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● *Original Contribution*

COMPARISON OF LINEAR AND SECTOR ARRAY PROBE FOR HANDHELD LUNG ULTRASOUND IN INVASIVELY VENTILATED ICU PATIENTS

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Abstract—International guidelines do not recommend a specific probe for assessment of lung aeration using lung ultrasound (LUS). The aim of this study was to assess the concordance between linear and sector array probes of a handheld ultrasound device in assessment of lung aeration in invasively ventilated intensive care unit patients. This study included intensive care unit patients who were expected to be ventilated for longer than 24 h. A 12-region LUS exam was performed with a linear and a sector array probe. In each image, the LUS aeration score and number of B-lines were determined. Adding the LUS aeration scores of all regions resulted in a global LUS aeration score. Agreement between the two probes was calculated using intra-class correlation coefficients (ICCs). A total of 30 LUS exams were performed in 19 patients, resulting in a total of 328 pairs of images. Twenty-nine pairs of images were excluded from analysis because the images from the linear probe could not be scored. ICCs calculated for the remaining images revealed good concordance the LUS aeration scores for individual images (ICC = 0.73, 95% confidence interval 0.67–0.78), number of B-lines (ICC = 0.79, 95% confidence interval 0.72–0.83) and global LUS aeration score (ICC = 0.74, 95% confidence interval 0.52–0.87). In conclusion, there is good concordance between linear and sector array probes of a handheld ultrasound device in assessment of lung aeration patterns in mechanically ventilated intensive care unit patients. However, in roughly 10% of the images acquired using the linear probe, the aeration pattern could not be scored. (E-mail: m.r.smit@amsterdamumc.nl)

Key Words: **Lung ultrasound, Intensive care, Mechanical ventilation, Linear probe, Sector array probe, Lung ultrasound aeration score.**

INTRODUCTION

Lung imaging is an essential part of intensive care because it facilitates the diagnosis of pulmonary disease, monitoring of therapy and titration of ventilation (Kruisselbrink et al. 2017; Mayo et al. 2019). Computed tomography (CT) provides 3-D images with great resolution (Gattinoni et al. 2001) but comes with drawbacks in terms of radiation exposure, transportation of critically ill patients and high costs (Beckmann et al. 2004; Brenner and Hall 2007). In recent years, lung ultrasound (LUS) has gained popularity as a diagnostic and monitoring tool, and it can nowadays be performed with a handheld ultrasound device (Ault and Rosen 2010; Cogliati et al. 2014). LUS is a relatively inexpensive, radiation-free imaging modality and can be performed at the bedside and repeated as often as needed (Bouhemad et al. 2007).

Contrary to conventional ultrasound, LUS is largely based on artifacts that are generated by the large impedance difference between tissue and air (Volpicelli 2013). A-lines are horizontal artifacts indicating a normally aerated lung, while B-lines are hyperechoic vertical artifacts that suggest lung tissue with diminished aeration. Complete loss of lung aeration will present as a real anatomic image of consolidation (Lichtenstein 2014). These LUS patterns are commonly used to semi-quantify lung aeration in people who are critically ill, and they correlate well with aeration measured in chest CT (Chiumello et al. 2018).

Guidelines do not recommend a specific probe for the detection of lung aeration patterns. A micro-convex

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probe is specifically recommended for the evaluation of pneumothorax and pleural effusion by international guidelines (Volpicelli et al. 2012), but it is rarely available in the intensive care unit (ICU). Linear and sector array probes are commonly available in the ICU and show good diagnostic accuracy in comparison to CT scans (Lichtenstein et al. 1997; Baldi et al. 2013; Chiumello et al. 2018, et al. 2019). Since LUS is an artifact-based technique, ultrasound findings might be influenced by technical factors including the type and shape of the probe being used (Dietrich et al. 2016). It is crucial to understand the influence of the probe on the variability of ultrasound findings, as these might affect diagnostic and therapeutic decisions.

The aim of this study was to assess the concordance in assessment of lung aeration between linear and sector array probes of a handheld ultrasound device in invasively ventilated ICU patients. We hypothesized that the LUS aeration score would be comparable between exams performed with a linear and a sector array probe.

MATERIALS AND METHODS

Study design and ethical concerns

This observational cohort study was performed in the ICU department of the Amsterdam UMC, Location AMC (Amsterdam, the Netherlands). The study was approved by the institutional review board of the Amsterdam UMC, Location AMC (W18_311). Written informed consent for use of data was obtained from patients or their legal representatives.

Patients

Patients were eligible if they were admitted to the ICU department and expected to be intubated and invasively ventilated for longer than 24 h. For this sub-study, patients were enrolled from June 12 to July 22, 2019, as part of a larger observational cohort study. Exclusion criteria were invasive ventilation for more than 48 h in the 7 d preceding the moment of inclusion and refusal of patients or legal representatives to take part in the study.

Lung ultrasound protocol

A trained examiner performed the LUS examinations with an S4-1 broadband sector array probe (4−1 MHz) and an L12-4 linear array probe (12−4 MHz) from the Philips Lumify system (Philips Ultrasound, Inc., Bothell, WA, USA), in random order for each exam. The examiner was not blinded to clinical parameters or patients' medical history. The LUS exam consisted of 12 scanned regions, dividing each hemithorax into two anterior, two lateral and two posterior regions (Fig. 1b). The probes were positioned on the chest wall perpendicular to the pleural line in a transverse scanning position. The exams were performed with the lung setting on the Lumify system, with disabled harmonic imaging. Depth was adjusted to position the pleural line at one third of the screen, and the gain was adjusted to optimize the brightness of the pleural line. The frequency was set automatically for the lung setting and could not be adjusted. No resolution or penetration mode was available in the lung setting. LUS clips 5 s long were recorded and saved in DICOM format for offline analysis.

Lung ultrasound scoring

To allow semi-quantification of lung aeration, every LUS image was scored as A (presence of lung sliding and A-lines), B1 (presence of >2 separated B-lines), B2 (presence of crowded or confluent B-lines) or C (presence of consolidative lung tissue with diameter >2 cm). Examples of LUS images with A-lines and B-lines for

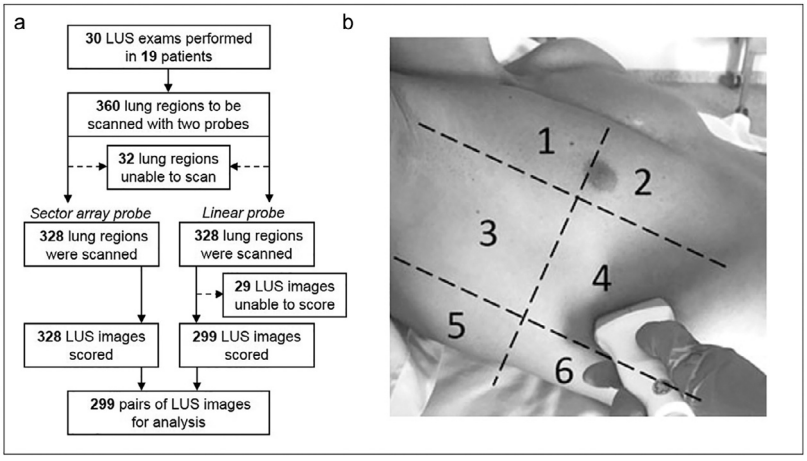

Fig. 1. (a) Flowchart for LUS data collection and (b) overview of lung regions scanned during the 12-region LUS exam for one side of the thorax. LUS = lung ultrasound.

both the linear and sector array probe can be found in Figure 2. If the lung aeration pattern was not clear, the annotation "unable to score" was made. For each region, points were allocated according to the worst pattern observed—A = 0, B1 = 1, B2 = 2, C = 3—resulting in the LUS aeration score for the individual image (Bouhemad et al. 2011). The global LUS aeration score (range 0−36) was calculated as the sum of the LUS aeration scores of all regions (Soummer et al. 2012). To account for missing region scores owing to regions that were impossible to scan or score, these were normalized by dividing the sum of available scores by the number of regions scored and then multiplying by 12 regions. Additionally, the number of B-lines was quantified in every lung field by counting separately spaced B-lines. In case of confluency, the percentage of the screen occupied by B-lines was estimated and divided by 10 (Volpicelli et al. 2012).

Study end points

The primary end point of the study was the agreement between a linear probe and a sector array probe, both connected to a handheld ultrasound device, in assessing the LUS aeration score for individual images. Secondary end points were the agreement of the two probes in the assessment of the global LUS aeration score, the number of B-lines and the LUS aeration score for each of the 12 lung regions separately.

Statistical analysis

Data were reported as counts with associated percentages for categorical data or as medians with interquartile ranges (IQRs) for continuous data. Intra-class correlation coefficients (ICCs) were used for pair-wise comparison between all end points. Pairs of images in which the linear or the sector array probe resulted in an image we were unable to score were excluded from the analysis. ICCs and their 95% confidence intervals (CIs) were based on a single-rating, absolute-agreement two-way random-effects model. ICCs were considered as poor (<0.30), fair (0.30−0.49), moderate (0.50−0.69), strong (0.70−0.89) or almost perfect (>0.90). Bland−Altman plots and analyses were used to calculate mean differences and 95% limits of agreement. A trained second observer scored all LUS images, and inter-observer agreement was calculated with the ICC. All analyses were carried out using R (version 3.6.1, www.r−project.org) and MATLAB (2019a, The MathWorks Inc., Natick, MA, USA).

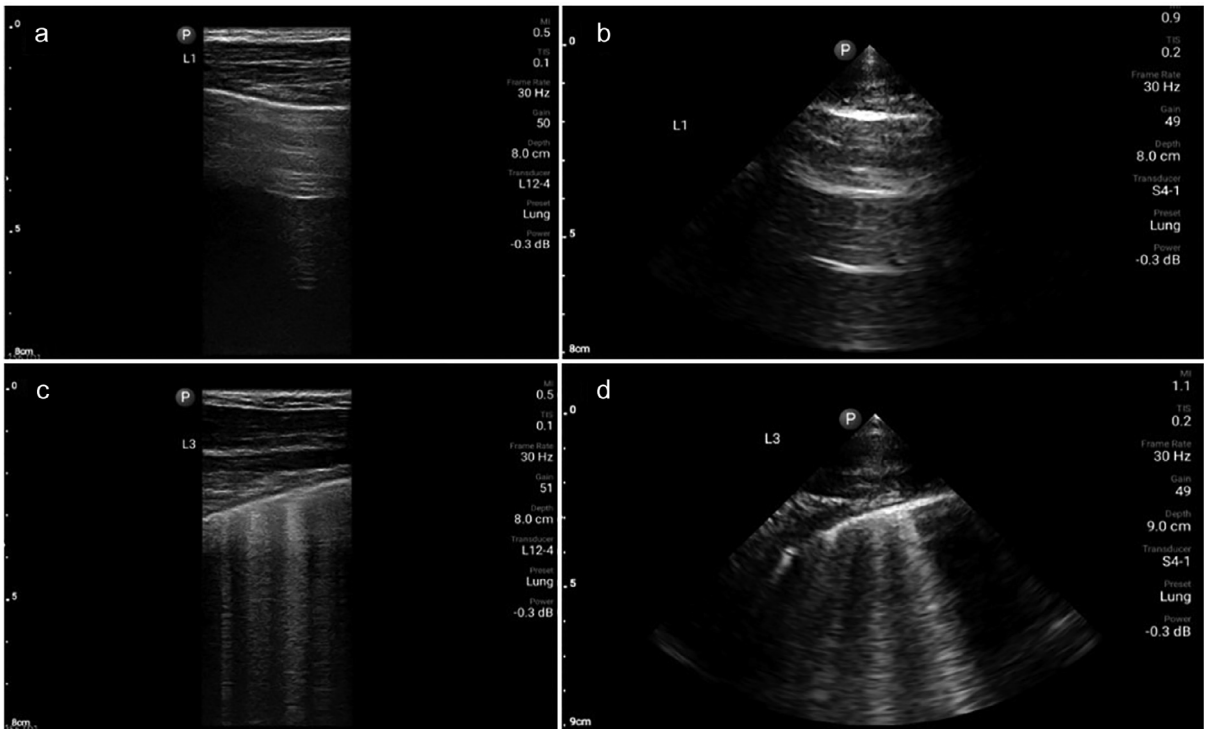

Fig. 2. LUS images acquired with the linear and the sector array probe in the same lung region. The upper LUS images show horizontal A-lines, indicating normally aerated lung tissue, scanned with the linear probe (a) and the sector array probe (b). The lower LUS images show vertical B-lines, indicating diminished aeration of lung tissue, scanned with the linear probe (c) and the sector array probe (d). LUS = lung ultrasound.

RESULTS

Nineteen patients were included in the study. Ten patients (52.6%) had one exam, seven (36.8%) had two exams and two patients (10.5%) had three exams, resulting in 30 LUS exams available for analysis. Patient characteristics are presented in Table 1. Of 360 lung regions, 32 regions (8.8%) were not scanned owing to chest tubes, large surgical or drainage dressings or patient position. A total of 328 pairs of images were obtained from all enrolled patients (Fig. 1a). Table 2 presents a cross tabulation of the lung aeration patterns scored with both probes. For the sector array probe, all LUS images could be scored, while for the linear probe, in 29 LUS images (8.8%) the investigator was unable to score the aeration pattern owing to the lack of A-lines, B-lines or a consolidation despite the presence of a clear pleural line (Fig. 1a). B patterns were found in 23 out of 30 (77%) LUS exams performed with the sector array probe and in 15 out of 30 (50%) LUS exams performed with the linear probe. C patterns were found in 14 out of 30 (47%) LUS exams for both the sector array and the linear probe.

Intra-class correlation coefficients between LUS scores of the linear and sector array probe are presented in Table 3. Bland–Altman plots are shown in Figures 3 (global LUS aeration and number of B-lines) and 4 (regional LUS aeration score for anterior, lateral and posterior regions). For the global LUS aeration score there was a mean bias of 2 points higher for the sector array probe compared with the linear probe (Fig. 3). The Bland–Altman plot of the number of B-lines shows that the error in the score is wider when the number of B-lines increases (Fig. 3). The ICC in assessment of the LUS aeration score for individual images was 0.98 (95% CI 0.98–0.99) for the linear probe and 0.93 (95% CI 0.91–0.94) for the sector array probe.

From the 29 images that could not be scored with the linear probe, 22 (75.9%) were derived from the four posterior lung regions. These areas are known to have a thicker subcutaneous layer. In a random sample of images, the median thickness of the subcutaneous layer was greater in the images that could not be scored (33.8 mm; IQR 25.1–37.4, $n = 14$) compared with the images that could be scored (21.9 mm; IQR 18.6–26.7, $n = 14$; unpaired t-test $p = 0.004$). Subsequently, a subgroup analysis was performed based on the patients' body mass index (BMI). The ICC for linear and sector array probes based on assessment of the LUS aeration score for the individual image was 0.77 (95% CI 0.70–0.82, $n = 202$) in patients with BMI <30 and 0.55 (95% CI 0.39–0.67, $n = 97$) in patients with BMI >30.

Table 1. Patient and LUS characteristics

Characteristic	Value
Total number of patients	19
Patient demographic characteristics	
Age, median (IQR), rounded y	70 (50–80)
Male, *n* (%)	17 (90%)
Female, *n* (%)	2 (10%)
Type of ICU admission	
Emergency surgical, *n* (%)	1 (5%)
Medical, *n* (%)	11 (58%)
Planned surgical, *n* (%)	7 (37%)
APACHE II score, median (IQR)	17 (14–24)
BMI, median (IQR), kg/m^2	29 (25–32)
Total number of LUS exams	30
Patient characteristics during LUS	
Length of stay in the ICU, median (IQR), d	1 (1–2)
Duration of mechanical ventilation, median (IQR), h	40 (23–51)
PaO_2/FiO_2, median (IQR)	184 (133–281)
Ventilator characteristics during LUS	
FiO_2, median (IQR), %	33 (26–44)
Tidal volume, median (IQR), mL/min	549 (432–640)
Respiratory rate, median (IQR), breaths/min	22 (16–32)
Positive end-expiratory pressure, median (IQR), cm H_2O	8 (5–12)

APACHE II = Acute Physiology and Chronic Health Evaluation II; BMI = body mass index; FiO_2 = fraction of inspired oxygen; ICU = intensive care unit; IQR = interquartile range; LUS = lung ultrasound; PaO_2 = oxygen arterial tension.

Table 2. Cross tabulation of LUS patterns scanned by linear and sector array probes

		Linear probe					
		A	B1	B2	C	UTS	Total
Sector array probe	A	185	7	2	4	14	212
	B1	23	10	1	2	8	44
	B2	6	7	23	1	3	40
	C	5	1	1	21	4	32
	UTS	0	0	0	0	0	0
	Total	219	25	27	28	29	328

LUS = lung ultrasound; UTS = unable to score.

DISCUSSION

In this prospective study we compared the assessment of lung aeration between a linear and a sector array handheld ultrasound probe in mechanically ventilated ICU patients. Our main findings can be summarized as follows: there is good agreement between the probes regarding LUS aeration score for individual images, global LUS aeration score and number of B-lines; concordance between the probes was lower in the latero-posterior lung zones compared with the anterior lung zones; and the ultrasound pattern of the lung can frequently not be assessed in images obtained with the linear probe, probably owing to high attenuation in the subcutaneous tissue layer.

The good concordance between the linear and sector array probes found in this study supports the LUS consensus statement that both linear and sector array

Table 3. Intra-class correlation coefficients (ICCs) between linear and sector array ultrasound probes

	ICC (95% CI)	*n*			
Individual image LUS aeration score	0.73 (0.67–0.78)	299			
Number of B-lines	0.79 (0.72–0.83)	264			
Global LUS aeration score*	0.74 (0.52–0.87)	30			
Right regions	ICC (95% CI)	*n*	Left regions	ICC (95% CI)	*n*
R1	0.85 (0.70–0.93)	29	L1	0.73 (0.50–0.87)	28
R2	0.81 (0.64–0.91)	29	L2	0.75 (0.53–0.88)	29
R3	0.67 (0.42–0.83)	30	L3	0.60 (0.28–0.80)	25
R4	0.49 (0.16–0.73)	29	L4	0.66 (0.34–0.84)	22
R5	0.39 (−0.01 to 0.68)	25	L5	0.78 (0.44–0.92)	15
R6	0.71 (0.41–0.87)	21	L6	0.78 (0.50–0.92)	17

* Global LUS aeration score was corrected for missing regions. CI = confidence interval; LUS = lung ultrasound.

probes are suitable for LUS (Volpicelli et al. 2012). It is currently uncertain which probe is most suitable for diagnosis of common pulmonary conditions. One study has shown better diagnostic concordance with CT for the linear probe than for the sector array probe using hand-held devices (Bobbia et al. 2018). Another study has shown that a linear probe has better diagnostic accuracy for pleural pathologies, while a sector array probe is superior for parenchymal pathologies (Tasci et al. 2016). Since we did not evaluate the association of the results obtained with either probe to a more accurate imaging technique such as CT, we cannot state that one is more accurate than the other. LUS exams were performed using a transversal approach, maximizing the amount of lung tissue scanned and minimizing rib-related shadows (Mongodi et al. 2017). Because the footprint and beam geometry are different for linear and sector array probes, the gain in scanned lung tissue with changing from a longitudinal approach to a transversal approach is larger for the linear probe than for the sector array probe. For this reason, the concordance of both probes in assessment of lung aeration might be different for LUS exams acquired with a longitudinal approach.

The main difference between the linear and sector array probes in this study is the structural higher global LUS score given to images recorded with the sector array probe. This finding contradicts our expectation that the linear probe would result in higher global LUS scores, as the linear probe tends to overestimate consolidated lung regions. B patterns were more often present in LUS exams scanned with the sector array probe than with the linear probe. The scarce literature available

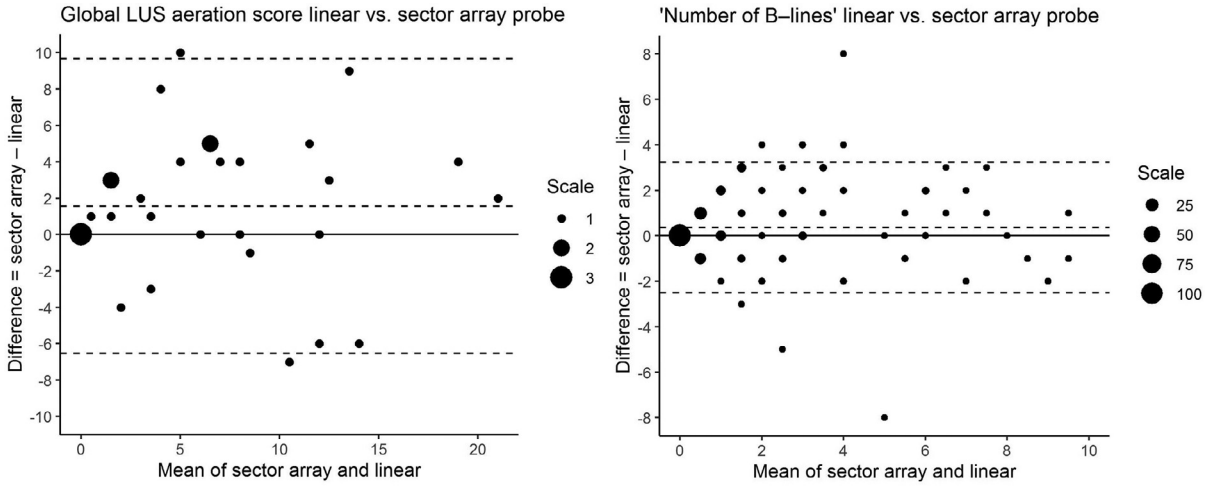

Fig. 3. Bland–Altman plots for global LUS aeration score (left) and number of B-lines (right) scored with the linear and sector array probes. The x-axes show the mean score of both probes, and the y-axes the difference in scores between the two probes. For the global LUS aeration score, the scale represents the number of patients having the same properties in the Bland–Altman plot. For number of B-lines, the scale represents the number of images having the same properties in the Bland–Altman plot. LUS = lung ultrasound.

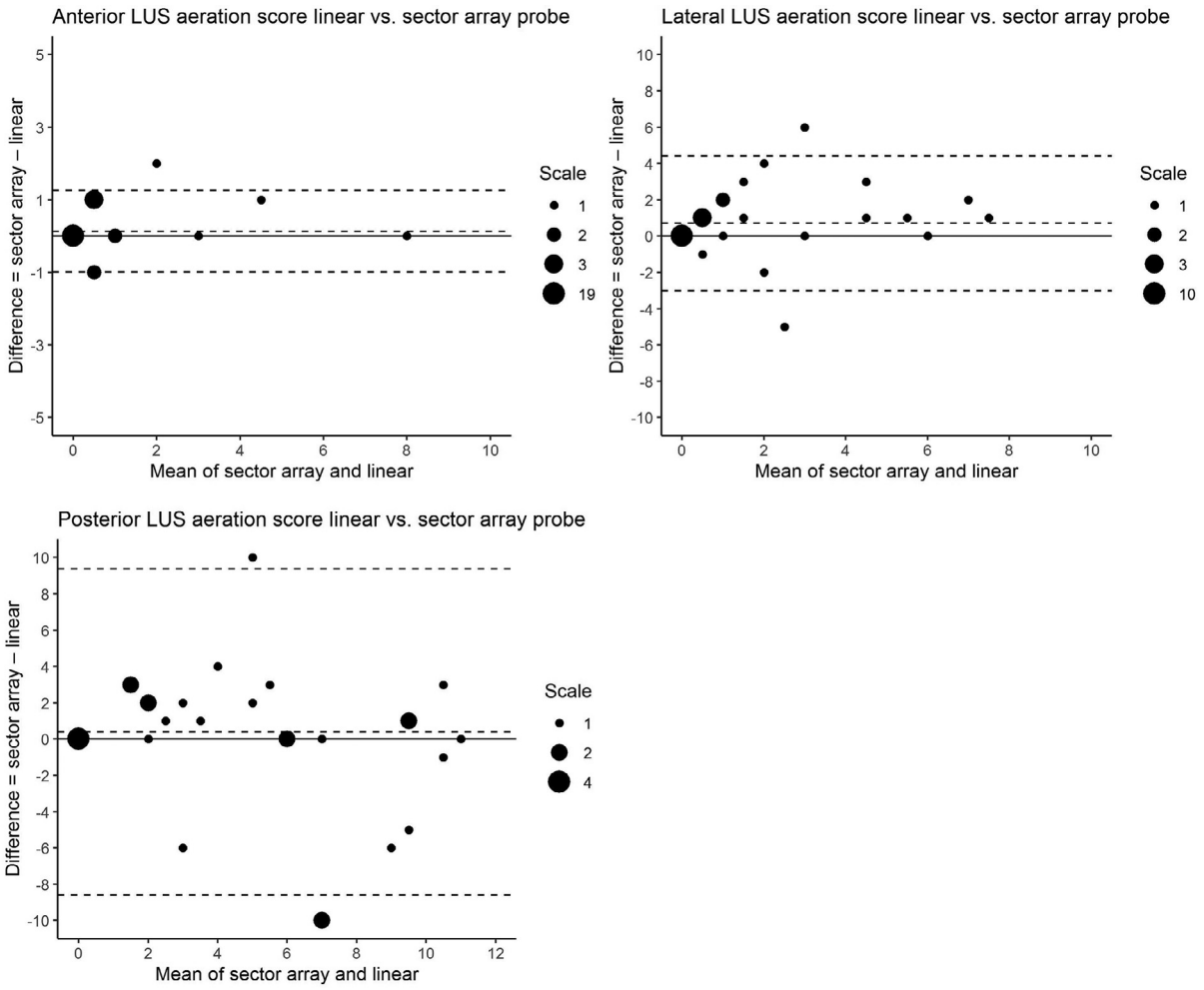

Fig. 4. Bland–Altman plots for the anterior LUS aeration score (upper left), lateral LUS aeration score (upper right) and posterior LUS aeration score (lower left), scored with the linear and sector array probes. The regional LUS aeration score is the sum of the LUS aeration scores of the four lung zones located in the anterior, lateral or posterior region. The x-axes show the mean score of both probes, and the y-axes the difference in scores between the two probes. The scale represents the number of images having the same properties in the Bland–Altman plot. LUS = lung ultrasound.

regarding the influence of frequency on B-lines shows a higher number of B-lines with probes using a low frequency compared with a higher frequency (Dietrich et al. 2016). This phenomenon might be the main reason for the higher global LUS score for the sector array probe in our study, as many lung regions that scored an A pattern with the linear probe were scored as a B1 pattern with the sector array probe.

Interestingly, there were considerable regional differences between the lung zones in terms of agreement. The highest agreement was found in the anterior lung zones (Table 3). Because the patients were in a supine or semi–recumbent position, the high agreement in the anterior lung zones might result from easier anatomic access to the ventral lung zones in contrast to the other zones, where several factors influence the image quality. Lateral and posterior lung zones have a larger amount of subcutaneous fat and have more pleural effusions, and posterior lung zones are difficult to reach in sedated patients because they were not tilted during the LUS exam. This finding suggests that particular care should be taken whenever lateral or posterior fields are scanned, especially in exams using a linear probe and in patients with higher BMI.

An unexpected finding was that in a substantial proportion of the LUS images recorded with the linear probe, the image was impossible to score despite good visualization of the pleural line, while with the sector array probe every image could be scored. We hypothesize that LUS images scanned with the linear probe were of insufficient quality owing to the high frequency and thus limited beam penetration. We substantiated this finding by showing a significant difference in the size of the subcutaneous fat layer between images that we were

and were not able to score. Moreover, the concordance between the linear and sector array probes in assessment of the LUS aeration score for individual images was lower in obese patients compared with non-obese patients. This is in line with previous reports of increased difficulty scanning obese patients (Gargani 2011; Bouhemad et al. 2015). Because LUS findings can be missed using the linear probe of a handheld ultrasound device with no possibility to manually adjust the frequency, this should be considered a major drawback of a handheld linear probe.

This study has several strengths. To the best of our knowledge, it is the first study comparing the agreement of linear and sector array probes of a handheld ultrasound device in assessment of lung aeration, through individual image and global LUS aeration scores and quantification of B-lines. Images were acquired using a systematic protocol because all LUS exams were performed by the same supervised examiner using both probes in the same lung regions. Another strength is the external validity of this study, because of its general population of patients who were expected to be ventilated for longer than 24 h in a mixed ICU.

Multiple limitations of this study should be acknowledged. First of all, the sample size was low. Even though the number of observations was sufficient to test our hypothesis, the inclusion of a small population may result in sampling error of a patient characteristic that has a large influence on the concordance between the two probes. The LUS images of the linear probe that could not be scored, together with the corresponding images from the sector array probe, were excluded from the ICC calculation of the LUS aeration score for individual images. It should be acknowledged that excluding those images might have resulted in an overestimation of the concordance between the linear and sector array probes. However, this overestimation does not apply for the global LUS aeration score, as that score was corrected for missing regions, and a similar concordance was found for both parameters. Finally, we used only one type of handheld ultrasound device, which might not be widely available in the ICU setting. Handheld and smartphone-based devices are becoming increasingly popular, and therefore it is crucial to know the influence of different probes on lung aeration measurements using those devices.

CONCLUSIONS

In this cohort of mechanically ventilated patients, there was good agreement between the linear and sector array probes of a handheld device in assessment of lung aeration by the global LUS aeration score and the LUS aeration score for individual images. This supports guidelines that suggest both probes can be used for lung ultrasound. However, a large number of images acquired with the linear probe were of insufficient quality to score, most likely caused by resorption of the ultrasound signal by the large subcutaneous layer in obese patients. Further testing of handheld ultrasound machines is pivotal before widespread application in critical care.

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Conflict of Interest—The authors declare that they have no competing interests.

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