

An Overview on Volume Status Assessment by Lung Ultrasound

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Abstract:

Assessment of volume status can be challenging, and clinical assessment is often imprecise. Therefore, different adjunctive diagnostic tools are used in clinical practice, such as bioelectrical impedance, chest radiography, weight monitoring, and blood biomarkers. More recently, lung ultrasound has been proposed for the assessment of extravascular lung water and therefore reflects lung congestion. Lung ultrasound is a noninvasive bedside technique that can accurately assess pulmonary congestion by evaluating extravascular lung water. This technique is expanding and is easily available.

Keywords: Volume Status, Lung Ultrasound, Inferior Vena Cava.

Introduction:

Despite rapid advancements in medicine, regulation of body fluid volume remains a key concern for modern clinicians. From the pathophysiologic perspective, it is most important to assess intracellular water volume as it directly impacts arterial and venous pressure, volume status, and, consequently, life functions of the body [1].

There is a considerable spectrum of available modalities to assess intracellular water volume: from a clinical evaluation of vital signs to advanced invasive methods, such as pulmonary artery catheterization. The point-of-care ultrasound is currently used to assist clinicians in problem solving at bedside, and one of the challenges involved is the evaluation of intravascular volume status [2].

This method allows for a real-time and noninvasive assessment of the degree of hydration, and owing to its reproducibility, it is also suitable for monitoring. The results of the ultrasound assessment of the degree of hydration correlate with those obtained with other referential methods. Moreover, the method is easy to learn even for inexperienced clinicians [3].

Ultrasound assessment of the inferior vena cava:

Method (equipment, technique):

An ultrasound device to assess fluid status should be equipped with a convex or phased array probe. The selection of an adequate probe depends on the patient's physique. Convex and phased array probes are effective for in-depth examination of tissues (about 25–30 cm) [4].

This enables an assessment of the inferior vena cava (IVC) and aorta (Ao) when the probe is placed over the epigastric region and over the right lateral abdominal wall. The standard placement of the probe to visualize both vessels is in the anterior median line over the epigastrium (inferior to the xiphoid process) [5].

In cases when the assessment over the epigastrium is difficult (e.g., due to substantial amounts of intestinal gas, large dressings or wounds in the median line), the probe should be placed over the lateral abdominal wall, in the right anterior axillary line [1].

An assessment with the probe placed over the lateral abdominal wall can be very effective because the liver is a perfect acoustic window for the imaging of the major abdominal vessels. The Color Doppler mode is not required for the evaluation of fluid status. The examination involves only the assessment of the vein diameter, and in the case of the IVC/Ao index, it also involves calculating the ratio of the IVC diameter to the aorta diameter [6].

First, the IVC collapsibility is assessed. The maximal and minimal IVC diameters are measured, using the M-mode, during the expiratory and inspiratory phases of the respiratory cycle. The obtained results are computed according to the following formula: $dIVC = ([D_{max} - D_{min}]/D_{max}) \times 100\%$, where d stands for distensibility (collapsibility); D_{max} , maximal diameter; and D_{min} , minimal diameter [2].

In fluid-responsive patients, the value of the IVC collapsibility exceeds 40%. Patients who do not respond adequately to fluid therapy have the IVC collapsibility index of less than 15%. Moreover, the IVC collapsibility index exceeding 50% is strongly associated with low values of the central venous pressure [4].

The value of the IVC/Ao index is obtained by calculating the ratio of the IVC to Ao diameters. The IVC diameter is assessed in the intrahepatic segment, about 3 cm below the diaphragm, during the expiration phase of the respiratory cycle. The Ao diameter is measured at the same level by moving the probe with a swinging motion to the left of the patient's body. A normal value of the IVC/Ao index ranges from approximately 0.8 to 1.2 [3].

The IVC/Ao index of less than 0.8 indicates that the patient requires fluid therapy, while the value of more than 1.2 indicates that the patient is most likely overhydrated. For patients undergoing respiratory therapy, the assessment of the IVC compressibility is helpful. Technically, the examination is analogous to the assessment of the IVC collapsibility index by measuring the minimal and maximal diameters in the M-mode [7].

However, to assess the volume status, the so-called IVC compressibility index is calculated using the following formula: $IVC \text{ compressibility index} = ([D_{max} - D_{min}]/D_{max}) \times 100\%$. The threshold of the IVC compressibility index is 18%. The use of this threshold allows a classification of patients into those potentially responsive ($>18\%$) and nonresponsive ($<18\%$) to fluid therapy [5].

Clinical usefulness of the inferior vena cava/aorta index and the inferior vena cava index:

The calculation of the IVC collapsibility and IVC/Ao indices is an auxiliary modality in determining the degree of the patient's hydration. The indexes are particularly useful when the clinical assessment is difficult and may fail to provide adequate results. To determine body fluid status in adults with the use of ultrasonography, initially the IVC collapsibility was evaluated [6].

The measurement of the IVC diameter on expiration and inspiration as well as its collapsibility ratio yields the so-called IVC index. The usefulness of the IVC/Ao index was initially confirmed in the pediatric population. Currently, both the IVC index and the IVC/Ao index are well documented as useful measurements in assessing body fluid status in adult patients [1].

One of the basic differences between the 2 methods is the impact of the patient's individual characteristics, such as age, sex, height, body surface, body mass, and waist circumference. The IVC/Ao index is more susceptible to patient characteristics than the IVC index. Additionally, the IVC/Ao index has been found to be useful for the evaluation of preoperative and intraoperative volume status, especially in a major surgery with marked fluid shift or blood loss [7].

Other target groups for the application of ultrasonography in the assessment of body fluid status are patients with cardiovascular diseases, for example, those with exacerbation of congestive heart failure (HF), kidney diseases (such as acute kidney injury and exacerbation of chronic kidney disease [CKD]), as well as

patients on dialysis. In these populations, the assessment of the initial body fluid status is essential, but more importantly, these patients should be carefully monitored during fluid therapy or fluid removal [2]

✚ Limitations of the inferior vena cava/aorta index and the inferior vena cava index:

The usefulness of ultrasound in the measurement of the IVC and IVC/Ao indices is limited by its high dependence on the experience of the operator and the presence of specific clinical conditions that prevent a reliable calculation, including pulmonary hypertension, elevated intra-abdominal pressure, cardiac tamponade, and mechanical ventilation [4].

Pathological obesity can be an obstacle to assessing the IVC diameter. When hypervolemia is detected, false-positive results should be considered due to pulmonary hypertension, high intra-abdominal pressure, or cardiac tamponade. The operator's experience and ability to obtain optimal views are of key significance in a correct assessment of body fluid status [3].

As in the case of any examination, training and gaining experience through practice are essential. Due to the high reproducibility of ultrasound examinations, especially when monitoring the patient, it is advisable that the examination is conducted by a clinician who is the treating physician [7].

Lung ultrasound in the assessment of body fluid status:

✚ Method (equipment, technique):

In a lung ultrasound examination, a convex probe is most often employed for the preliminary assessment, and a linear probe, for the visualization of small subpleural lesions and the pleural line. The linear probe helps differentiate B-line artifacts, for example, irregularities, fragmentation, or the blurring of the pleural line in pulmonary fibrosis [7].

In emergency cases, phased array probes are used as an extension of echocardiography (additionally, a small probe head facilitates intercoastal access) as well as micro-convex probes. The assessment of body fluid status is based on the analysis of artifacts. Consequently, it is necessary to switch off additional options improving visualization such as compound imaging, algorithms that reduce speckle, haze, and clutter artifacts, as well as harmonic imaging [1].

Features of the ultrasound device that facilitate bedside examination include a small size, a few-second switching time, and an easily cleaned transducer. Additionally, Doppler options are not required. Modern pocket-size imaging devices seem to be useful tools for assessing the lungs [4].

In recumbent patients, when searching for B-line artifacts, the region along the middle and posterior axillary lines is mainly assessed. In the case of patients mainly in the erect position, in order to search for interstitial and alveolar-interstitial syndromes, first the lower lung fields are assessed. Then, the level up to which B-line artifacts are present is analyzed by moving the probe up to the middle and upper lung fields [5].

This examination technique is a result of the gravitation-dependent presence of air and fluid. There are numerous imaging protocols that can be used for lung examination. The best-known protocol is the evaluation of 8 regions. An anterior 2-region scan may be sufficient to exclude interstitial syndrome in cardiogenic acute pulmonary edema [2].

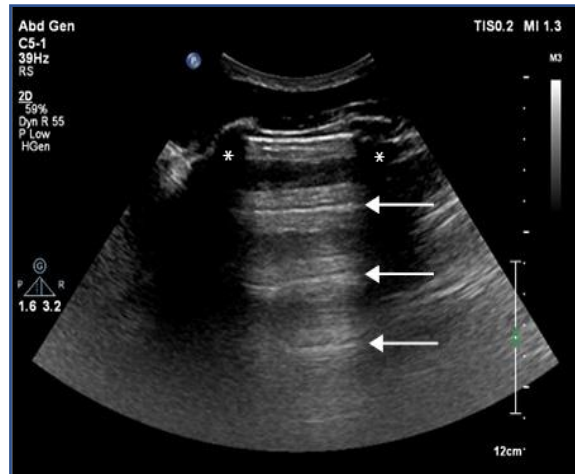


Figure (1): A probe placed perpendicularly to the rib surface at the chest apex. Asterisks indicate the ribs with visible shadows at the bottom of the screen. Arrows indicate A-line artifacts regularly spaced and extending towards the bottom of the screen [8].

Lung ultrasound facilitates the assessment of extravascular lung water. It has been proved that the degree of lung aeration, dependent on the fluid volume in the interstitial and interalveolar spaces, directly correlates with the ultrasound image. Extravascular lung water assessment can be reliable and effective irrespective of the operator's experience in lung ultrasound [6].

Another important feature of extravascular lung water is the symmetric bilateral localization of the lesions. B-line artifacts detected unilaterally may correspond to different processes within pulmonary interstitial spaces (e.g., inflammation), and the presence of fluid in the interstitial and interalveolar spaces usually produces a symmetrical image on both sides of the chest [3].

✚ Artifact analysis

Ultrasound assessment of body fluid status involves the analysis of artifacts seen on an ultrasound image [7].

❖ **A-line artifacts:**

In a normal aerated lung, ultrasound images show A-line artifacts. A lines are horizontal regularly spaced lines and a type of reverberation artifacts that appear between 2 bordering surfaces: the probe/body surface and the pleura/air in the alveoli. The distance between A lines is equal. When fluid status is assessed, such an image is interpreted as the so-called dry lung. An image showing A-line artifacts may be also seen in pneumothorax; however, the pleural sliding sign is then absent [7].

❖ **B-line artifacts:**

The major reason for B-line artifacts is the presence of fluid in the interstitial or interalveolar spaces. These artifacts can also be found in pneumonia and fibrosis. B-line artifacts are caused by a reverberation phenomenon. The area where reverberation occurs covers a small space—the interlobular septa or pulmonary alveoli [1].

Consequently, the obtained image shows an apparent vertical line consisting of numerous small horizontal lines. B-line artifacts are defined as laser-like vertical hyperechoic reverberation artifacts that arise from the pleural line, extend to the bottom of the screen (without fading irrespective of the programmed depth of penetration), and move synchronously with the respiratory cycle [5].

Depending on the fluid volume in the lung, B-line artifacts produce:

- The interstitial syndrome, corresponding to the presence of fluid in the interstitial spaces. Three or more B-line artifacts are present within a single intercostal window with a longitudinal probe position. The distance

between them is larger than 7 mm, which results from the anatomical structure and equates the thickness of interlobular septa. B-line artifacts move synchronously with the respiratory cycle and pleural sliding and remain separated.

- The alveolar-interstitial syndrome, corresponding to the presence of fluid in the interstitial and interalveolar spaces. The distance between the artifacts is 3 mm, and B-line artifacts overlap synchronously with the respiratory cycle.
- The white lung sign, a completely white image of the lung, without visible single artifacts, corresponding to large fluid volumes within the alveolar-interstitial spaces, the next stage being airless consolidation [2].

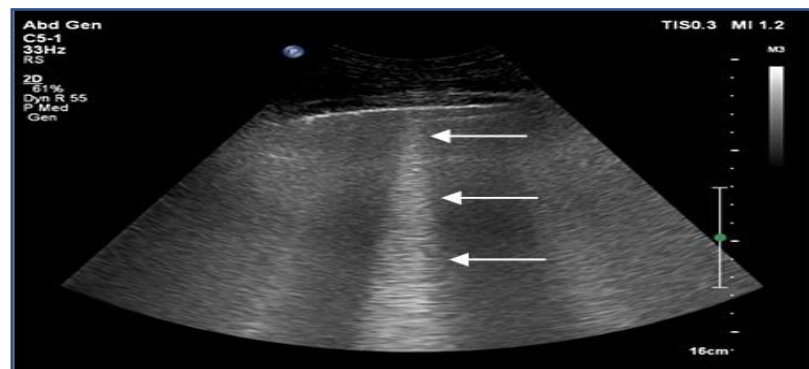


Figure (2): A probe placed parallel to the intercostal spaces; a visible B-line artifact (arrows): hyperechoic, arising from the pleural line, extending to the bottom of the screen [8].

Clinical usefulness of lung ultrasound in heart failure:

In everyday clinical practice, the assessment of HF exacerbation is based on clinical examination, chest radiography, N-terminal fragment of the prohormone brain natriuretic peptide (NT-proBNP) levels, and echocardiography. Physical examination is still the initial diagnostic modality [6].

However, it does not yield reliable results in asymptomatic patients and does not allow for a precise assessment of the degree of HF exacerbation. In asymptomatic patients, lung ultrasound facilitates the detection of pulmonary congestion, which in the early stage does not present any signs on auscultation. Crackles over the lung fields appear only when the fluid volume is large enough to be present in the interalveolar space [3].

Additionally, the number of B-line artifacts in HF increases synchronously with an increase of the New York Heart Association (NYHA) functional class and is directly dependent on the ejection fraction and degree of diastolic dysfunction. Moreover, a stable number of B-line artifacts was observed in patients who, despite their heart disease, retained a stable level of exercise capacity [4].

In HF exacerbation, lung ultrasound is employed to monitor the resolution of pulmonary congestion and treatment efficacy, and the results correlate directly with NT-proBNP levels and radiologic examinations. Lung ultrasound is also useful in monitoring patients with pulmonary congestion who undergo intensive diuretic therapy or hemodialysis [1].

Clinical usefulness of lung ultrasound in renal failure and dialysis therapy:

Fluid overload is one of the most important prognostic factors in patients with CKD. Hypervolemia results in left ventricular (LV) hypertrophy. More than one-third of patients undergoing dialysis die of cardiovascular incidents (arrhythmia, myocardial infarction). The most common causes of cardiovascular incidents include LV hypertrophy and arterial hypertension [5].

A successful control of extracellular volume in patients on chronic dialysis allows clinicians to monitor arterial blood pressure, largely reducing or even eliminating the use of antihypertensive drugs [7].

In patients on dialysis, fluid balance is still controlled on the basis of physical examination, assessment of the so-called dry weight, and the measurement of arterial blood pressure. Such an evaluation is not reliable as

it involves parameters that depend on too many factors—consider, for example, the amount of fluid volume change necessary to obtain an alteration in arterial pressure, peripheral edema, and cardiac function [2].

In hemodialyzed patients, the number of B-line artifacts before and after dialysis directly correlates with the measurements of the IVC diameter and bioelectrical impedance analysis. This correlation was revealed in both asymptomatic and symptomatic patients in all NYHA classes [6].

Additionally, lung ultrasound appears to be an effective tool for detecting and monitoring patients with HF and CKD who develop pulmonary congestion despite the absence of symptoms. The use of lung ultrasound for monitoring in this population may reduce the risk of decompensated HF, which is the most frequent cause of death in patients on dialysis [3].

The use of the B-line score defined as the percentage of regions where B lines are present also correlates with the extravascular lung water before and after hemodialysis. In patients undergoing peritoneal dialysis, lung ultrasound enables a determination of extravascular lung water, especially in asymptomatic individuals [1].

Lung ultrasound limitations:

Lung ultrasound is a relatively new modality for the assessment of body fluid status. It is an easy-to-use tool but has some limitations.⁴⁸ It may prove problematic in patients who have undergone pneumonectomy. B-line artifacts are found in many different clinical conditions including cardiogenic and noncardiogenic pulmonary edema, pneumonia, interstitial lung disease, and lymphangitis carcinomatosa [7].

It is extremely important for the operator to differentiate between these conditions. The assessment of lesion distribution, localization of B-line artifacts, regularity of B-line artifact distribution, as well as the pleural line and associated lesions may help determine whether the condition is cardiogenic or lung related. It should be noted that in the population of hemodialyzed patients with HF, the assessment may be limited [7].

The development of guidelines and an algorithm for the assessment of body fluid status with lung ultrasound that would allow physicians to refer the examination to the general population would be an important step [2].

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