP)
- Improve cardiac function
  - Decreases preload
  - Decreases afterload
  - Decreases metabolic demand

Permissive Hypercapnia

- Ventilation strategy that allows P_aCO_2 to rise by accepting a lower alveolar minute ventilation to avoid specific risks:
  - Dynamic hyperinflation ("auto-peep") and barotrauma in patients with asthma
  - Ventilator-associated lung injury, in patients with, or at risk for, ALI and ARDS
- Contraindicated in patients with increased intracranial pressure such as head trauma



* Avoid ventilator induced lung injury and dynamic hyperinflation

Other Issues to Consider When Initiating Mechanical Ventilation

- Do not wait for frank respiratory acidosis especially with evidence of:
  - Inability to protect airway
  - Persistent or worsening tachypnea (respiratory rate >35/minute)
  - Respiratory muscle fatigue
- Always consider risks and benefits of initiation and continuation of mechanical ventilation

Other Issues in Intubated & Mechanically Ventilated Patients

- Always elevate the head of the bed >30º and use ulcer and DVT prophylaxis, unless contraindicated
- Use lung protective ventilation strategy for patients with Acute Lung Injury (TV ~ 6 ml/kg ideal body weight, Plat pressure < 30 cmH_2O)
- Modify ventilator settings primarily to achieve patient-ventilator synchrony. If this fails, use the least amount of sedation required to achieve comfort and avoid unnecessary neuromuscular blockade

Other Issues in Intubated & Mechanically Ventilated Patients

- Monitor patient comfort, gas exchange, mechanics, and ventilator waveforms daily, or more frequently if indicated

- When minimal settings are required for oxygenation (F_IO_2 <55%, PEEP<8) and patient is hemodynamically stable, perform a spontaneous breathing trial daily

References

- Arora,V.K., Shankar, U. (1995). Acute Lung Injury. *Lung India, Volume* XIII, *Number 1, p 32-34.*
- Behrendt C.F. (2000). Acute respiratory failure in the United States: Incidence and 31-day survival. *Chest, Volume 118, Number 4, p 1100-1105.*
- Brochard L., Mancebo J., Elliott M.W. (2002). Noninvasive ventilation for acute respiratory failure. *European Respiratory Journal, Volume 19, Number 4, p 712-721*
- Hall J.B., Schmidt G.A, Wood L. D.H. (2005). *Principles of Critical Care, 3rd Edition.* New York: McGraw-Hill Professional.
- *http://upload.wikimedia.org/wikipedia/en/thumb/d/db/Alveoli_diagram.png/300px-Alveoli_diagram.png*. Retrieved Nov., 16, 2006 from http://www.wikimedia.org.
- Hurford W.E. (2002). Sedation and paralysis during mechanical ventilation. *Respiratory Car, Volume 47, Number 3, p 334-346.*
- Kasper D.L, Braunwald E., Fauci A.S., Hauser S.L., Longo D.L., Jameson J.L., Isselbacher, K.L. (2004).*Harrison's Principles of Internal Medicine, 16th Edition.* New York: McGraw-Hill Professional.
- Masip J., Roque M., Sa´nchez B., Ferna´ndez R., Subirana M., Expo´ sito J.A., (2005). Noninvasive Ventilation in Acute Cardiogenic Pulmonary Edema: Systematic Review and Meta-analysis. *Journal of the American Medical Association, Volume 294, Number 24, p 3124-3130.*
- Michael E. Hanley M.E., Welsh, C.H. (2003). *Current Diagnosis & Treatment in Pulmonary Medicine.* New York: McGraw-Hill Professional.

References

- Midelton G.T., Frishman W.H., Passo S.S. (2002). Congestive heart failure and continuous positive airway pressure therapy: support of a new modality for improving the prognosis and survival of patients with advanced congestive heart failure. *Heart Disease, Volume 4, Number 2, p 102-109.*
- Plant P., Owen J., Elliott M. (2000). Early use of non-invasive ventilation for acute exacerbations of chronic obstructive pulmonary disease on general respiratory wards: a multicentre randomised controlled trial. *The Lancet, Volume 355, Issue 9219, p 1931-1935.*
- Ryland B.P., Jr. *emedicine- Ventilation, Mechanical.* Retrieved Nov., 24, 2006 from http://www.emedicine.com/med/topic3370.htm
- Sharma S. *emedicine-Respiratory Failure.* Retrieved Nov., 24, 2006 from http://www.emedicine.com/med/topic2011.htm
- The Acute Respiratory Distress Syndrome Network (2000). Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. *New England Journal of Medicine, Volume 342, Number 18, p 1301-1308.*
- Tobin, M.J. *Principles and Practice of Mechanical Ventilation, 2nd Edition (2006).* New York: McGraw-Hill Medical Publishing Division.