Ultrasound of Lung

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Abstract

Ultrasound (US) is a very common tool in today's clinical practice. Lung ultrasound was popularized by Daniel Lichtenstein, a French intensivist. He noted that sonographic artifacts during lung ultrasound could differentiate between various lung diseases and subsequently noted the ultrasound's ability to differentiate various diseases. He also popularized the points of probe placement and various signs and lines in lung ultrasound, which includes the A line, B-lines, Lung sliding sign, seashore sign etc. based upon which the BLUE protocol was introduced. Lung ultrasound has rapidly gained popularity over the past 10 years, mainly due to its wide availability in emergency and trauma settings, lack of radiation exposure, easy availability and cost effectiveness. Although there are limitation to Lung ultrasound, like being user dependent, limited role in surgical emphysema, in severely obese patients, and CT still remains a gold standard for diagnosis of lung pathologies, ultrasound has shown to be equally effective or even better in diagnosis and management of patients in critically ill patients, where obtaining CT scan or other imaging technique is not feasible. Hence, lung ultrasound is a must have tool and knowledge and skills related to lung ultrasound should not only be limited to Radiologist, but also to all thoracic surgeons and physicians involved in managing critically ill patients.

Keywords: *Lung, Ultrasound, Pneumothorax, Effusion, Lung diseases*

Introduction

Ultrasound (US) is a very common tool in today's clinical practice. It is believed that use of ultrasound accounts for around 30% of all the medical imaging done worldwide. In UK, they have now stopped recording the number of US being done in clinical setups since 2014 due to its overwhelming numbers which reach in millions per year.[1] In Nepal, the ultrasound started being used since 1976 in limited indications. [2] The use of ultrasound in recent years have become so common for multiple clinical uses. In year 1942, neurologist Karl Dussik was the first person to use ultrasound machine as a diagnostic tool in medicine. [3] Fraçois Jardins and his intensive care

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team introduced the utility of lung ultrasound in emergency care in 1989. Since 1991, Point of care ultrasound (POCUS) was utilized by intensivists for diagnosis and vascular access in critical care medicine including lung ultrasound. In recent years, Lung ultrasound in critically ill (LUCI) has gained its popularity in diagnostic and therapeutic approach. The World Interactive Network Focused on Critical Ultrasound (WINFOCUS) established nomenclature and indications to use lung ultrasound in critical care practice in the International Consensus Conference on Lung Ultrasound (ICC-LUS). [4] Now the use is being expanded in Thoracic Oncology as well.

Ultrasound Generation Ultrasound waves are generated by tiny piezoelectric crystals that are packed within the ultrasound transducers. When an alternate current is applied to these crystals, they contract and expand at the same frequency at which the current changes polarity and generate an ultrasound beam. This generated ultrasound travels through the body and is reflected back to the transducer and an image is created.

Basic Characteristic of Ultrasound Sound is a form of energy and has various frequencies. Humans can perceive the sound waves with frequency from 20-20000 Hz. Ultrasound are the non-audible sounds with frequencies higher than 20000 Hz. Infrasounds are the soundwaves with frequency of less than 20 Hz. Ultrasound has existed in nature for more than a million years and animals use these sound to locate its prey and navigate its flight in darkness. The discovering how bats navigate in 1938 by Donald R. Griffin and Robert Galambos led to the discovery of Ultrasound. [5]

Most fluids and blood have relatively fewer acoustic impedance and hence produce hypoechoic signals. Air is a poor conductor of sound and hence can result in difficult visualization or artifact. It is impossible to view the structures under the bone, as the bone results in complete reflection of the sound waves. The ultrasound machine works in the range of one to 20 megahertz (MHz). Transducers with a frequency range of 5 to 15 MHz are beneficial to image superficial structures like lung and vascular anatomy whereas transducers with a frequency of 2 to 5 MHz are used to image deeper tissues like intra-abdominal organs.

The common transducers used in ultrasound imaging are linear, phased and curvilinear array type. The linear array probe is used to image the superficial structures and vasculatures. The phased array type is used to image the cardiac domain, and the curvilinear array is used to image the intra-abdominal organs.[6]

Modes of Ultrasound There are three basic modes to study ultrasound. Amplitude Mode (A-Mode): Amplitude mode is the display of amplitude spikes on the screen with X (depth) and Y (amplitude) axis plotted as a graph. It is frequently used to study the eye. [7] Brightness mode (B-mode): An array of transducers produces a planar 2D image. This is the most commonly used mode and is the mode of choice in our discussion unless mentioned otherwise. [7] Motion Mode (M-Mode): A sequence of two dimensions with time on the horizontal axis and tissue depth on vertical axis follow each other and help in the detection of movement of organ boundaries as the depth from the probe changes in moving organs.[8]

Lung Ultrasound

Lung ultrasound was popularized by Daniel Lichtenstein, a French intensivist. He noted that sonographic artifacts during lung ultrasound could differentiate between various lung diseases and subsequently noted various signs in ultrasound imaging to differentiate various diseases. With these findings he and his team developed the BLUE protocol for dyspneic patients being admitted to the ICU. [9] The BLUE protocol diagnosed six common respiratory diseases, including pulmonary edema and pneumonia, with 90.5% accuracy. Later the same group developed the FALLS protocol (Fluid Administration Limited by Lung Sonography). This protocol was used to guide the clinicians to guide the clinicians to administer fluid in ICU with the use of ultrasound. Hence with these works, lung ultrasound shows variety of situations especially in the setting of trauma, ICU, where transporting patients to the radiology department would be cumbersome.

Lung ultrasound allows the clinicians to examine the lung and pleural space. It can reduce the use of standard chest radiography (CXR) and computerized tomography (CT) in the intensive care unit (ICU).[10] Point-of-care ultrasound (POCUS), which also includes lung ultrasound can be defined as the use of an image-producing ultrasound device for diagnostic and procedural guidance, by the clinician himself, at the point of care, in real time allowing for direct correlation with signs and symptoms.[11]

Lung ultrasound is usually performed with a high-frequency linear probe of 7.5-10 MHz. However in obese patients, who could have skin to deep surface distance of around 5-8cms, linear probe would be unsuitable, and a curvilinear probe would be better suited in these situations. [12] Lung ultrasound has rapidly gained popularity over the past 10 years, mainly due to its wide availability in emergency and trauma settings, as well as trends toward the point of care ultrasound (POCUS) usage in training programs. Additionally, ultrasound circumvents many of the issues that arrive with traditional radiography, such as delay of care and radiation exposure. In an unstable patient, who is unfit for extended delays due to transport to the CT scanner or even bedside chest radiography, bedside ultrasound is readily available to physicians. In addition, numerous studies have shown equivalent or often improved sensitivity and specificity of POCUS compared with conventional radiography, namely chest x-rays. Bedside ultrasound (US) may also aid in differentiating between pathologies that conventional radiography may be unable to determine. [13] [(14)]

According to a systematic review performed by Sorensen B which mainly focused in the use of Lung ultrasound by GPs across various countries found that French emergency departments have seen an increase in the availability of ultrasound equipment from 52 to 71% between 2011 and 2016. Around 89% of Danish emergency physicians had access to ultrasound in 2013. Similarly, 54% in China had acesss to ultrasound in 2016, of which 43% of them reported using POCUS in their clinical work. In South Korea, more than 82.7% of clinicians used POCUS daily on adult patients, but only in 23.6% of pediatric patients. The use of POCUS is integrated in the emergency physician training in the USA. [15]

Indications of Lung Ultrasound

- Pneumonia or other recurring infections
- Cardiogenic pulmonary edema
- Acute Respiratory Distress Syndrome (ARDS)
- COPD/Asthma
- Pneumothorax
- Shortness of breath

The major limitations of lung ultrasound are:

- Subcutaneous emphysema:
- Severely obese patients

Image Acquisition in Lung Ultrasound Lung ultrasound can be performed in various ways. The main objective of lung ultrasound is to rapidly examine all the areas of the lung in order to not miss important diagnosis.

Position of the patient The examination can be performed in supine, upright or lateral decubitus position, however, in most clinical scenarios, supine position remains most commonly performed position. According to Liechtenstein, 6 points of lung ultrasound probe positioning have been defined. [14] According to Vi dinh article on Lung ultrasound made easy, these points have been labeled as R1, R2, R3 and L1, L2, L3 (Fig1). R1/L1 corresponds to Anterior Superior lung fields and the probe is placed in mid-clavicular line at the 2nd intercostal space. R2/L2 corresponds to lateral lung fields midaxillary line around the 6-7th intercostal space. This should be just lateral to the nipple line in males. R3/L3 corresponds to Posterior Inferior also known as PLAPS point at the intersection of the posterior axillary line and a rib space between the 10th and 12th ribs.

Signs and Lines in the Lung Ultrasound: While using lung ultrasound, almost 99% of the waves are reflected back from the soft tissue and air interface. Therefore, the structures below the pleura which is the air filled lung will not be visualized and only the artifacts will be seen. The appearance of these artifacts will vary depending on the relative amount of air and fluid in the lungs or pleural cavity which leads to appearance of various signs in lung ultrasound image.[16] Liechtenstein suggested various signs seen during lung ultrasound based on this principle. These include the following.[1]

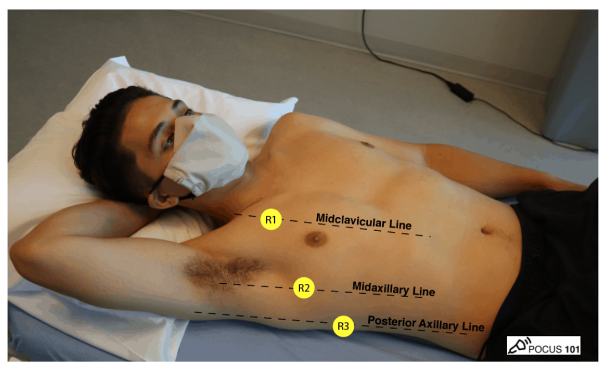

Figure 1. Lung ultrasound 6 points of probe placement

Bat Sign: The bat sign refers to the characteristic hyperechoic line that appears in the ultrasound image of the pleural line along with the adjacent ribs.[15] The ribs resemble the bat wings while the pleural line below the ribs mimics the body of the bat. Pleural line lies about half a centimeter below the ribs. When the probe is placed longitudinally on the chest wall, this sign can be noted. If placed obliquely along the intercostal space, only the pleural line is seen without the ribs. The bat sign is seen in almost all conditions, exception being subcutaneous emphysema, as the air in the subcutaneous tissues prevents adequate imaging of the structures underneath.

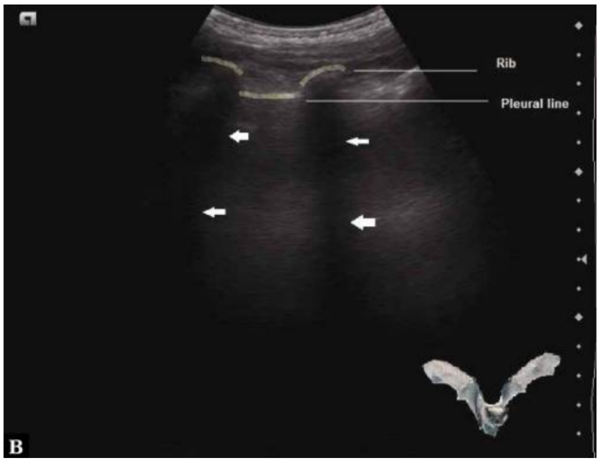

Figure 2. Ribs and pleural line are outlined in white; arrows point to rib shadows showing bat wing appearance

A-lines: A-lines are echogenic, gradually fading horizontal lines that appear at equal intervals below the pleural line. They represent the repetition artifact of the parietal pleura. Their presence indicates that air present below the pleura, which reflects the ultrasound waves back to the probe. This causes movement of waves to and fro between the transducer and the air beneath the pleura, hence, this artifact. [9,15] The distance between A-lines is almost the same as the distance between the skin surface and the pleural line. A-lines are seen both in the normal lung and in pneumothorax. A-lines are better visualized with the linear probe.

Lung sliding sign: The lung sliding sign refers to the movement between the two pleural layers during respiration. Its presence indicates that the two pleural layers are in apposition to each other and sliding with respiration. [15]This sign is better appreciated when a higher frequency linear transducer is used. This sign is not seen in conditions in which the two pleural layers are not opposed to each other as in pneumothorax or in pleural effusion. It cannot be seen when the pleura are firmly adherent to each other, for example: pneumonia complicated by adhesions, pleurodesis or in cases of pneumonectomy, one lung intubation.[9] It needs to be emphasized that even though the sign is not seen in pneumothorax, its absence does not always mean that pneumothorax is present. [16] In critical patients it might be difficult to obtain lung sliding alone, therefore, an addition of power Doppler to the test would help identify the lung sliding called as power slide sign

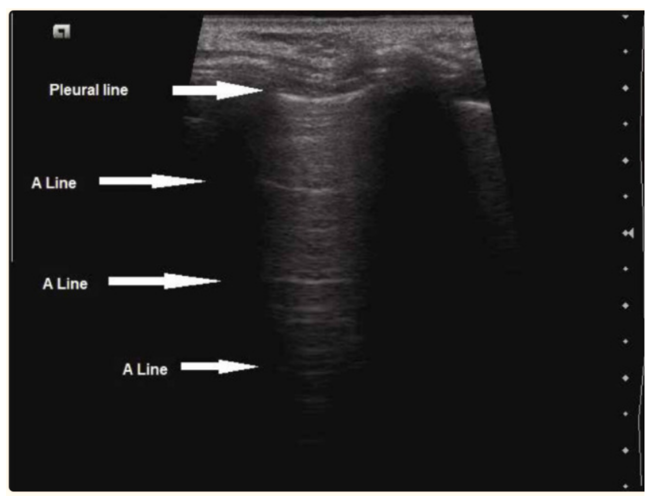

Figure 3. Image showing A lines indicated by arrow.

Sea-shore and Barcode sign: Lung sliding seen on the motion (M) mode images appears as the sea-shore. This sign appears as horizontal echogenic lines represent the pleura and the overlying structures, while the underlying lung gives a grainy or sand-like appearance. The stratified appearance above the pleural line is due to the motionless chest wall (sea waves); whereas below the pleural line, the movement of the lung shows a sandy pattern (the shore). [9, 15] If lung sliding is absent, it will appear on the M-mode images as uniform horizontal straight lines known as the stratosphere sign or the barcode sign. This sign suggests pneumothorax as a probable cause.

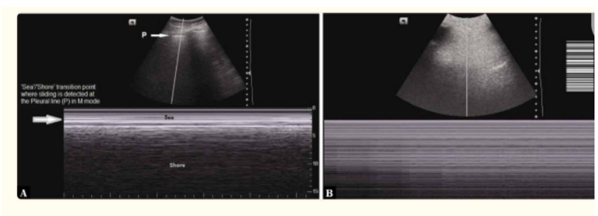

Figure 4. Image in M mode of ultrasound; Image A represents a normal sea shore sign. Image B represents stratosphere/barcode sign where the pleura has no motion.

B-lines: B-lines are also known as ultrasound lung comets due to vertical wave artifacts that originate from the pleural line and extend to the depth of the image without decreasing in intensity and move synchronously with lung sliding. [9] Their characteristic feature is that they conceal A-lines. An increase in the density of the underlying lung caused by exudate, transudate, collagen, blood lowers the acoustic mismatch between the pleura and the underlying structures. This causes the reflection of the ultrasound beam back to the transducer, and to and fro movement of the reflected beam produce distinctive comet tail like Artifacts. [17, 18] B-lines are not seen in pneumothorax as they are seen only at pleura/ tissue acoustic interface. Occasional B-lines (up to two) can be seen in normal lungs commonly at the bases. They are considered significant if three or more B-lines are seen in a single image between two ribs.

7.

Figure 5:Image representing vertical B lines (white arrow).

Quad sign and Sinusoid sign: In cases of pleural effusion, the two pleural layers are separated by fluid in-between, the visceral pleura appears as a line (the lung line), which is regular and almost parallel to the parietal pleura (the pleural line) along with the shadows from the adjacent ribs, these lines appear as a four-sided figure which is known as the quad sign. On the M-mode ultrasonography, a sinusoid pattern is seen due to the movement of the lung line towards the pleural line on inspiration and back on expiration. This is referred to as the sinusoid sign. The appearance of this sign indicates the presence of low-viscosity fluid in between the two pleural layers. Thereby, sinusoid sign may also be of use in differentiating between pleural effusion and pleural thickening. Its presence indicates the movement of free fluid in an effusion. [19]

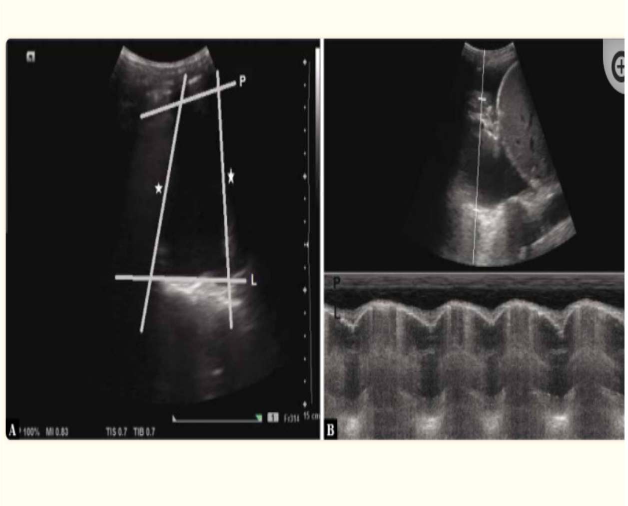

Figure 6. Grey scale longitudinal ultrasound scan of the intercostal space depicting the quad sign. The area of pleural effusion is framed within four regular borders: the pleural line-P, the shadow of the ribs (stars)

Jelly-fish sign: In case of significant pleural effusion, the collapsed lung moves along with respiration and appears as a swimming or flapping jellyfish which is referred to as the jellyfish sign. [15] This sign implies the absence of consolidation and pleural adhesions in the region. [20] Free movement as seen in this sign signifies presence of low viscous fluid, which further suggests transudative type of pleural effusion as opposed to high viscosity associated with exudative effusion that obstructs free movement of the collapsed lung. A similar appearance may also be noted in cases of rupture of the hydatid cyst of the lung into the pleural cavity.

Spine Sign: Spine sign is seen in pleural effusion. [15] Pleural effusion creates an acoustic window which allows the visualization of the vertebral bodies above the diaphragm. Normally, the vertebral bodies are not seen through the aerated lungs.

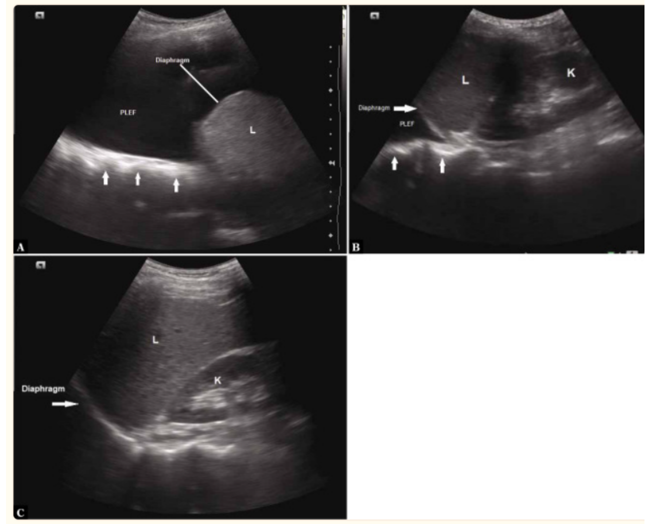

Figure 7. Grey scale longitudinal ultrasound scan of the intercostal space depicting the visualization of vertebral bodies above the diaphragm in a case of pleural effusion (A and B). The vertebral bodies are not normally seen above the level of the diaphragm (C)

Shred Sign or Fractal sign and Tissue-like sign: Fractal sign is seen when the margin between the consolidated and aerated lung is an irregular (shredded/fractal) line which is opposed to the lung line. If the area of consolidation is large, the deeper border is not appreciated, and the consolidated lung appears as a tissue [15] i.e. as liver on the right side, and as spleen on the left side (though separated from them by the diaphragm)

Curtain sign: This sign is seen in the inferior most part of the lateral lung along the costophrenic angles. It is seen in normal lungs as the aerated part of the lungs overlap the tissue or organs below the diaphragm as liver or spleen giving the appearance of curtain above those organs.

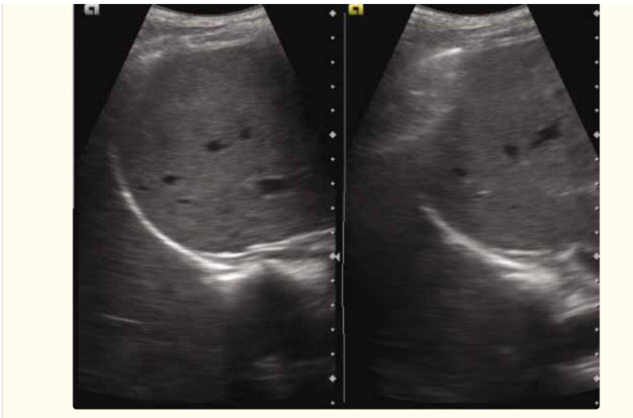

Figure 8. showing curtain sign

Plankton sign: Plankton sign refers to the appearance of freely floating debris on ultrasonographic image. Its appearance denotes the pleural effusion to be highly of exudative or hemorrhagic variety.

Figure 9. Plankton sign (L- liver, PLEF- pleural effusion) [16]

Lung Point sign: This sign is highly specific for pneumothorax. It is the point where normal sliding lung meets the point of pneumothorax where lung sliding is absent. It may help in estimating the size of pneumothorax as the probe is moved posteriorly and laterally searching the lung sliding, the bigger pneumothorax is suspected. However, it cannot be elicited in all cases of pneumothorax.

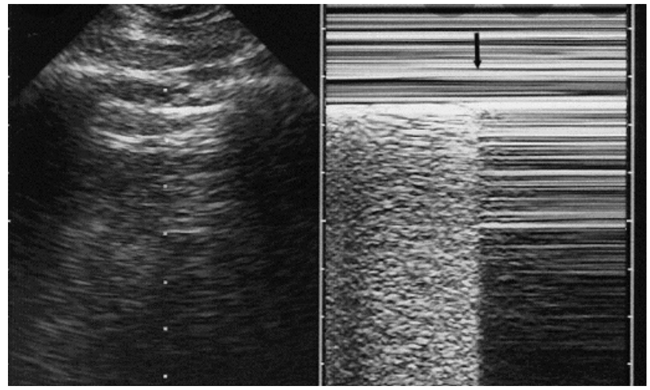

Figure 10: Lung point sign (normal sea-shore sign on M mode followed by barcode sign) [14]

The Blue Protocol: The blue protocol was developed by Lichtenstein and team for the patients with acute respiratory failure where the patients undergo lung ultrasound and the cause of acute respiratory failure is tried to interpret. This protocol uses a series of findings of above signs and line in the ultrasound to reach the diagnosis. [14] Fig 8

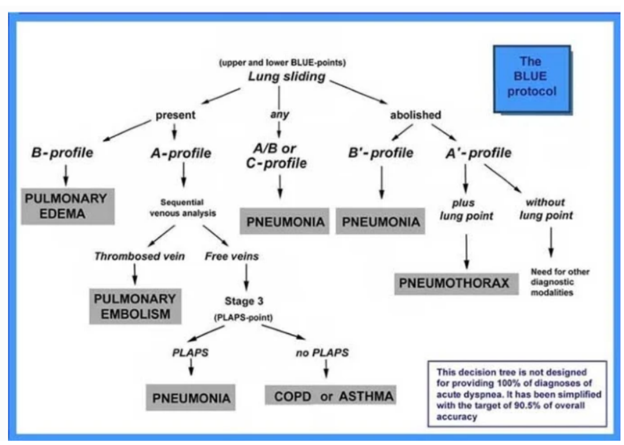

Figure 8 . The BLUE protocol for acute dyspnea

Ultrasonography for the evaluation of pneumothorax:

According to Alrajab S lung ultrasound is superior to anteroposterior view chest Xray for detection of pneumothorax, in critically ill patients for whom transport to radiological department would not be possible. In their study, ultrasonography had sensitivity of 78.6% (95% CI 68.1–98.1) and a specificity of 98.4% (95% CI 97.3–99.5) and the sensitivity and specificity of Chest radiography was 39.8% (95% CI 29.4–50.3) and 99.3% (95% CI 98.4–100) respectively.[25] This study emphasizes the use of ultrasound in ICU, or a postoperative setting.

Shostak E et. Al, performed a study which was focused on detection of iatrogenic pneumothorax using lung ultrasound and comparing it with chest radiograph in patient undergoing lung biopsy; either bronchoscopic or percutaneous biopsy. The average time required for chest radiography report interpretation was around 49 mins where as that of obtaining an ultrasonography was around 36 mins.[26] According to Bholi et al., lung ultrasound to detect 43 of 48 patients with pneumothorax in trauma cases with sensitivity accounting for sensitivity of around 89.6. The sensitivity of Chest X-ray in supine position was only about 68.8%. Hence, they concluded lung ultrasound was better than supine x-ray in detecting traumatic pneumothorax.[16]

Lung ultrasound not only offers advantages over X-ray chest but also has advantages over computed tomography (CT), which is considered the gold standard investigation.[9] It includes lack of radiation, lack of need for patient transportation, reduced cost and ready availability.

Although above studies highlight the better performances of lung ultrasound, there are certain situations where ultrasound fails to detect pneumothorax. These situations include bullous lesions, loculated pneumothorax, pleural calcifications and surgical emphysema.

Hence the role of lung ultrasound in detecting pneumothorax may be used as an adjunct to clinical scenarios, however, it cannot replace the CT imaging as a gold standard for diagnosis of pneumothorax.

Pleural Effusion

There are various etiologies of pleural effusion. In cases of patient in either postoperative and ICU patients volume overload, pleuro-pulmonary infections, congestive cardiac failure and reactive effusions are quite common. The use of lung ultrasound is gaining a wide acceptance in diagnosis and to identify the cause of pleural effusion in ICU settings. According to Goligher EC et al., early drainage of pleural effusion can result in improved ventilation and ultimately better outcome in patients.[27] In these situation lung ultrasound is an excellent non-invasive tool to have to look for the presence of effusion. The role of ultrasound is not only limited in diagnosis of pleural effusion, infact, it can help to guide the accurate location of puncture for thoracocenthesis or thoracostomy with minimal complications and also help to decide the right time for removal of chest drain.[28] Various studies have shown a good sensitivity and specificity of lung ultrasound in detecting pleural effusion surpassing that of physical examination and bedside radiography.[29, 30]

Pleural Complications in Early Postoperative Period

Respiratory failure in early postoperative period can be due to atelectasis, which actually is contributed by diaphragmatic dysfunction and inability to clear secretions. Physical examination with auscultation, percussion and bedside chest x-ray are commonly used modalities in the diagnosis of postoperative complications. However, their diagnostic accuracy is limited. [31] It is so because patients required an upright position for these modalities which might not be always possible in postoperative settings. Computed tomography (CT) is the gold standard for pulmonary pathology but radiation exposure and also transport of patients may not always be feasible and could be associated with added risk to the patient. [23] In a study by Goudy et al., where patients undergoing cardiothoracic surgery were checked for postoperative complications using lung ultrasound and found that it was feasible in 97% of the cases despite the patient having dressing and tubes in situ.[32]

In thoracic surgery, the timely detection of postoperative complications is difficult due to the absence or late presentation of clinical symptoms. The chest tube can be used for diagnosis, but may be insufficient due to obstructions from clotted blood. In postoperative cases with complications, chest X-ray frequently reveals a partial or complete opacification of the hemithorax such that it is not possible to distinguish between hemothorax, pleural effusion, obstructive atelectasis, and pneumonia. In contrast, sonography is capable of determining the cause of opacification; various causes of lung consolidation, including pneumonia, compression, and obstructive atelectasis, are easily distinguished by ultrasound.[4]

Ultrasound in Lung Pathologies

Lung ultrasound is a valuable tool in identifying various lung pathologies and has been found to be better suited when the pulmonary interstitium thickens either due to fluid or fibrosis, B lines replaces the normal A lines and hence represents any disease of the lung parenchyma. The use of lung ultrasound had a significant role in COVID era and various reports suggested advantages of lung ultrasound for diagnosis of interstitial pneumonia.[33] According to Wang M et al., in patient with COVID pneumonia both lung ultrasound and CT scan could be used in diagnosis, assessment of disease severity, and evaluation of prognosis of the disease especially in cases of emergency and critically ill patients.[34]

Limitation of lung Ultrasound

Although lung ultrasound is a valuable tool to have, it also has its limitations and every physicians using it should realize it. Performing and interpreting the images of lung ultrasound remains one of the major limitations as the clinician must go through some form of training to gain adequate knowledge and skills. According to Liechtenstein, performing lung ultrasound on daily basis with trained supervision for at least six week could result inter and intra observer difference to less than 5% for lung ultrasound.[33]

Patient characteristics also determines the usefulness of ultrasound. In severe obese patients, clinicians might find it difficult to acquire the images due to the thickness of the adipose tissue and distance of rib cage form the skin.

Surgical emphysema is a major limitation to perform lung ultrasound as the ultrasound waves fail to propagate through air and hence non-visualization of deeper structures.

Conclusion

Lung ultrasound is relatively cheap, easily available and quite useful tool to have in ICU or postoperative ward. Although there are limitation to Lung ultrasound, and CT still remains the gold standard for diagnosis of lung pathologies, ultrasound has shown to be equally effective in diagnosis and management of patients in critically ill set ups, where obtaining CT scan or other imaging technique is not feasible. Hence, lung ultrasound is a must have tool and knowledge and skills related to lung ultrasound should not only be limited to Radiologist, but also to all thoracic surgeons and physicians involved in managing critically ill patients. It is also important for all the hospitals to have portable ultrasound machines easily available to those involving in managing these cases.

References

1. Duck F. Ultrasound–The first fifty years. Med Phys Int J. History of Medical Physics. 2020;5:470-98
2. Subedi KS, Sharma P. Development of radiology in Nepal: gearing up for mountainous challenges. J Am Coll Radiol. 2013 Apr;10(4):291-5. doi: 10.1016/j.jacr.2012.12.020. Epub 2013 Mar 7. PMID: 23465888.
3. Dussik KT. On the possibility of using ultrasound waves as a diagnostic aid. Neurol Psychiat. 1942;174:153-68.
4. Volpicelli G, Elbarbary M, Blaivas M, Lichtenstein DA, Mathis G, Kirkpatrick AW, Melniker L, Gargani L, Noble VE, Via G, Dean A, Tsung JW, Soldati G, Copetti R, Bouhemad B, Reissig A, Agricola E, Rouby JJ, Arbelot C, Liteplo A, Sargsyan A, Silva F, Hoppmann R, Breitkreutz R, Seibel A, Neri L, Storti E, Petrovic T; International Liaison Committee on Lung Ultrasound (ILC-LUS) for International Consensus Conference on Lung Ultrasound (ICC-LUS). International evidence-based recommendations for point-of-care lung ultrasound. Intensive Care Med. 2012 Apr;38(4):577-91. doi: 10.1007/s00134-012-2513-4. Epub 2012 Mar 6. PMID: 22392031.
5. Kane D, Grassi W, Sturrock R, Balint PV. A brief history of musculoskeletal ultrasound: 'From bats and ships to babies and hips'. Rheumatology (Oxford). 2004 Jul;43(7):931-3. doi: 10.1093/rheumatology/keh004. PMID: 15213339.
6. Ferrada P, editor. Ultrasonography in the ICU: Practical Applications. Springer; 2015 May 18
7. Carovac A, Smajlovic F, Junuzovic D. Application of ultrasound in medicine. Acta Inform Med. 2011 Sep;19(3):168-71. doi: 10.5455/aim.2011.19.168-171. PMID: 23408755; PMCID: PMC3564184.
8. Saul T, Siadecki SD, Berkowitz R, Rose G, Matilsky D, Sauler A. M-Mode Ultrasound Applications for the Emergency Medicine Physician. J Emerg Med. 2015 Nov;49(5):686-92. doi: 10.1016/j.jemermed.2015.06.059. Epub 2015 Aug 17. PMID: 26293413.
9. Lichtenstein DA, Menu Y. A bedside ultrasound sign ruling out pneumothorax in the critically ill. Lung sliding. Chest. 1995 Nov;108(5):1345-8. doi: 10.1378/chest.108.5.1345. PMID: 7587439
10. Brogi E, Bignami E, Sidoti A, Shawar M, Gargani L, Vetrugno L, Volpicelli G, Forfori F. Could the use of bedside lung ultrasound reduce the number of chest x-rays in the intensive care unit? Cardiovasc Ultrasound. 2017 Sep 13;15(1):23. doi: 10.1186/s12947-017-0113-8. PMID: 28903756; PMCID: PMC5597991.
11. Moore CL, Copel JA. Point-of-care ultrasonography. N Engl J Med. 2011 Feb 24;364(8):749-57. doi: 10.1056/NEJMra0909487. PMID: 21345104.
12. Kiley S, Cassara C, Fahy BG. Lung ultrasound in the intensive care unit. J Cardiothorac Vasc Anesth. 2015 Feb;29(1):196-203. doi: 10.1053/j.jvca.2014.10.017. PMID: 25620145.

13. Wongwaisayawan S, Suwannanon R, Sawatmongkorngul S, Kaewlai R. Emergency Thoracic US: The Essentials. Radiographics. 2016 May-Jun; 36(3):640-59. doi: 10.1148/rg.2016150064. Epub 2016 Apr 1. PMID: 27035835.

14. Lichtenstein DA. Lung ultrasound in the critically ill. Ann Intensive Care. 2014 Jan 9;4(1):1. doi: 10.1186/2110-5820-4-1. PMID: 24401163; PMCID: PMC3895677.

15. Sorensen B, Hunskaar S. Point-of-care ultrasound in primary care: a systematic review of generalist performed point-of-care ultrasound in unselected populations. Ultrasound J. 2019 Nov 19;11(1):31. doi: 10.1186/s13089-019-0145-4. PMID: 31749019; PMCID: PMC6868077.

16. Bhoil R, Kumar R, Kaur J, Attri PK, Thakur R. Diagnosis of Traumatic Pneumothorax: A Comparison between Lung Ultrasound and Supine Chest Radiographs. Indian J Crit Care Med. 2021 Feb;25(2): 176-180. doi: 10.5005/jp-journals-10071-23729. PMID: 33707896; PMCID: PMC7922442.

17. Lichtenstein DA. Whole body ultrasonography in the critically ill. Springer Science & Business Media; 2010 Jul 3.

18. Miller A. Practical approach to lung ultrasound. Bja Education. 2016 Feb 1;16(2):39-45

19. Murphy M, Nagdev A, Sisson C. Lack of lung sliding on ultrasound does not always indicate a pneumothorax. Resuscitation. 2008 May;77(2):270. doi: 10.1016/ j.resuscitation.2007.10.026. Epub 2008 Feb 20. PMID: 18243478.

20. Vieira JR, Castro MR, Guimarães TP, Pinheiro AJT, Figueiredo ACTC, Martins BJ, Carmo DRD, Oliveira WA. Evaluation of pulmonary B lines by different intensive care physicians using bedside ultrasonography: a reliability study. Rev Bras Ter Intensiva. 2019 Oct 14;31(3):354-360. doi: 10.5935/0103-507X.20190058. PMID: 31618355; PMCID: PMC7005945.

21. Lichtenstein D, Mezière G, Biderman P, Gepner A. The comet-tail artifact: an ultrasound sign ruling out pneumothorax. Intensive Care Med. 1999 Apr;25(4): 383-8. doi: 10.1007/s001340050862. PMID: 10342512.

22. Lichtenstein DA, Mauriat P. Lung Ultrasound in the Critically Ill Neonate. Curr Pediatr Rev. 2012 Aug;8(3): 217-223. doi: 10.2174/157339612802139389. PMID: 23255876; PMCID: PMC3522086.

23. Han J, Xiang H, Ridley WE, Ridley LJ. Jellyfish sign: Pleural effusion. J Med Imaging Radiat Oncol. 2018 Oct;62 Suppl 1:33. doi: 10.1111/1754-9485.20_12785. PMID: 30309093.

24. Alrajab S, Youssef AM, Akkus NI, Caldito G. Pleural ultrasonography versus chest radiography for the diagnosis of pneumothorax: review of the literature and meta-analysis. Crit Care. 2013 Sep 23;17(5):R208. doi: 10.1186/cc13016. PMID: 24060427; PMCID: PMC4057340.

25. Shostak E, Brylka D, Krepp J, Pua B, Sanders A. Bedside sonography for detection of postprocedure pneumothorax. J Ultrasound Med. 2013 Jun;32(6): 1003-9. doi: 10.7863/ultra.32.6.1003. PMID: 23716522; PMCID: PMC4041153.

26. Goligher EC, Leis JA, Fowler RA, Pinto R, Adhikari NK, Ferguson ND. Utility and safety of draining pleural effusions in mechanically ventilated patients: a systematic review and meta-analysis. Crit Care. 2011;15(1):R46. doi: 10.1186/cc10009. Epub 2011 Feb 2. PMID: 21288334; PMCID: PMC3221976.

27. Havelock T, Teoh R, Laws D, Gleeson F; BTS Pleural Disease Guideline Group. Pleural procedures and thoracic ultrasound: British Thoracic Society Pleural Disease Guideline 2010. Thorax. 2010 Aug;65 Suppl 2:ii61-76. doi: 10.1136/thx.2010.137026. PMID: 20696688.

28. Rocco M, Carbone I, Morelli A, Bertoletti L, Rossi S, Vitale M, Montini L, Passariello R, Pietropaoli P. Diagnostic accuracy of bedside ultrasonography in the ICU: feasibility of detecting pulmonary effusion and lung contusion in patients on respiratory support after severe blunt thoracic trauma. Acta Anaesthesiol Scand. 2008 Jul;52(6):776-84. doi: 10.1111/j. 1399-6576.2008.01647.x. Epub 2008 May 12. PMID: 18477080.

29. Xirouchaki N, Magkanas E, Vaporidi K, Kondili E, Plataki M, Patrianakos A, Akoumianaki E, Georgopoulos D. Lung ultrasound in critically ill patients: comparison with bedside chest radiography. Intensive Care Med. 2011 Sep;37(9):1488-93. doi: 10.1007/s00134-011-2317-y. Epub 2011 Aug 2. PMID: 21809107.

30. Touw HR, Schuitemaker AE, Daams F, van der Peet DL, Bronkhorst EM, Schober P, Boer C, Tuinman PR. Routine lung ultrasound to detect postoperative pulmonary complications following major abdominal surgery: a prospective observational feasibility study. Ultrasound J. 2019 Sep 16;11(1):20. doi: 10.1186/s13089-019-0135-6. PMID: 31523784; PMCID: PMC6745303.

31. Goudie E, Bah I, Khereba M, Ferraro P, Duranceau A, Martin J, Thiffault V, Liberman M. Prospective trial evaluating sonography after thoracic surgery in postoperative care and decision making. Eur J Cardiothorac Surg. 2012 May;41(5):1025-30. doi: 10.1093/ejcts/ezr183. Epub 2011 Dec 23. PMID: 22219462.

32. European Society of Radiology (ESR). The role of lung ultrasound in COVID-19 disease. Insights Imaging. 2021 Jun 19;12(1):81. doi: 10.1186/s13244-021-01013-6. PMID: 34146161; PMCID: PMC8214066.

33. Wang M, Luo X, Wang L, Estill J, Lv M, Zhu Y, Wang Q, Xiao X, Song Y, Lee MS, Ahn HS, Lei J, Tian J. A Comparison of Lung Ultrasound and Computed Tomography in the Diagnosis of Patients with COVID-19: A Systematic Review and Meta-Analysis. Diagnostics (Basel). 2021 Jul 27;11(8):1351. doi: 10.3390/diagnostics11081351. PMID: 34441286; PMCID: PMC8394642.

34. Lichtenstein D, Goldstein I, Mourgeon E, Cluzel P, Grenier P, Rouby JJ. Comparative diagnostic performances of auscultation, chest radiography, and lung ultrasonography in acute respiratory distress syndrome. Anesthesiology. 2004 Jan;100(1):9-15. doi: 10.1097/00000542-200401000-00006. PMID: 14695718.

35. Gargani L, Volpicelli G. How I do it: lung ultrasound. Cardiovasc Ultrasound. 2014 Jul 4;12:25. doi: 10.1186/1476-7120-12-25. PMID: 24993976; PMCID: PMC4098927.

36. Piette E, Daoust R, Denault A. Basic concepts in the use of thoracic and lung ultrasound. Curr Opin Anaesthesiol. 2013 Feb;26(1):20-30. doi: 10.1097/ACO.0b013e32835afd40. PMID: 23103845.