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Ultrasound Assessment of Respiratory Physiology: Lungs, Diaphragm, and Cardiopulmonary Interaction

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Objectives

Introduction

Lung-Brain axis

Lung-Kidney axis

Lung-Gastrointestinal axis

Metabolic, Immunological, Endocrine Lung regulatory function

Interaction between the Lung and the Endocrine system

Conclusion

References

Table of Contents

Introduction

Ultrasound has become a key tool in the assessment of the human body, allowing for a non-invasive, precise, and real-time analysis of various structures and functions. This chapter is intended for all healthcare professionals, including students, physicians, specialists, respiratory therapists, and individuals interested in respiratory physiology. Its goal is to provide a comprehensive perspective on the use of ultrasound in both ventilated and non-ventilated patients across diverse clinical settings.

From the early years of medical education, learning physiological concepts can be challenging when relying solely on textbooks and theoretical diagrams. However, ultrasound enables real-time observation of many physiological processes involved in ventilation and cardiopulmonary interaction, facilitating a faster and deeper understanding of these mechanisms. This tool not only enhances the comprehension of physiology but also improves the subsequent interpretation of pathologies related to the respiratory and cardiovascular systems.

Additionally, advanced concepts such as the ventilation-perfusion (V/Q) relationship, responses to variations in intrathoracic pressure, and the effects of effort and stress can be better understood and clinically applied by integrating physiological knowledge with real-time ultrasound findings.

Ultrasound has emerged as an innovative tool for studying and monitoring respiratory physiology, enabling real-time visualization of processes occurring in the lungs, diaphragm, and their interaction with the cardiovascular system. Traditionally, the understanding of pulmonary physiology has been based on theoretical models; however, ultrasound provides a practical and dynamic approach that enhances comprehension and clinical application.

This chapter explores the fundamentals of functional anatomy and ultrasound correlation, integrating West’s classic principles of pulmonary ventilation and perfusion with Lichtenstein’s contributions to lung ultrasound. The physical principles of ultrasound, transducer types, and artifacts essential for accurate interpretation of ultrasound findings are discussed.

Ultrasound techniques for respiratory system evaluation are detailed, including pleural line assessment, pneumothorax diagnosis, pulmonary edema detection via B-lines, and the identification of lung consolidations using dynamic bronchograms. Additionally, the assessment of cardiopulmonary interaction is analyzed, highlighting how mechanical ventilation impacts cardiac function and how ultrasound enables real-time evaluation of these effects.

A special section is dedicated to mechanical ventilation, exploring the physiological changes it induces in the respiratory system and the role of ultrasound in its monitoring. Emerging strategies such as diaphragmatic ultrasound for weaning assessment and the use of the Lung Ultrasound Score (LUSS) to quantify lung aeration in ARDS are presented.

Finally, the future of ultrasound in respiratory physiology is discussed, emphasizing its value not only in clinical practice but also in undergraduate education in anatomy and physiology. While growing evidence supports its utility, further advancements are needed to develop standardized protocols and solidify its role as a fundamental tool in respiratory and critical care medicine.

Functional anatomy and its Ultrasound correlation: from theory to imaging

Pulmonary physiology, as described by West, is considered a fundamental reference for medical students learning respiratory physiology. It explains the relationship between structure and function in the respiratory system, emphasizing key aspects such as ventilation, perfusion, and their interdependence in gas exchange at the alveolar level. West details how gravity influences the distribution of ventilation and perfusion, creating pulmonary zones with distinct ventilation-perfusion (V/Q) ratios. This physiological foundation finds a clinical and practical counterpart in lung ultrasound, a tool revolutionized by Daniel Lichtenstein, who identified ultrasound patterns such as B-lines, indicative of interstitial edema; A-lines, associated with normally aerated lungs; and lung consolidations, which reflect significant alterations in the V/Q relationship.

Integrating West's physiological principles with Lichtenstein's contributions enables a more comprehensive and dynamic assessment of the respiratory system. For instance, ultrasound can detect areas with reduced or absent pleural sliding, suggesting atelectasis or pneumothorax, and visualize consolidations or pleural effusions that impact pulmonary perfusion. Additionally, the ability to assess changes in the distribution of these features in different patient positions highlights the effects of gravity, aligning with West's theories. This integration of theory and practice not only enhances the academic understanding of respiratory physiology but also expands diagnostic and therapeutic capabilities in clinical practice.

Physics of Ultrasound and relevant terms

Ultrasound imaging is based on the emission of high-frequency sound waves that travel through body tissues. These waves are generated by a piezoelectric crystal located within the transducer of the ultrasound device, which converts electrical energy into mechanical vibrations. These vibrations produce ultrasonic waves that propagate through tissues, and when they encounter different interfaces (changes in tissue density and elasticity), a portion of these waves is reflected back to the transducer.

The transducer receives these reflected waves, known as echoes, and converts them back into electrical signals, which the ultrasound machine processes to generate a two-dimensional image. The quality of these images depends on the interaction between the sound waves and tissues, giving rise to characteristic artifacts and patterns.

Ultrasound Modes

- **2D Mode (Two-Dimensional):** Provides a real-time grayscale image of anatomical structures. It is the primary mode for structural assessment.
- **M Mode (Motion Mode):** Displays a time-motion graph that captures the movement of structures, useful for evaluating the diaphragm and thoracic wall dynamics.
- **Color Doppler:** Allows visualization of blood flow in color, differentiating direction and velocity. It is essential in the assessment of pulmonary and cardiac vessels.
- **Tissue Doppler:** Evaluates tissue motion, such as myocardial movement, making it valuable in cardiopulmonary interaction studies.

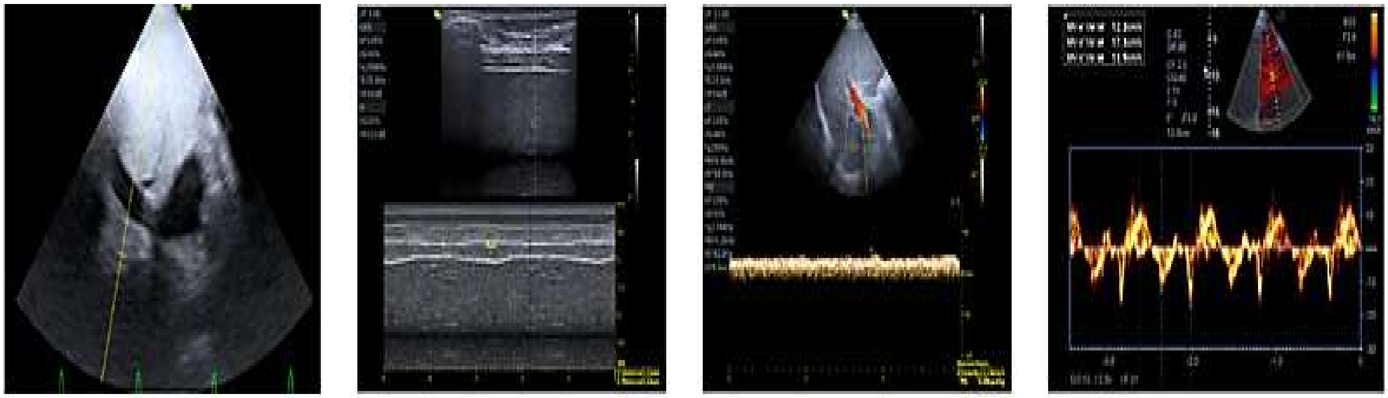


Figure 1: Ultrasound Modes. The image illustrates the most commonly used ultrasound modes. From left to right, it displays examples of 2D mode, M mode, Color Doppler, and Tissue Doppler, respectively.

Types of Transducers

- Linear Transducer:
  - ○ Characteristics: High frequency (7-15 MHz), excellent resolution for superficial structures.
  - ○ Pros: Provides fine anatomical detail, ideal for evaluating the pleura and nearby structures.
  - ○ Cons: Limited penetration, not suitable for deep structures.
- Convex Transducer:
  - ○ Characteristics: Lower frequency (2-6 MHz), greater penetration.
  - ○ Pros: Broad field of view, useful for deeper structures such as the lung bases and diaphragm.
  - ○ Cons: Lower resolution for superficial structures.
- Microconvex Transducer:
  - ○ Characteristics: Smaller footprint with intermediate frequencies (3-8 MHz).
  - ○ Pros: Good balance between resolution and penetration, allowing maneuverability in small areas such as between ribs.
  - ○ Cons: Somewhat more limited field of view compared to standard convex transducers and not widely available in most healthcare settings.

Figure 2. Transducers. From left to right, the most commonly used transducers for lung ultrasound are shown: linear, sectorial (phased-array), and convex. Note: The microconvex transducer is not commonly used due to its limited availability in most units. Instead, the sectorial (cardiac) transducer can be used, which, with proper settings and in trained hands, can be the most helpful tool for this type of study.

Relevant Terms

- Echo: The return of ultrasound waves after reflecting off a tissue interface.
- Reverberation: An artifact caused by multiple reflections between the transducer and a reflective surface, producing equidistant lines in the image.
- Artifact: Imaging phenomena that do not represent actual anatomical structures, such as A-lines and B-lines, which are useful for clinical interpretation.
- Anechoic: Areas in the ultrasound image that do not reflect echoes and appear black, such as fluids.
- Hyperechoic: Structures that reflect a large number of waves, appearing white in the image.
- Hypoechoic: Structures that reflect fewer waves, appearing gray on the scale.

These concepts are fundamental for correctly interpreting ultrasound findings and understanding how the physical properties of ultrasound influence the formation of diagnostic images.

Ultrasound Assessment of the Lungs and Diaphragm

Introduction

For a long time, lung ultrasound was considered an unfeasible technique due to the nature of air as a barrier to the propagation of ultrasound waves. This initial skepticism limited the development of ultrasonography in respiratory medicine, as it was assumed that the images obtained would lack diagnostic value. However, in the 1990s, Daniel Lichtenstein demonstrated that lung ultrasound is not only feasible but also an invaluable tool for real-time assessment of pulmonary physiology. This technique, relatively young compared to other imaging modalities, has opened a broad field of exploration, significantly expanding the number of respiratory pathologies that can be accurately diagnosed and monitored.

Clinical Importance

Lung and diaphragmatic ultrasound represent an invaluable tool for exploring respiratory physiology in real time. Based on the principles detailed by West, this technique allows visualization of key phenomena such as the ventilation-perfusion (V/Q) balance, which is essential for gas exchange. Additionally, Lichtenstein demonstrated that lung ultrasound can rapidly detect abnormalities such as pneumothorax, pleural effusions, and consolidations, providing direct physiological information that complements theoretical understanding.

Technique

Pleural Sliding Assessment

The pleural line is a key structure in lung ultrasound, representing the interface between the parietal and visceral pleura. Accurate assessment requires attention to technique and the correct transducer selection.

- Recommended Transducer: A high-frequency linear transducer (7-15 MHz) is used to maximize resolution in superficial structures. If greater penetration is needed, a microconvex or convex transducer can be used, though at the cost of lower superficial resolution.
- Transducer Positioning: The transducer should be placed initially in the second or third intercostal space, perpendicular to the thorax (90 degrees), with the marker oriented toward the patient’s head. This position allows identification of the "bat sign," where the ribs appear as hyperechoic structures with posterior acoustic shadows, and the pleural line appears as a hyperechoic line between the ribs. The anterolateral thorax is the ideal region to begin scanning, as it is easily accessible and facilitates pleural line visualization.

- Expected Structures:
  - Pleural Line: Appears as a hyperechoic line that moves synchronously with respiration. Pleural sliding represents the relative motion of the parietal and visceral pleura in their "virtual" space during ventilation. This movement is a direct reflection of lung expansion and contraction against the chest wall, driven by negative pressure in the pleural space and muscle contraction. Its presence indicates the absence of pneumothorax and confirms a functional connection between both pleural layers.
  - Intercostal Spaces: The ribs are identified as hyperechoic structures with posterior acoustic shadowing.

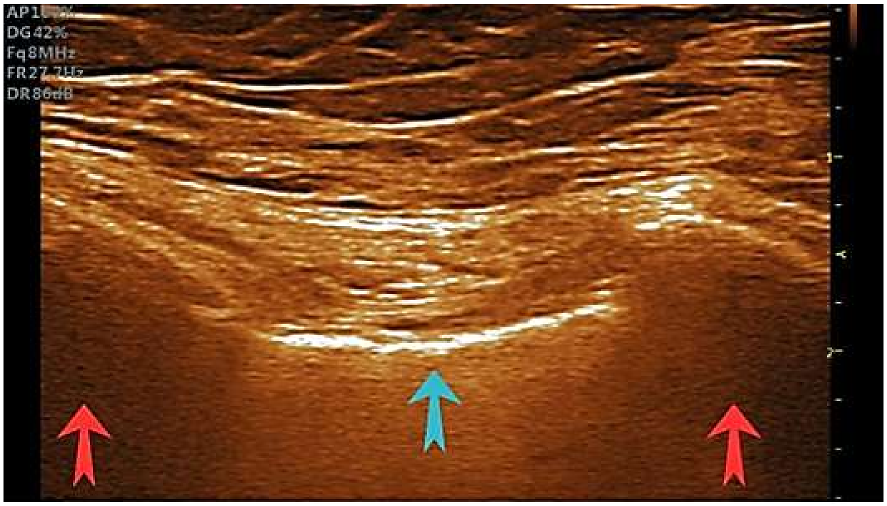


Figure 3: Lung ultrasound image obtained with a linear transducer. The blue arrow indicates the pleural line within the intercostal space, while the red lines highlight the posterior acoustic shadow caused by the calcium density of the ribs. The following link provides a video demonstrating pleural sliding. https://www.instagram.com/p/DCIdyXyu2Ro/?igsh=MTRob2NybHN1NWdhag==

Pulmonary Artifacts

A-Lines

- Definition: Hyperechoic horizontal artifacts parallel to the pleural line.
- Formation: Result from multiple reflections of ultrasound waves between the pleura and the transducer due to alveolar air.
- Appearance: Parallel, equidistant lines below the pleural line.
- Clinical Significance: Represent a normally aerated lung. Their presence suggests the absence of fluid or alveolar collapse.

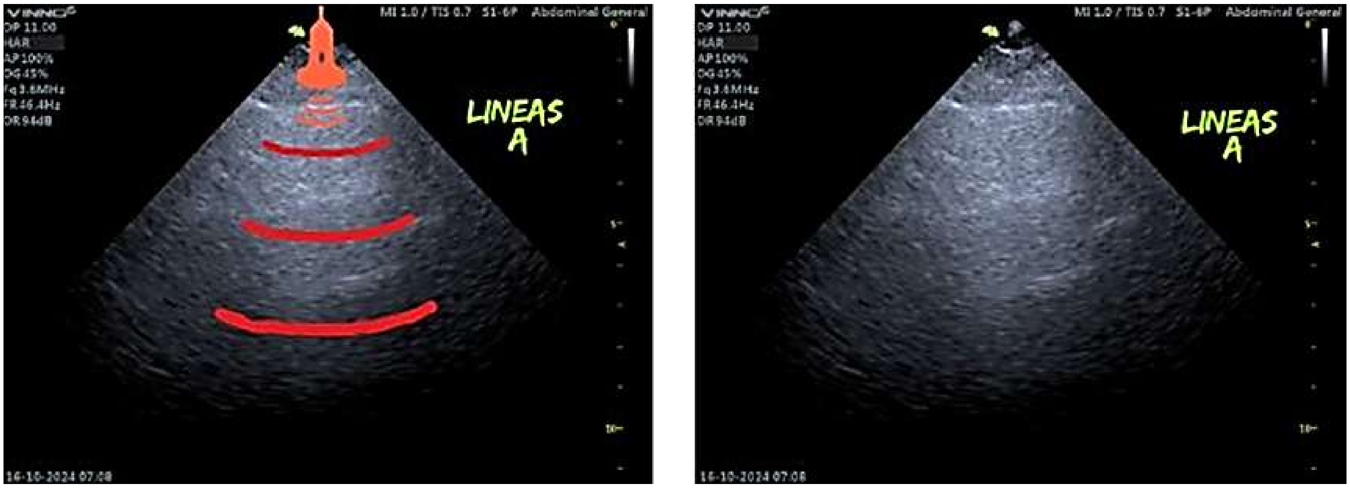


Figure 4: Ultrasound view of lung tissue obtained with a sectorial transducer. On the left, a schematic representation illustrates the repetitive hyperechoic artifacts originating from the pleura, characteristic of a well-aerated and healthy lung. On the right, the actual ultrasound image demonstrates how these findings appear in clinical practice.

B-Lines

- Definition: Hyperechoic vertical artifacts that originate from the pleural line and extend indefinitely without attenuation.
- Formation: Caused by ultrasound wave interaction with small amounts of interstitial fluid in the lung.
- Appearance: Resemble "light beams" or "comet tails" crossing the entire ultrasound field from the pleural line.
- Clinical Significance: Indicate the presence of interstitial or alveolar fluid, associated with pulmonary edema, acute respiratory distress syndrome (ARDS), or pulmonary fibrosis.

Figure 5. Lung ultrasound image obtained with a sectorial transducer. On the right, B-lines can be seen, resembling concert light beams. On the left, vertical hyperechoic artifacts originate from the pleural line

and extend to the lower part of the ultrasound window. It is important to set the ultrasound depth to 10 cm for optimal visualization.
Mixed Pattern

- Definition: A combination of A-lines and B-lines in the same ultrasound field.
- Formation: Reflects heterogeneous lung areas with both air and fluid coexistence.
- Appearance: Zones with predominant A-lines interspersed with areas of B-lines.
- Clinical Significance: May indicate evolving lung pathology, such as partial consolidation or early-stage pneumonia.

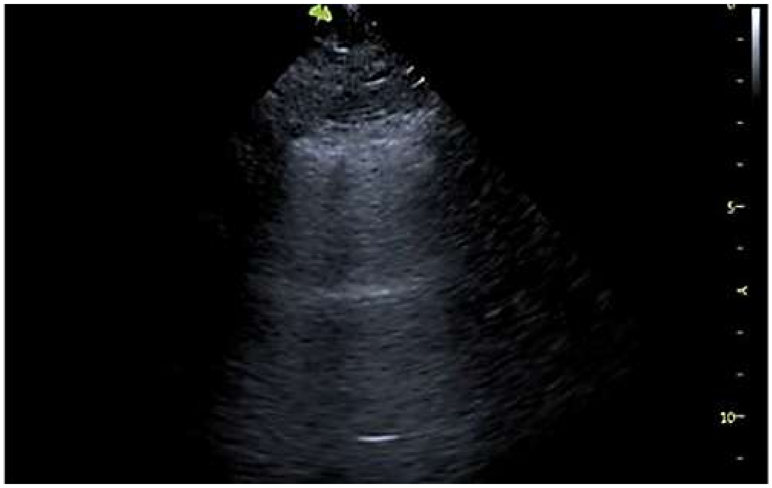


Figure 6. Lung ultrasound image obtained with a sectorial transducer. The image shows A-lines combined with B-lines. In real-time scanning, A-lines remain static, while B-lines move in synchrony with the patient's respiratory cycle.

Specific Technique

- The patient should be in a supine or semi-Fowler position.
- The patient is asked to breathe normally while multiple points on both hemithoraces are examined following the BLUE protocol:
  - Anterior Superior Point: Located at the second intercostal space, parasternal line.
  - Anterior Inferior Point: Located at the fourth or fifth intercostal space, midclavicular line.
  - Lateral Point: Located at the fifth or sixth intercostal space, midaxillary line.
  - Posterior Inferior Point: Located at the posterolateral region, near the lung base.

These points allow for a systematic assessment of the lungs to identify pneumothorax, pleural effusions, and consolidations, in a manner comparable to pulmonary auscultation.

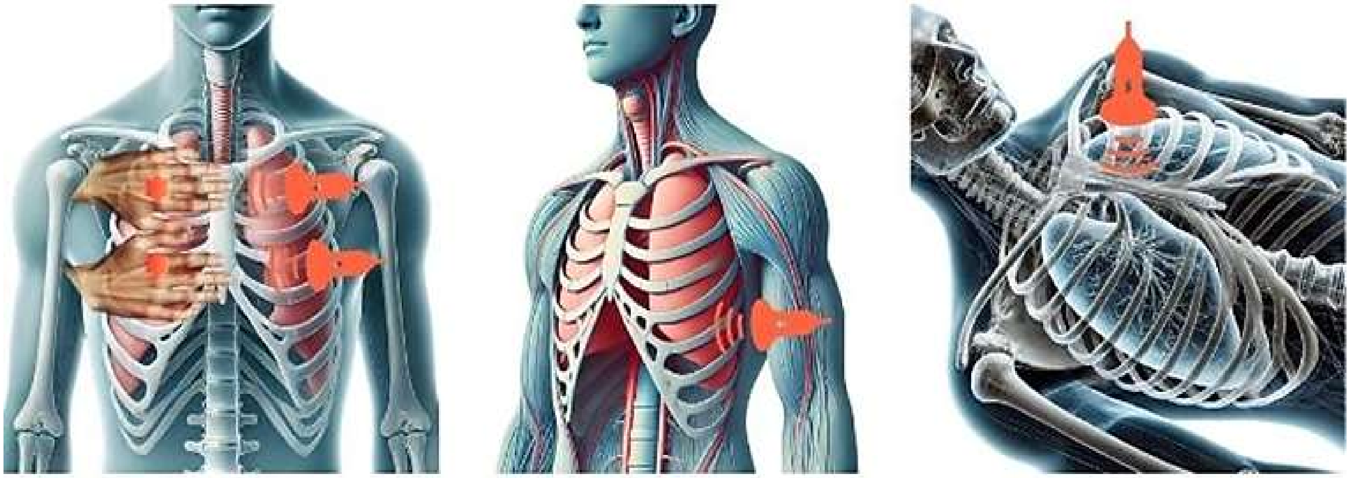


Figure 7. Lung insonation points in ultrasound assessment. The first image illustrates the anterior insonation points, using the hands as anatomical reference. The left hand is positioned with the outer edge of the fifth finger resting on the lower border of the clavicle, where the first insonation point is approximately at the level of the third metacarpophalangeal joint. Next, the right hand is placed immediately below the left, marking the second insonation point at the level of the second metacarpophalangeal joint. The central image depicts the PLAPS point, located at the same level as the second insonation point but with the transducer moved toward the mid and posterior axillary line, aiming toward the xiphoid process of the sternum. Finally, the last image demonstrates the proper transducer orientation relative to the thorax. The transducer should be positioned at 90° to the lung, ensuring that its center aligns with the corresponding intercostal space to optimize lung insonation.

Lung Bases

Positioning: Place the transducer on the lateral thorax, using either a longitudinal or transverse orientation, focusing on posterior and basal regions. It is essential to inspect the PLAPS point (Posterior and Lateral Alveolar and/or Pleural Syndrome), which represents the most gravity-dependent pulmonary zones where fluid or consolidations tend to accumulate.

Pneumothorax

- Pathophysiology: Pneumothorax represents the accumulation of air in the pleural space, causing partial or total lung collapse by eliminating the negative pressure that normally keeps the visceral pleura adhered to the parietal pleura. This impairs lung expansion during ventilation.
- Ultrasound Findings:
  - Absence of pleural sliding, indicating that the visceral pleura is not moving in sync with the parietal pleura due to air separation.
  - Lung Point Sign: A transition between pleural sliding (Seashore sign) and absent sliding (Barcode sign) using the M-mode, confirming pneumothorax.
  - Absence of B-lines, reinforcing the diagnosis.

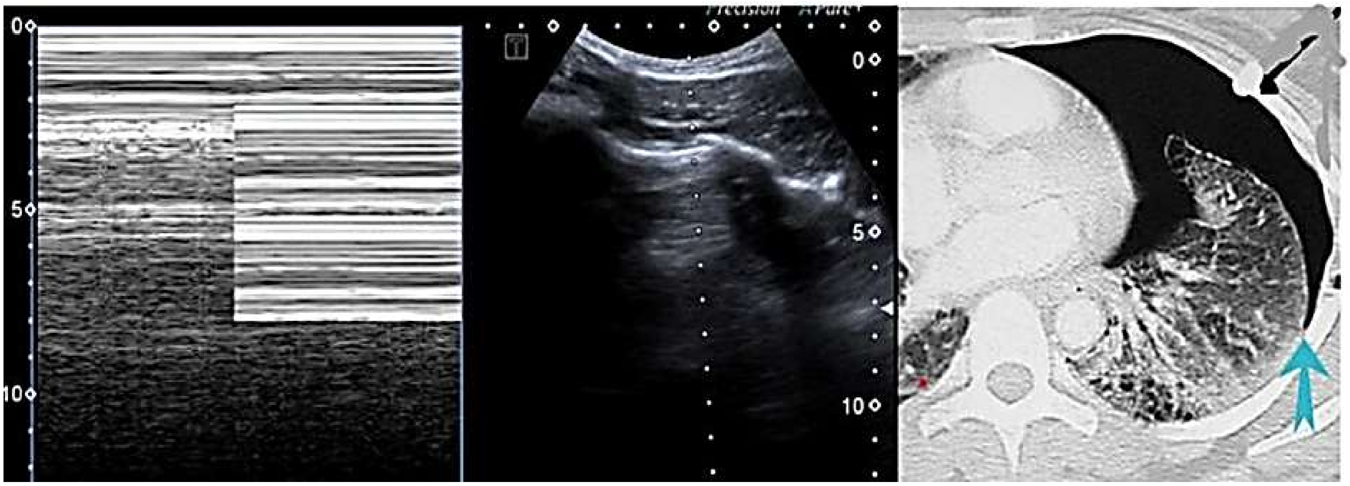


Figure 8: Pneumothorax. In the central image, lung tissue is visualized using a convex transducer, showing a pleural line without sliding, but with slight oscillation due to the ventilatory cycle. The first image displays an M-mode scan, where the transition from the seashore sign to the barcode sign occurs due to the separation of the parietal and visceral pleura caused by the presence of air. In the last image, a chest CT scan illustrates the lung point, indicated by the blue arrow, which marks the exact location where the pleural separation occurs, confirming the phenomenon described above.

Pulmonary Edema

- Pathophysiology: Pulmonary edema results from an imbalance between hydrostatic and oncotic pressures in pulmonary capillaries, leading to fluid extravasation into the interstitium and, in advanced cases, into the alveolar space. This disrupts gas exchange, leading to hypoxemia and ventilation-perfusion (V/Q) mismatch.
- Ultrasound Findings:
  - Multiple B-lines extending from the pleural line without attenuation, resembling "light beams."
  - Diffuse B-line distribution suggests interstitial pulmonary edema, whereas focal B-lines may indicate pneumonia or ARDS. Figure 5

Pleural Effusion

- Pathophysiology: Pleural effusions occur due to an imbalance between pleural fluid production and reabsorption. Excess fluid can result from increased hydrostatic pressure (heart failure), decreased oncotic pressure (nephrotic syndrome, liver disease), pleural inflammation (infections), or trauma.
- Ultrasound Findings:
  - Anechoic or hypoechoic fluid collection in the pleural space, displacing adjacent lung structures.
  - Internal septations suggest exudates, empyema, or hemothorax.
  - Mobile fluid with respiration can help differentiate transudates from exudates.

Figure 9: Pleural Effusion. Image obtained using a sectorial transducer at the left PLAPS point. From right to left, the kidney, spleen, and hypoechoic (black) thoracic cavity can be identified. Under normal conditions, healthy lung tissue displays an A-line pattern. However, when liquid accumulation occurs, whether pleural fluid or blood, the thoracic cavity appears hypoechoic. A curved hyperechoic (white) line can be observed between the thoracic cavity and the spleen, corresponding to the diaphragm.

Lung Consolidations

Physiologically, pulmonary consolidations represent the loss of alveolar aeration due to the accumulation of fluid, inflammatory cells, or purulent material within the alveoli. They can arise from various mechanisms, with the most common being pneumonia and atelectasis. Pneumonia leads to alveolar inflammation and exudate accumulation, compromising gas exchange and reducing pulmonary compliance. In contrast, atelectasis occurs due to airway obstruction or external compression, causing alveolar collapse without significant inflammation.

On ultrasound, consolidations appear as lung areas with a hepatized appearance, meaning they exhibit echogenicity similar to that of the liver due to the absence of air. A key finding to differentiate pneumonia from atelectasis is the dynamic air bronchogram: in pneumonia, air-filled bronchi may move with ventilation, indicating some degree of airflow; whereas in atelectasis, the air bronchogram tends to be static due to the absence of ventilation in the affected area.

Another valuable tool for distinguishing these conditions is color Doppler. In pneumonia, due to inflammation and increased blood flow in the affected lung parenchyma, vascularization can be detected within the consolidated area. In contrast, in atelectasis, where perfusion is significantly reduced or absent, color Doppler will show little to no vascular signal.

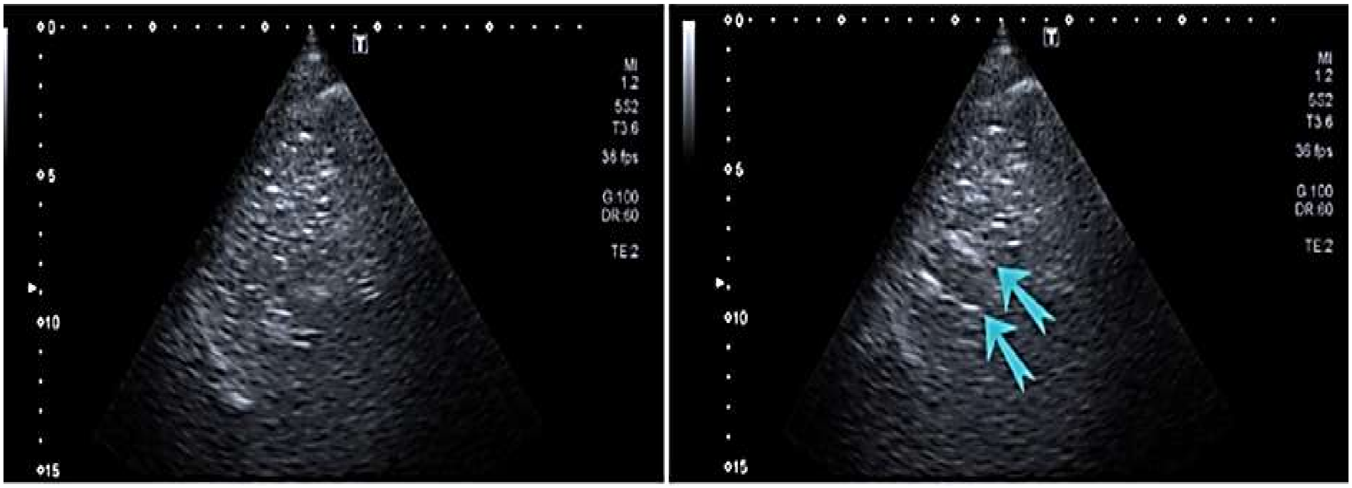


Figure 10. Pneumonia. Lung tissue image obtained using a sectorial transducer in 2D mode. Two frames from a video clip are shown. In the left image, the lung appears hepatized, a characteristic feature of pulmonary consolidation. In the right image, two hyperechoic (white) lines move synchronously with respiration, a finding known as dynamic air bronchogram. The full video can be viewed at the following link https://www.instagram.com/reel/DCXweYGOSFq/?igsh=MWR1aDBqbnZybmttaA==

Ultrasound Assessment of Cardiopulmonary Interaction

Clinical Importance

Cardiopulmonary interaction is a central concept in respiratory physiology, addressing how variations in ventilation affect the heart and vice versa. Studying this interaction is crucial, as proper cardiac filling and ejection depend on intrathoracic pressure and venous return. Alterations in these mechanisms can lead to significant pathophysiological consequences.

For instance, impaired right ventricular filling due to increased intrathoracic pressure (as seen in tension pneumothorax or cardiac tamponade) can reduce cardiac output and compromise tissue perfusion. Conversely, conditions that lead to heart failure and elevated central venous pressure can induce pulmonary congestion, impairing ventilation and oxygenation. Figure 11.

Ultrasound enables dynamic evaluation of this relationship, particularly in critically ill patients, by assessing the heart's response to ventilation changes, variations in inferior vena cava (IVC) diameter as a preload marker, and the impact of respiratory effort on ventricular function.

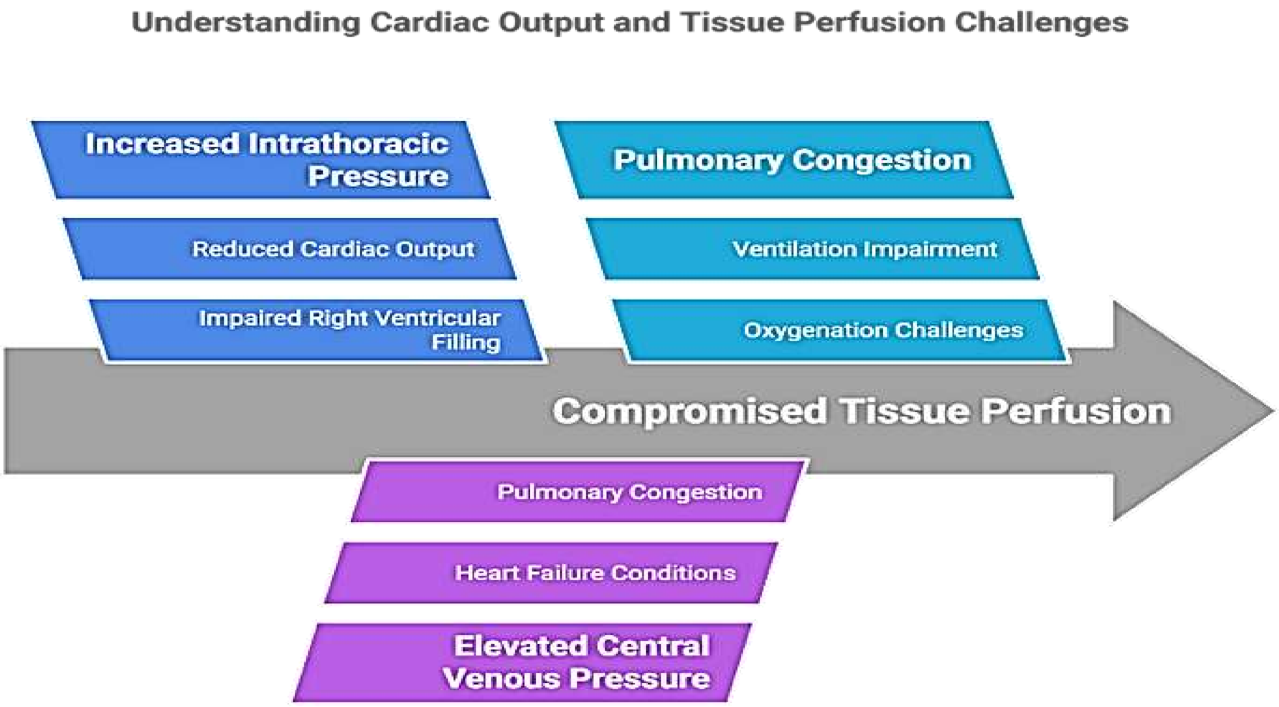


Figure 11: Mechanisms of cardiopulmonary interaction.

Technique

For ultrasound evaluation of cardiopulmonary interaction, different echocardiographic windows are used to visualize cardiac structures and their relationship with ventilation.

- Recommended Transducer: A low-frequency sectorial or phased-array transducer (1-5 MHz) is preferred due to its penetration capability and narrow field of view, allowing for the assessment of deep structures such as the heart through limited intercostal spaces.

Echocardiographic Windows and Views

- **Subcostal Window:** The transducer is placed in the epigastrium, with the marker oriented toward the patient's head. This view allows evaluation of the long axis of the heart and the inferior vena cava (IVC), making it useful in patients where other windows are difficult to obtain.

- **Parasternal Window:** The transducer is positioned in the third or fourth intercostal space, along the left parasternal line, with the marker directed toward the right shoulder. This view is ideal for assessing left ventricular function and the relationship between right and left heart chambers.

- **Apical Window:** The transducer is placed at the cardiac apex, with the marker oriented toward the patient's head. This view provides a clear four-chamber image, allowing precise evaluation of ventricular and valvular function.

- **Suprasternal Window:** The transducer is positioned in the suprasternal notch, with the marker directed toward the base of the neck. This view is used to visualize the aortic arch and assess blood flow in major vessels.

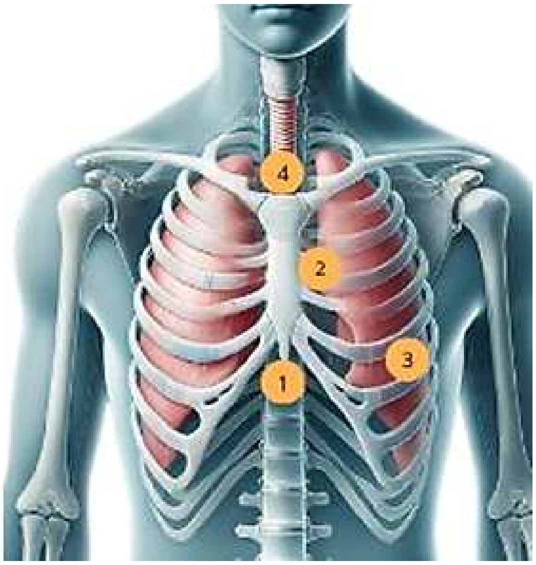


Figure 12: Echocardiographic Windows. The image displays the main echocardiographic windows: (1) subxiphoid window, (2) parasternal window, (3) apical window, and (4) suprasternal window.

Inferior Vena Cava (IVC)

IVC evaluation is fundamental as a preload marker. The IVC's diameter and its respiratory variability provide critical information:

- Respiratory Collapse >50% → Suggests hipovolemia or volume responsiveness.
- Dilated IVC with No Collapse → Indicates elevated central venous pressure, seen in right heart failure or cardiac tamponade.

Figure 13. Inferior Vena Cava (IVC) Collapse. Echocardiographic view of the right atrium and IVC, obtained using a sectorial transducer in 2D mode (top) and M-mode (bottom). This technique is used to assess respiratory collapse of the IVC and indirectly estimate part of the patient's preload status. Measurement is performed by determining the IVC diameter during expiration and inspiration, followed by calculating the average of both values. Note: IVC collapse alone is not a definitive predictor of preload status but serves as an additional parameter to consider in its assessment.

Doppler Ultrasound

Doppler techniques, including color and pulsed-wave Doppler, are used to:

- Analyze flow patterns across cardiac valves.
- Evaluate cardiac output and its impact on pulmonary function.

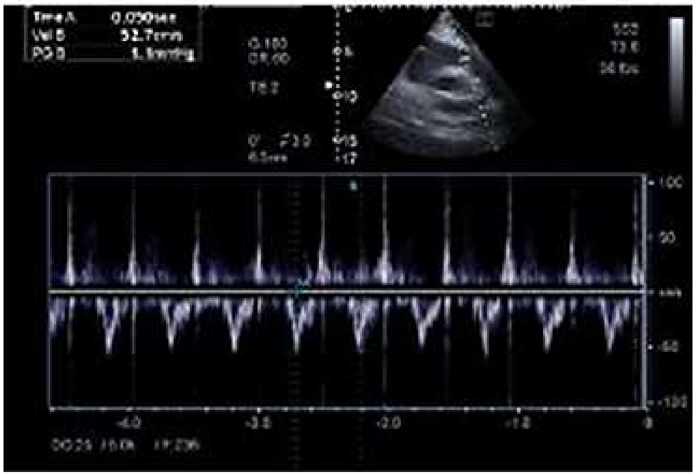


Figure 14. Pulsed Doppler. The upper part of the image shows a short-axis suprasternal 2D view, obtained using a sectorial transducer. The lower part displays the pulsed Doppler waveform, representing blood flow through the pulmonary valve. In this case, the combination of low flow velocity and a mid-systolic notch suggests pulmonary hypertension, likely due to an acute pulmonary embolism (PE).

Ventilation-Perfusion (V/Q) Relationship

The V/Q ratio is a fundamental determinant of pulmonary gas exchange. Under normal conditions, alveolar ventilation should be well-matched with capillary perfusion to ensure adequate oxygenation. However, V/Q mismatches can lead to hypoxemia:

- Increased ventilation without adequate perfusion → Creates physiologic dead space, as seen in pulmonary embolism.
- Perfusion without effective ventilation → Leads to pulmonary shunt, as observed in pneumonia or pulmonary edema.
- Ultrasound can identify these abnormalities by detecting pulmonary consolidations or diffuse B-lines, indicating gas exchange impairment.

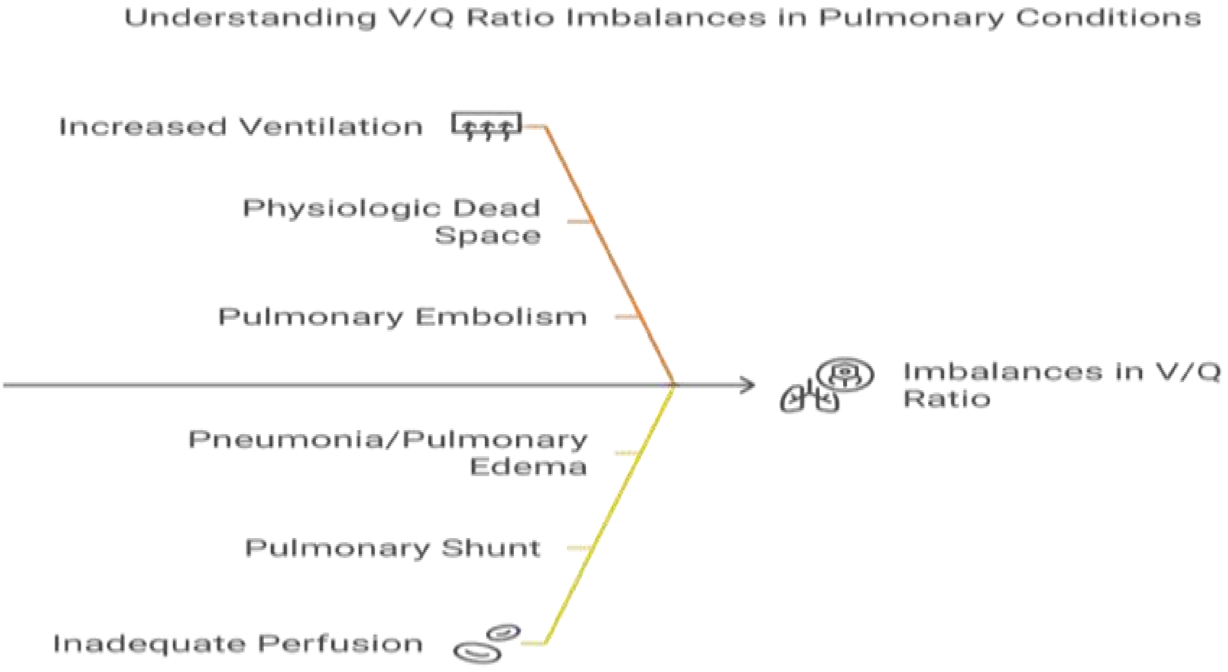
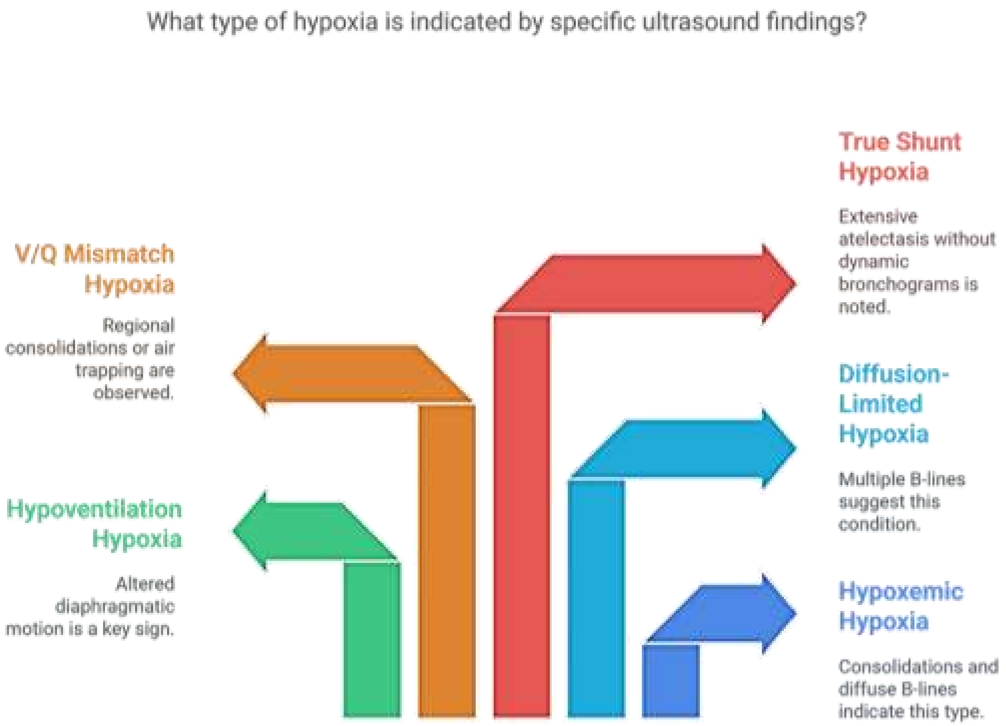


Figure 15: Relationship V/Q. The ventilation-perfusion (V/Q) ratio is essential for pulmonary gas exchange. Increased ventilation without adequate perfusion creates physiological dead space (e.g., pulmonary embolism), while perfusion without effective ventilation leads to a pulmonary shunt (e.g., pneumonia, pulmonary edema).

Hypoxemia and Its Types

Hypoxemia is defined as a decrease in arterial oxygen pressure (PaO_2) and can be classified as follows

- **Hypoxemic Hypoxia:** Due to impaired oxygenation, as in pneumonia or ARDS. Ultrasound findings: Consolidations and diffuse B-lines.
- **Hypoventilation Hypoxia:** Caused by reduced tidal volume, seen in neuromuscular diseases. Ultrasound findings: Altered diaphragmatic motion.
- **Diffusion-Limited Hypoxia:** Seen in interstitial lung diseases, where the alveolar-capillary barrier is thickened. Ultrasound findings: Multiple B-lines.
- **V/Q Mismatch Hypoxia:** Results from disruptions in the ventilation-perfusion balance. Ultrasound findings: Regional consolidations or air trapping.
- **True Shunt Hypoxia:** Occurs when there is perfusion without ventilation, as in severe alveolar collapse. Ultrasound findings: Extensive atelectasis without dynamic bronchograms.


What type of hypoxia is indicated by specific ultrasound findings?

True Shunt Hypoxia
Extensive atelectasis without dynamic bronchograms is noted.

V/Q Mismatch Hypoxia
Regional consolidations or air trapping are observed.

Diffusion-Limited Hypoxia
Multiple B-lines suggest this condition.

Hypoventilation Hypoxia
Altered diaphragmatic motion is a key sign.

Hypoxemic Hypoxia
Consolidations and diffuse B-lines indicate this type.

Figure 16: Examples of ultrasound findings in different types of hypoxemia.

Left Ventricular Function and Pulmonary Congestion

Left ventricular function is critical in hemodynamics and tissue perfusion, as it generates the cardiac output necessary for oxygen and nutrient distribution. Dysfunction can lead to heart failure, increasing pulmonary venous pressure and causing pulmonary congestion and alveolar edema, which impair oxygenation and gas exchange.

Ultrasound Evaluation of Left Ventricular Function

- Left Ventricular Ejection Fraction (LVEF): Calculated using Simpson’s method in the apical four-chamber view or by measuring end-diastolic and end-systolic diameters in the parasternal window. Reduced LVEF indicates systolic dysfunction.
- Tissue Doppler Imaging (TDI): Assesses myocardial movement velocity, providing insights into diastolic function.
- Pulsed Doppler at the Left Ventricular Outflow Tract (LVOT): Estimates cardiac output and hemodynamic status.
- E/e’ Ratio:
  - The ratio between early mitral inflow velocity (E) and mitral annular tissue velocity (e’), measured using Tissue Doppler Imaging (TDI).

  - Serves as a surrogate for pulmonary artery occlusion pressure (PAOP, or wedge pressure).
  - High E/e’ values suggest increased left ventricular filling pressures, associated with diastolic heart failure and pulmonary congestion.

Ultrasound Manifestations of Left Ventricular Dysfunction

- Pulmonary B-Lines (Diffuse, Bilateral): Indicate interstitial edema due to elevated pulmonary capillary hydrostatic pressure.
- Pleural Effusion (Anechoic Fluid Collection): Suggests severe pulmonary congestion in cases of advanced heart failure.
- Combined Cardiac and Lung Ultrasound: Differentiates cardiogenic pulmonary edema from other causes, such as pneumonia or ARDS.

Inferior Vena Cava (IVC) and Its Role in Cardiopulmonary Interaction

The IVC serves as a key marker of preload and volume status.

Ultrasound Assessment of IVC

- Positioning:
  - A sectorial transducer is used in the subcostal window, with the marker oriented toward the patient’s head to obtain a longitudinal view of the IVC.
- Interpretation:
  - >50% collapse during inspiration → Suggests hypovolemia and low central venous pressure.
  - Dilated IVC without inspiratory collapse → Indicates elevated central venous pressure, seen in right heart failure, cardiac tamponade, or pulmonary hypertension.

Impact on Pulmonary Function

- Elevated central venous pressure can lead to pulmonary congestion, promoting fluid extravasation into pulmonary capillaries.
  - Ultrasound Findings: Pulmonary B-lines suggest interstitial edema.
- Right heart failure or volume overload may cause bilateral pleural effusions, detectable as anechoic fluid collections in pleural ultrasound.
- Severe pulmonary hypertension leads to a dilated IVC with an enlarged right atrium, reflecting right ventricular dysfunction, which compromises pulmonary perfusion and gas exchange efficiency.

Respiratory Physiology and Mechanical Ventilation: An Ultrasound Perspective

Introduction

Respiratory physiology in mechanically ventilated patients undergoes significant changes due to the application of artificial positive pressures. Unlike spontaneous breathing, where lung expansion occurs through the generation of negative pressure within the thoracic cavity, mechanical ventilation inflates the lungs via positive pressure delivered by the ventilator. This alters respiratory mechanics, cardiopulmonary interaction, and the distribution of ventilation and perfusion, which can have both beneficial and harmful effects depending on the ventilatory settings.

Mechanical ventilation can improve oxygenation and reduce respiratory workload in patients with respiratory failure, but it can also cause complications such as volutrauma, barotrauma, and atelectrauma, especially if not properly adjusted to the patient’s physiology.

In this context, lung and diaphragmatic ultrasound has become an essential tool for monitoring and tracking lung function in ventilated patients. It allows for the assessment of ventilation distribution, detection of abnormalities such as alveolar collapse, consolidations, or interstitial and pleural fluid accumulation, and evaluation of diaphragmatic function, which is crucial in weaning strategies.

The systematic use of ultrasound in this setting enables real-time physiologically guided ventilation management, helping to personalize ventilatory therapy and improve patient outcomes.

Ultrasound in Monitoring, Tracking, and Weaning from Mechanical Ventilation

Monitoring in Mechanical Ventilation

Ultrasound has proven to be an invaluable tool for real-time monitoring of mechanically ventilated patients, allowing for rapid assessment of pulmonary and cardiovascular status. Its use provides the ability to diagnose, treat, and immediately evaluate the response to therapeutic interventions, making it an essential technique in ICU decision-making. Unlike other imaging techniques such as chest X-ray or CT scan, ultrasound enables instant visualization of physiological changes in response to ventilatory maneuvers, parameter adjustments, secretion suctioning, or prone positioning.

Lung ultrasound can detect consolidations, atelectasis, pneumothorax, pulmonary edema, or pleural effusions, allowing for immediate ventilatory adjustments.

Evaluation of Diaphragmatic Function in Ventilated Patients

Diaphragm assessment using ultrasound has gained relevance in the management of ventilated patients, particularly in the identification of ventilator-induced diaphragmatic dysfunction (VIDD). Recent studies, have explored how ultrasound can be used to monitor diaphragmatic activity and optimize ventilator weaning.

Ventilator-Induced Diaphragmatic Dysfunction (VIDD)

- Prolonged mechanical ventilation can lead to diaphragmatic atrophy due to reduced respiratory effort (disuse atrophy) or structural damage from excessive mechanical loading.
- Patient-ventilator asynchrony and high PEEP levels can impair diaphragmatic function, affecting post-extubation respiratory efficiency.

Ultrasound Monitoring

- Diaphragmatic Excursion (DE) and Thickening Fraction (TF) can be used to assess diaphragm function in real-time.
- The normal range of DE varies depending on factors such as age, gender, and body size. In general, a DE of 3-5 cm is considered normal.
- TF values < 20% correlate with weaning failure.

Importance of Ultrasound in Ventilator Weaning

- Ultrasound differentiates between diaphragmatic fatigue and other factors contributing to extubation failure.
- Preliminary studies suggest that routine ultrasound monitoring of diaphragmatic function may improve clinical outcomes, though further research is needed to validate these findings.

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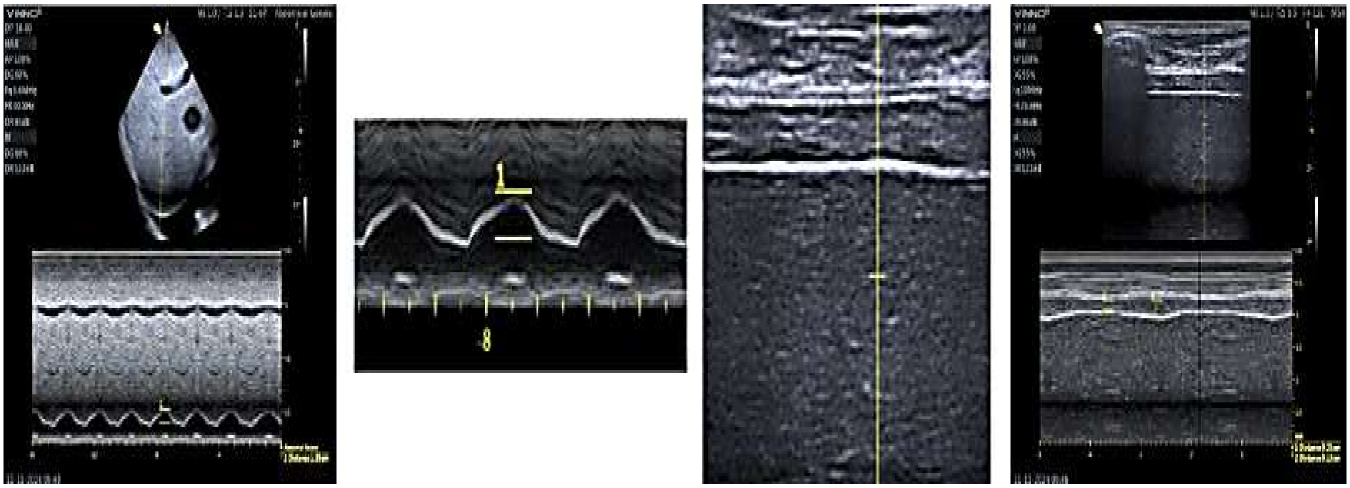

Figure 17: Diaphragmatic Ultrasound. The first image displays a diaphragmatic ultrasound with a 2D mode view (top) and its corresponding representation in M-mode (bottom). The M-line (yellow) crosses the diaphragm at an angle close to 90°, allowing visualization of the diaphragmatic wave-like movement and measurement of its excursion, which should be greater than 11 mm for optimal function. In the second image, the wave-like motion of the diaphragm is shown in greater detail, highlighting the measurement from valley to peak to quantify its displacement. The third image presents the diaphragmatic muscle, with enhanced clarity due to the use of a linear transducer. From top to bottom, the subcutaneous tissue is seen first, followed by the diaphragm with its characteristic "sandwich-like" appearance, where the hyperechoic (white) lines represent the parietal and visceral pleura, and the hypoechoic muscular diaphragm is located between them. In the fourth image, a similar view is shown, but with an M-mode measurement, allowing assessment of diaphragmatic thickening. The measurement is taken at the peak of inspiration and expiration, with an optimal thickening fraction not lower than 20%. M-mode provides real-time evaluation, enabling observation of the diaphragm's oscillatory movements. The videos can be accessed at the following links.
https://www.instagram.com/reel/DCsEV7RzBMA/?igsh=bmU2ZmI2OWRteXEx
https://www.instagram.com/reel/DCwMWw1T3Oi/?igsh=ZzRscG9qaHA2dGY5

Ultrasound in the Assessment of Lung Aeration in ARDS

Ventilation and perfusion within the lung are heterogeneously distributed, as described by West's pulmonary zones theory. These zones are determined by the relationship between alveolar, arterial, and venous pressures, creating regions with varying gas exchange efficiency. Under normal conditions, ventilation is greater in the lung bases due to gravity, whereas in ARDS, alterations in pulmonary mechanics disrupt this distribution, leading to atelectasis and alveolar collapse in dependent regions.

Lung ultrasound allows real-time monitoring of aeration and re-aeration patterns, enabling the evaluation of PEEP titration, prone positioning, and alveolar recruitment maneuvers.

Lung Ultrasound Score (LUSS) for ARDS

One of the most widely used methods for quantifying lung aeration changes is the Lung Ultrasound Score (LUSS). This system assigns scores to different lung regions based on the degree of aeration loss:

- Score 0: Normal lung aeration (A-lines, no pathological B-lines).
- Score 1: Mild interstitial edema (scattered B-lines, no consolidations).
- Score 2: Moderate-severe interstitial edema (coalescent B-lines, no consolidations).
- Score 3: Complete loss of aeration (extensive consolidations).

The LUSS protocol involves dividing each hemithorax into four quadrants (anterior superior, anterior inferior, lateral, and posterior) and summing the scores from each area to obtain a total lung aeration score. Higher scores indicate greater severity and can be used to evaluate responses to PEEP adjustments or recruitment maneuvers.

Ultrasound in ARDS enables dynamic, real-time pulmonary evaluation, assisting in ventilatory strategy optimization and preventing complications such as volutrauma and atelectrauma.

Monitoring Cardiopulmonary Interaction in Mechanical Ventilation

In ventilated patients, ventilation-induced variations in cardiac output, filling pressures, and venous return can be evaluated using ultrasound. Cardiopulmonary interaction is a key concept in critical care physiology, as mechanical ventilation alters both respiratory and cardiovascular mechanics through the application of intrathoracic positive pressure.

Physiology of Cardiopulmonary Interaction

The heart and lungs are interconnected through intrathoracic pressure changes.

- In spontaneous breathing, negative intrathoracic pressure during inspiration enhances venous return to the right ventricle (RV) and improves ventricular filling.
- In mechanical ventilation, positive pressure ventilation reverses this mechanism, potentially reducing venous return and compromising cardiac output, particularly in patients with RV dysfunction.

Effects of Positive Pressure on Respiratory and Cardiovascular Mechanics

- Increases alveolar and transpulmonary pressure, reducing alveolar collapse and improving oxygenation.
- Can compress pulmonary vasculature, increasing RV afterload, potentially causing RV dysfunction in cardiopulmonary disease.
- In severe cases, ventricular interdependence may develop, where RV dilation shifts the interventricular septum, impairing left ventricular (LV) filling and reducing cardiac output.

Ultrasound Assessment of Cardiopulmonary Interaction

Ultrasound provides detailed evaluation of cardiopulmonary function and the cardiovascular response to mechanical ventilation:

- PEEP titration and ventricular function: Assessing PEEP's impact on hemodynamics by measuring:
  - IVC diameter variability
  - E/e' ratio (LV filling pressures)
  - RV function

Right Ventricular Function

- RV S-wave velocity (Tissue Doppler Imaging - TDI): Assesses RV contractility and response to intrathoracic pressure changes.
- TAPSE (Tricuspid Annular Plane Systolic Excursion): Evaluates RV systolic function and adaptation to ventilatory changes.
- MAPSE (Mitral Annular Plane Systolic Excursion): Evaluates LV systolic function, complementing ventricular interaction analysis.

Conclusion

Ultrasound as a Key Tool in Respiratory Physiology

Ultrasound has established itself as an evolving tool for the monitoring and assessment of the respiratory system, enabling a dynamic, real-time approach to pulmonary, diaphragmatic, and cardiopulmonary physiology. Its ability to visualize ventilation-perfusion interactions, diagnose respiratory abnormalities, and guide therapeutic interventions makes it an invaluable technology for the management of both ventilated and non-ventilated patients.

Beyond its clinical applications, ultrasound represents a revolutionary opportunity in the teaching of respiratory physiology. Integrating ultrasound into undergraduate medical education, particularly in anatomy and physiology courses, would allow students to correlate anatomical structures with their function in real time, reinforcing learning and enhancing their understanding of fundamental physiological mechanisms.

However, challenges remain. While scientific evidence increasingly supports its use, ongoing research is crucial to develop standardized guidelines and clinical protocols that optimize its application. Lung and diaphragmatic ultrasound is currently in a phase of expansion and consolidation, offering an innovative perspective for the future of respiratory medicine and critical care monitoring.

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