Research Article

TEHRAN UNIVERSITY OF MEDICAL SCIENCES

Archives of Anesthesiology and Critical Care (Summer 2023); 9(3): 220-226.

Available online at http://aacc.tums.ac.ir

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Ultrasound for Perioperative Lung Monitoring of Patients Undergoing Thoracic Surgery with One-Lung Ventilation

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ARTICLE INFO

Article history:
Received 20 May 2022
Revised 10 Jun 2022
Accepted 24 Jun 2022

Keywords:
Diagnostic imaging;
One-lung ventilation;
Thoracic surgery;
Lung ultrasonography

ABSTRACT

Background: The diagnostic efficacy of lung ultrasonography (LUS) has been widely investigated. However, the clinical value of LUS for perioperative monitoring has rarely been reported. The aim of this study was to evaluate the ability of LUS to assess lung aeration status after one-lung ventilation (OLV) using a validated scoring system.

Methods: In this prospective observational study, patients undergoing elective video-assisted thoracic surgery (VATS) with OLV underwent a lung ultrasound examination just after induction of anesthesia and at the end of the surgery. After each lung ultrasound examination, a semiquantitative score, the LUS score, was calculated to assess lung aeration on the ventilated dependent side and the non-dependent side separately. The relationship between the LUS scores and various patient-related factors was also investigated.

Results: Twenty-five patients were studied. All lung ultrasound examinations were successfully completed. LUS scores after OLV on the dependent side (median [IQR]: 2 [1–4]) increased significantly from baseline (1 [0–1.5], $P < 0.001$). Further, LUS scores on the non-dependent side (2 [1.5–3.5]) increased significantly from baseline (1 [0–1.5], $P < 0.001$). None of the factors analyzed was significantly correlated with LUS scores after OLV.

Conclusion: LUS examination is possible after VATS with OLV on both sides of the thorax. Ultrasonography-measured lung aeration scores increased from baseline on both sides.

Aeration loss due to atelectasis, pleural effusion, or pulmonary edema is a relatively common side effect of general anesthesia [1–5]. Such lung collapse causes a decline in arterial oxygenation and increases the risk of ventilation-induced lung injury and other postoperative pulmonary complications [1–4]. Therefore, early detection of these lesions is desirable. Anesthesia-induced atelectasis and pulmonary edema are typically small and invisible on standard chest radiographs, but they can be easily diagnosed by computed tomography (CT) or magnetic resonance imaging (MRI) [5-6]. However, these modalities are expensive, time consuming, involve harmful exposure to X-rays, and can cause risk of infection or accidental removal of endotracheal tubes during transportation in intubated patients [7].

Lung ultrasonography (LUS) is noninvasive and is superior to chest X-rays in detecting minimal aeration loss by visualizing the lesion near the pleura [6, 8–11]. It is recognized as a promising diagnostic technique in infants with bronchiolitis [12], mechanically ventilated adult patients with acute respiratory distress syndrome

The authors declare no conflicts of interest.
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(ARDS) [4, 8-9, 13–17]. Furthermore, since the pandemic of coronavirus disease 2019, many health care providers have become interested in the specific applications of LUS for patients with this disease [18]. Recent investigations have demonstrated that a validated scoring system allows follow-up assessment of these patients [8, 17, 19]. LUS can be also useful as a perioperative pulmonary lesion screening method that enables early treatment of pulmonary complications, prevents prolonged hospital stay, and leads to reductions in the cost of medical care. However, there are few reports describing the efficacy of ultrasonography for lung monitoring during anesthesia [5, 10, 20-21]. Moreover, evidence is lacking for the use of LUS during lung surgery. One-lung ventilation (OLV) is a challenging task that often causes hypoxia due to lung atelectasis or edema [22–26]. Thus, it can also be an object of LUS.

In this prospective observational study, we performed LUS in patients undergoing thoracic surgery requiring OLV. Referring to the LUS scoring system described in previous reports [8, 10, 19], we compared the aeration scores after OLV with those of baseline, on the ventilated dependent side and on the operated side separately. Specifically, we tested the primary hypothesis that lung aeration status on the dependent side is worse after OLV using LUS. We also investigated the relationship between the LUS scores and various patient-related factors.

Methods

Patients

After approval by the Institutional Review Board of Osaka National Hospital and registration with the University Hospital Medical Information Network (UMIN 000023507), we prospectively studied a consecutive series of patients who received video-assisted thoracic surgery (VATS) for lung tumor or anterior mediastinal tumor in the lateral decubitus position with unilateral OLV. Written informed consent was obtained from each participant. Patients were eligible if they were over the age of 20 and had an American Society of Anesthesiologists (ASA) physical status of I–III. Exclusion criteria were as follows: patients with spontaneous pneumothorax, emphysematous lung bullae, emergency surgery, or refusal or inability to give informed consent.

Anesthesia

On arrival in the operating room, a thoracic epidural catheter was inserted by an experienced anesthesiologist into the thoracic epidural space at the T5–T7 level under sterile conditions. The catheter was advanced 4–5 cm inside the epidural space, and a test dose of 3 ml lidocaine 1.5% with epinephrine 1:400 000 was administered to exclude misplacement of the catheter.

General anesthesia was induced with propofol 3–4 mcg/ml using a target controlled infusion (TCI) system and 2 mcg/kg fentanyl. Endobronchial intubation with a double-lumen tube (DLT) was facilitated with 0.6 mg rocuronium, and the position of the DLT was confirmed with a fiberoptic bronchoscope. Anesthesia was maintained with fentanyl and sevoflurane up to 2% or propofol using TCI at an adequate concentration to maintain the bispectral index between 40–60 in the electroencephalogram. The epidural catheter was used to provide analgesia during the surgery. During OLV, volume-controlled or pressure-controlled ventilation with a 5–8 ml/kg tidal volume (TV) of predicted body weight and a 5 cmH2O positive end-expiratory pressure (PEEP) was used. The respiratory rate was adjusted to maintain end-tidal carbon dioxide tension (ETCO2) between 30 and 40 mmHg, and FiO2 was maintained at 0.7–1.0 to keep peripheral oxygen saturation (SpO2) at 90% or higher.

At the end of OLV, recruitment maneuvers were performed as sustained inflation aimed at reexpansion of the operative lung.

In all cases, patients were scheduled to be extubated and transferred to the intensive care unit (ICU) after surgery. Chest X-rays were performed immediately after the transfer to detect or rule out postoperative pulmonary complications.

LUS

LUS was performed by experienced investigators on both the nonoperated side (dependent lung) and operated side (nondependent lung) in the supine position twice that is, just after induction of anesthesia and at the end of the operation. A Prosound alpha 6 ultrasound machine (Hitachi Aloka Medical Ltd. Mitaka, Tokyo, Japan) with a 6–12 MHz linear probe was used for imaging.

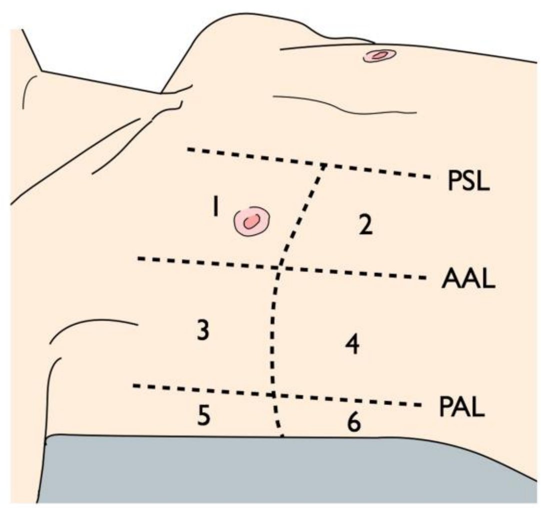

Figure 1- Scanning zones for lung ultrasonography

Each hemithorax is systematically divided in six regions (two anterior, two lateral, and two posterior regions) according to anatomical landmarks set by anterior and posterior axillary lines.

AAL, anterior axillary line; PAL, posterior axillary line; PSL, parasternal line.

Methods for evaluation were generally based on previous reports [5, 8, 10, 17, 19]. Each hemithorax is systematically divided in six regions (two anterior, two lateral, and two posterior regions) according to anatomical landmarks set by anterior and posterior axillary lines (Figure 1). Each region is divided in half, superior, and inferior. To perform a comprehensive examination, all adjacent intercostal spaces except the surgical wound must be explored in each region of interest, sliding the probe along the space.

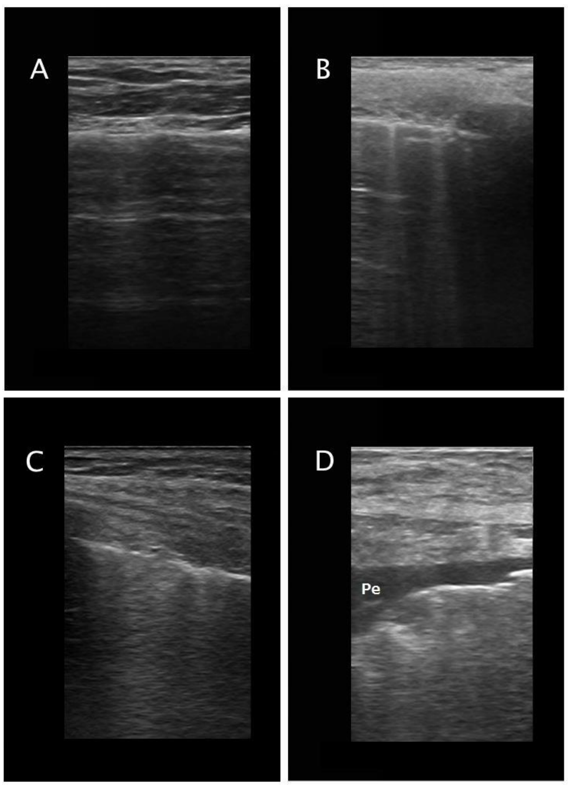

Figure 2- Lung ultrasound patterns corresponding to progressive loss of aeration

(A) Normal pattern. The pleural line is visible with multiple horizontal A-lines. (B) The pleural line is visible, with separated B-lines arising from the pleural line. This pattern corresponds to moderate lung aeration loss. (C) The pleural line is visible with coalescent B-lines. This pattern corresponds to severe lung aeration loss. (D) A consolidated lung lobe is visible behind the pleura. Lung has a tissue-like echotexture.

Pe, pleural effusion

For the assessment of lung aeration, four LUS patterns were used semiquantitatively (Figure 2): (1) presence of lung sliding with A-lines or fewer than two isolated B-lines (normal aeration, N); (2) presence of multiple separated B-lines (B1); (3) presence of multiple coalescent B-lines (B2); and (4) presence of a lung consolidation (C). Beyond the pleural line, motionless and regularly spaced horizontal lines to the pleura, A-lines, are visualized by ultrasonography; they correspond to normal reverberation artifacts of the pleural line [8, 27, 28]. The presence of lung sliding easily rules out a pneumothorax [8, 27]. A-lines and lung sliding define normal aeration (Figure 2A). Signs and patterns indicating aeration loss include B-lines, which are vertical hyperechoic lines that arise from the pleural line, spread without fading, and move synchronously with respiration. Multiple separated B-lines correspond to moderate lung aeration loss resulting from interstitial syndrome (Figure 2B). Coalescent B-lines correspond to severe lung aeration loss resulting from partial filling of alveolar spaces (Figure 2C). Lung consolidation pattern corresponds to massive aeration loss resulting from lobar atelectasis. It appears as a tissue-like echotexture (Figure 2D).

LUS scores were calculated based on the LUS patterns described above. For a given region of interest, points were allocated according to the worst ultrasound pattern observed: N = 0, B1 = 1, B2 = 2, and C = 3. The cumulative LUS score ranging from 0 to 36 corresponds to the sum of each examined region score. Increase in the LUS score indicates a decrease in aeration [8, 10, 17, 19]. To qualify aeration status in the dependent and the nondependent lung separately, the LUS scores on the left and right sides (ranging from 0 to 18) were also calculated.

Data collection

Preoperative demographics including age, weight, height, preoperative forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), FEV1/FVC ratio (FEV1%) were recorded. Intraoperative and postoperative parameters included the following: type of surgery, anesthesia time, operation time, duration of OLV, intraoperative infusion volume, the LUS scores before and after OLV on each side, and incidence of abnormal findings seen on chest radiograph after operation.

The primary outcome for this study was the temporal change in the LUS scores after OLV on the dependent side from the baseline. Secondary outcomes were changes in the LUS scores after OLV on the nondependent side from the baseline and correlation of the LUS scores after OLV with demographic, anesthetic, and surgical factors.

Power analysis and statistics

For power analysis and statistical analysis, the G*Power 3.1.3 and the JMP Pro 11® (SAS Institute) software were used, respectively. A power analysis indicated that 25 patients were needed. The sample size determination was based on a power of 80%, a type I error of 5%, a clinically significant change in the LUS score of 3, and a LUS score standard deviation of 5. Assuming a certain number of cases would be expected to withdraw from the study, we decided to increase the sample size to 35 patients. Continuous data were expressed as means with standard deviation (SD) or medians with interquartile range (IQR). Wilcoxon signed-rank test was performed to compare LUS scores before and after OLV. Spearman's coefficient was used to determine correlations. The significance level was set at 0.05 and the Bonferroni correction for multiple comparisons was used where appropriate.

Results

Table 1- Patient characteristics and surgical outcomes

Sex (M/F)	14/11
Age, years	70.3 ± 11.1
Height, m	1.59 ± 0.07
Weight, kg	57.7 ± 12.4
BMI, kg/m2	22.8 ± 3.9
ASA-PS classification	
I	4
II	20
III	1
VC, ml	2880 ± 657
FEV1, ml	2209 ± 575
FEV%	78.0 ± 7.2
Type of surgery	
Lobectomy	12
Segmentectomy	6
Partial resection	4
Anterior mediastinal tumor resection	3
Operative duration, min	287 ± 108
Anesthesia duration, min	384 ± 115
Duration of OLV, min	253 ± 104
Fluid balance during anesthesia, ml	1071 ± 423
Abnormal findings on postoperative chest radiograph	3

Continuous variables are presented as the mean ± SD.

ASA-PS, American Society of Anesthesiologists physical status; BMI, body mass index; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; FEV%, FEV1/FVC ratio; OLV, one-lung ventilation

Table 2- Abnormal findings seen on postoperative chest radiograph

Patient#	Abnormality	Operative side	LUS score on the left side	LUS score on the right side
2	Intralobar effusion on the right side	Left	6	6
3	Atelectasis in the right upper lobe	Left	9	6
12	Atelectasis in the right lower lobe	Right	2	2

LUS, lung ultrasonography; OLV, one-lung ventilation

Table 3- Correlation between LUS scores after OLV and demographic, anesthetic, surgical factors

	Coefficient with LUS score on the dependent side (ρ)	P	Coefficient with LUS score on the non-dependent side (ρ)	P value
Age	0.15	0.48	0.24	0.26
BMI	-0.12	0.57	-0.31	0.14
FVC	-0.04	0.84	-0.21	0.31
FEV1	-0.16	0.46	-0.34	0.11
FEV%	-0.34	0.10	-0.32	0.13
Operative duration	0.19	0.37	0.12	0.57
Anesthesia duration	0.22	0.28	0.12	0.56
Duration of OLV	0.10	0.64	0.01	0.95
Fluid balance during anesthesia	0.29	0.16	0.17	0.42

The Spearman's coefficient was used to determine correlations. BMI, body mass index; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; FEV%, FEV1/FVC ratio; LUS, Lung ultrasonography; OLV, one-lung ventilation

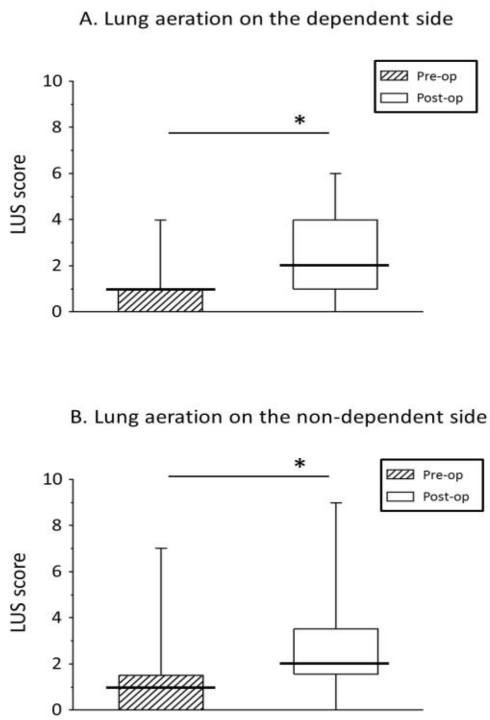

Figure 3- Temporal comparison of the LUS scores on the dependent side (A) and nondependent side (B)

Time points: pre-op = just after induction of anesthesia, post-op = after one-lung ventilation (OLV). The horizontal bars, the boxplots, and the vertical bars show the median, 50% of the results (interquartile ranges), and 5 to 95 percentiles, respectively. The LUS scores both on the dependent side (P< 0.001) and the non-dependent side (P< 0.001) were significantly greater after OLV than before OLV.

*P < 0.001 by Wilcoxon signed-rank test.

Of the 35 patients who were eligible to enter our study from November 2015 to March 2016, 8 patients were excluded due to the following reasons: refusal to participate (4 patients), emphysematous bullae (2 patients), spontaneous pneumothorax (1 patient), and emergency surgery (1 patient). Finally, 27 patients were enrolled. Two additional patients were excluded before the end of surgery due to bilateral OLV and absence of investigators at the time of measurement, respectively. Thus, 25 patients were included in the final analysis. The patient characteristics and surgical outcomes are presented in (Table 1). All patients were successfully extubated in the operating room and transferred to the ICU uneventfully. Abnormal findings on the postoperative chest radiograph were as follows: atelectasis (2 patients) and transient interlobar effusion (1 patient) (Table 2).

All examinations were successfully completed and required no more than 10 min per time point. There were no cases of difficult LUS assessment on the nondependent side due to residual pneumothorax. LUS scores after OLV on the dependent side (median [IQR]: 2 [1–4]) increased significantly from baseline (1 [0–1.5], P < 0.001; Fig. 3A). LUS scores on the nondependent side (median [IQR]: 2 [1.5–3.5]) also increased significantly from baseline (1 [0–1.5], P < 0.001; Figure 3B). None of the factors analyzed was significantly correlated with LUS scores either on the dependent or the non-dependent side (Table 3).

Discussion

LUS has not yet been widely used in anesthesia management for thoracic surgery itself [30-32]. However, it is believed that LUS assessment can be performed in patients undergoing OLV. The results of the present study, which show a decrease in lung aeration after OLV, are consistent with those of previous studies [10, 20]. Various factors such as general anesthesia, body position of the patients, and fluid overload are assumed to worsen lung aeration on the dependent side in a complex manner [1, 3, 26]. As for the nondependent lung, we could compare the LUS scores before and after OLV. Despite temporary lung collapse during surgery and minor residual pneumothorax, LUS provided assessable images as long as the operative lungs were thoroughly reinflated and a chest drainage system was used appropriately. LUS assessment of the nondependent side might be less accurate than assessment of the dependent side, due to surgical incision and intrathoracic insult. However, it is reasonable to think that the increased LUS scores on the nondependent side resulted from lung tissue injury, which was caused by surgical procedure and shear forces secondary to tidal collapse and reopening of alveolar units [22–25].

Based on our results and previous studies [5, 10, 20-21], we confirmed that LUS can detect minimal change in thoracic cavity near the pleura, and enable temporal observation. In addition, this method using cumulative LUS scores can provide a global picture of lung aeration [8]. It is expected that ultrasound evaluation is also useful for respiratory management in various other surgeries, especially long-duration operations, operations requiring massive infusion or transfusion, and operations performed in patients with respiratory failure [30-31]. Thus, it is worth verifying whether this technique aids decision making for extubation in the operating room, and whether it can be utilized for temporal lung monitoring in patients who are kept intubated postoperatively.

Despite an increase in the LUS scores in both sides, we could not find any significant correlation between the LUS scores and other factors, including abnormal findings in postoperative chest radiography. This can be explained by several reasons. First, the changes in LUS scores in this study were quantitatively minor. The patients received recruitment maneuvers sufficient to reopen the alveolar units just before the second LUS examination. In addition, there were no cases of difficult circulatory or respiratory management because the patients were generally in good medical condition before anesthesia and received relatively small surgical injuries. Hence, they were rarely anticipated to have long-term lung complications such as severe pneumonia and ARDS, where LUS can detect clinically significant lesions under the pleura. Second, atelectasis and interlobar effusion can shrink the corresponding lung segments and relegate them to the deep layer of the thoracic cavity, where ultrasound waves are seriously weakened before their arrival [6]. A soft-tissue well containing the air, such as healthy lung tissue, attenuates ultrasound waves more than other media do and degrades ultasonographic imaging. As the LUS scoring method used in this study is designed with management of ARDS in mind, it is suitable for assessing diffuse peripheral lung aeration loss [8, 16-17, 29]. Meanwhile, chest radiography is sensitive for detecting a regional lesion even in the deep layer of the thoracic cavity, unless it is small and overlaps the shadows of the heart or bones [6]. Considering the difference in these characteristics between the two modalities, it is reasonable that there is poor or no correlation between the LUS scores and incidence of atelectasis on chest radiography. Therefore, their combined use may enable more effective lung monitoring in the perioperative period.

We should address some limitations of this study. First, the accuracy of the LUS assessment for the operative lung is limited, and it can be a matter of debate. Since the dependent and nondependent lungs are decisively different from each other under aeration conditions affected by OLV and surgery, it did not seem appropriate to collect temporal changes in the global LUS score in both sides combined following other reports [8, 10, 17, 19]. Thus, we performed LUS evaluation for left and right sides separately. Second, we were not able to use a convex ultrasound probe dedicated to this study, but were only able to use a linear probe with higher frequency that cannot visualize deep structures. As most participants in this study were relatively slim, we were able to obtain assessable images using even a linear probe. However, it is unclear that these results can be applied for other groups, including obese patients. Further studies using the LUS assessment after OLV with a convex probe, or evaluating patients with medium or large builds, are needed. Third, since this study was simply designed to test temporal transition of the LUS scores, it had insufficient sample size and parameters for showing any correlation among various factors. Larger randomized trials and appropriate protocols will provide more definitive results.

Conclusion

In conclusion, LUS examination is possible after VATS with OLV on both sides of the thorax. Lung aeration scores on both sides assessed with ultrasonography increased from baseline, but there was no significant correlation between the LUS scores and other patient-related factors in this patient population. Given the few diagnostic modalities available in the operation room, its continued use and further investigations are recommended.

Acknowledgements

We are grateful to all the nurses, surgeons, anesthesiologists, and other staff who made the study possible.

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