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ORIGINAL ARTICLE

The Effectiveness of Lung Ultrasound for Diagnosis of Ventilator Associated Pneumonia Compared to Standard Radiological Strategies

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ABSTRACT

Background: The common and dangerous ICU-acquired infection known as ventilator-associated pneumonia (VAP) raises morbidity, mortality, antibiotic use, and healthcare costs. Because chest X-ray and CT have limited diagnostic performance and feasibility in critically ill patients, lung ultrasound has emerged as a rapid, noninvasive bedside tool that may improve early diagnosis and management of VAP. This study aimed to evaluate the effectiveness of lung ultrasound as a simple bedside tool for the early diagnosis of ventilator-associated pneumonia compared with the standard radiological diagnostic strategy, and to assess its impact on patient outcomes.

Methods: This prospective randomized controlled study was conducted on 126 mechanically ventilated adult patients who admitted to the surgical and emergency ICUs of Zagazig University Hospitals from January to July 2024. Patients were randomly assigned into two groups: the control group (n= 63), diagnosed using chest X-ray and CT, and the lung ultrasound group (n=63), assessed primarily using daily lung ultrasound monitoring. Clinical, radiological, and laboratory data were collected, and outcomes included diagnostic accuracy, ventilator-free days (VFDs), SOFA score, ICU stay length, and mortality.

Results: The lung ultrasonography group experienced a considerably shorter duration from ICU admission to VAP diagnosis than the control group (5.08±1.6 vs. 6.35±1.8 days, $p<0.001$). After a week, patients in the LUS group had significantly less SOFA scores, shorter ICU stays, and ventilator-free days. ($p<0.001$ for all). The diagnostic performance of LUS showed 84.62% sensitivity, 66.67% specificity, 80.49% PPV, 72.73% NPV, and 77.78% accuracy, outperforming conventional radiology. Logistic regression analysis identified pleural effusion detected by LUS at 72 hours as a significant independent predictor of mortality ($p<0.001$). **Conclusion:** Lung ultrasound is a reliable, safe, and accurate bedside modality for the early detection and monitoring of VAP, enabling earlier intervention and improved clinical outcomes.

Keywords: Lung Ultrasonography; Ventilator-Associated Pneumonia; bedside Diagnosis; Intensive Care Unit; Mechanical Ventilation.

INTRODUCTION

The most frequent nosocomial infection among patients admitted to intensive care units (ICUs) is ventilator-associated pneumonia (VAP). It is linked to higher rates of death, longer hospital stays, longer periods of mechanical breathing, increased use of antibiotics, and a significant increase in medical expenses [1]. Early and accurate diagnosis of VAP remains a major clinical challenge in the ICU, as delayed recognition often leads to inappropriate antibiotic use, prolonged ventilation, and worsened patient

outcomes. The hallmarks of VAP, which is defined as pneumonia that manifests 48–72 hours after endotracheal intubation or later, include a new or progressive pulmonary infiltrate, fever, leukocytosis or leukopenia, purulent tracheal secretions, and microbiological evidence of a causative pathogen [2]. The onset of VAP is caused by a variety of risk factors. Major contributing factors have been identified, such as advanced age, male sex, extended artificial breathing, and altered consciousness, burn injuries, comorbidities, past antibiotic exposure, and invasive operations. In addition, genetic polymorphisms have been reported to play a role in susceptibility to VAP [3]. In terms of diagnostic imaging, chest radiography (CXR) remains the most frequently used technique for the evaluation of suspected VAP despite its limited sensitivity and specificity. Computed tomography (CT) for radiographic diagnostics, the chest is regarded as the gold standard. However, CT scanning exposes the patient to ionizing radiation and necessitates their transfer to the radiology department., and increases healthcare costs [4]. Point-of-care ultrasound has emerged as a non-invasive, radiation-free, bedside imaging technique that has become increasingly integrated into critical care practice in recent years [5]. Lung ultrasound (LUS) has demonstrated high diagnostic performance in various pulmonary conditions, including acute respiratory failure and community-acquired pneumonia [6]. Moreover, accumulating evidence suggests that the application of LUS can significantly reduce the need for conventional imaging modalities such as chest radiography and CT in the assessment of pneumonia [7]. Lung ultrasonography's significance in diagnosing and tracking ventilator-associated pneumonia is still poorly understood and unstandardized, despite mounting evidence that it is useful in treating a variety of pulmonary disorders. Small sample sizes or inconsistent diagnostic standards constrain the majority of current research [8]. Therefore, determining the clinical relevance and diagnostic accuracy of lung ultrasonography in comparison to traditional imaging modalities should greatly improve patient outcomes in critically ill groups, decrease radiation exposure, and improve bedside decision-making.

AIM OF THE WORK

In order to enhance patient outcomes when compared to the conventional diagnostic approach, this study sought to evaluate the efficacy of lung ultrasound monitoring as a straightforward bedside tool for the early detection of ventilator-associated pneumonia.

METHODS

This prospective, randomized, controlled, cross-sectional study involved 126 patients admitted to the surgical and emergency intensive care units of the Department of Anesthesia, Intensive Care and Pain Management, Zagazig University Hospitals, over a six-month period, from January to July 2024. The study protocol was reviewed and approved by the Research Ethics Committee of the Faculty of Medicine at Zagazig University in Egypt (IRB# 11282-21/11-2023). Sufficient measures were taken to guarantee the confidentiality of the data gathered and the privacy of every participant. Since all study participants were on artificial ventilation and unable to give their own consent, before enrollment, each patient's first-degree relatives provided written informed consent. All research methods were conducted in accordance with the ethical principles of the Declaration of Helsinki and any relevant national research guidelines.

Sample size:

The sample size was calculated based on data from a previous study by Pradhan et al. [8], which reported the mean ± SD of ventilator-free days (VFD) a composite outcome with the intervention group's mortality and ventilator duration at 8.07±9.9 and the control group's at 3.7±6.4. The necessary sample size was determined using Open Epi software, resulting in 58 patients each group (a total of 116 participants), assuming a two-sided confidence level of 95% and a power of 80%. The overall sample size was raised to 126 patients in order to account for a possible 10% dropout rate. Inclusion criteria were adult male and female patients, ages 18 to 70, who needed mechanical ventilation for longer than 48 hours and who, based on clinical signs of ventilator-associated pneumonia (VAP). Exclusion criteria included patients having a clinical, radiographic, or sonographic diagnosis of the main cause of mechanical ventilation at the time of admission was pneumonia. Because these conditions may affect how lung ultrasound results are interpreted, patients with a history of thoracic trauma or prior chest surgery, including the insertion of a chest tube, were also disqualified. In addition, individuals with extensive chest wall dressings, open wounds, or dermatological conditions preventing adequate thoracic access for ultrasound examination were not eligible for inclusion. Withdrawal criteria stated that participants could leave the research at any moment without it having an adverse effect on their therapy or medical care, ensuring full adherence to ethical research standards and patient rights.

Randomization

Randomization was conducted by assigning a random sequence created by a computer patients divided into two equal groups in a 1:1 allocation ratio. The process ensured balanced distribution between study arms and minimized selection bias. According to the randomization list, Patients were divided into two groups: the intervention group, which used lung ultrasound (LUS) as the main diagnostic method for VAP detection and monitoring, and the control group, which received standard radiological evaluation using chest X-ray and CT. There were 63 patients in each group, for a total sample size of 126 people. To preserve the study's neutrality and integrity, the randomization process was carried out and hidden by a separate researcher who was not engaged in the evaluation or data analysis that followed. All patients included in the study were subjected to thorough clinical evaluation and data collection at baseline and during the study period. A detailed medical history was obtained from relatives and available medical records, including demographic information such as age, gender, comorbidities, smoking history, and chronic medication use. The primary diagnosis on admission and the indication for initiation of mechanical ventilation was also recorded. Clinical assessment focused on signs and symptoms suggestive of ventilator-associated pneumonia (VAP), which included fever, new or progressive pulmonary infiltrates on chest radiography, purulent tracheal secretions, increased oxygen requirements, and new-onset confusion. Additional information such as duration of mechanical ventilation, recent antibiotic exposure, and any recent invasive procedures were documented for each patient. Baseline and follow-up laboratory investigations were performed for all participants. These included complete blood count (CBC), lactate dehydrogenase (LDH), C-reactive protein (CRP), procalcitonin (PCT), blood

cultures, and sputum cultures to identify the causative pathogens and monitor the systemic inflammatory response. Comprehensive clinical and follow-up data were gathered during the ICU stay in order to evaluate the results. These included how long the patient was on antibiotics, how many days they were ventilator-free, how long they were in the intensive care unit, and how the Sequential Organ Failure Assessment (SOFA) score changed over time, especially when comparing the SOFA score on day 0 at diagnosis to day 7 after VAP started. 28 days mortality and primary cause of death (e.g., sepsis, VAP, renal failure, or other reasons) were among the mortality statistics that were also documented.

The Sequential Organ Failure Assessment (SOFA) Every patient admitted to the ICU was tracked and monitored using the score. It has been extensively validated as a clinical tool in many healthcare settings and was initially created to evaluate the acute morbidity and severity of severe disease. It is now known that a change in the SOFA score of two points or more is clinically significant and a hallmark of sepsis. Additionally, variations in the SOFA score have been approved by the European Medicines Agency as a valid surrogate endpoint for efficacy in exploratory clinical studies of new treatment medicines for sepsis [9]. Patients were randomly assigned into two equal groups according to the diagnostic approach used for the detection of ventilator-associated pneumonia (VAP).

Control Group (Radiological Group; n = 63)

The control group's patients received standard radiological evaluations. All patients were clinically evaluated for the onset of VAP following 48 hours of mechanical breathing. Every time clinical symptoms of VAP, such as fever, leukocytosis or leukopenia, a chest computed tomography (CT) and chest X-ray (CXR) were performed when purulent tracheal secretions and fresh or developing pulmonary infiltrates appeared.

Intervention Group (Lung Ultrasound Group; n = 63)

In the intervention group, patients were evaluated using lung ultrasound (LUS) as the primary diagnostic modality. Following 48 hours of mechanical ventilation, the presence of purulent sputum or other clinical suspicion of VAP prompted the performance of a lung ultrasound examination, which was subsequently repeated on a daily basis. Lung ultrasound was performed using a Siemens Acuson X300 ultrasound machine equipped with two probes: a convex low-frequency probe (3–5 MHz) for deep parenchymal visualization, and a linear high-frequency probe (7–10 MHz) for pleural and superficial assessment. Patients were examined in the supine position for anterior lung zones and the lateral decubitus position for posterior and postero-lateral zones. The parasternal, anterior axillary, posterior axillary, and paravertebral lines were used to split each lung into six sections, for a total of twelve lung zones assessed per patient. The degree of lung aeration was assessed in B-mode imaging, focusing on the pattern of reverberation artifacts. The transition from normal A-lines to multiple or coalescent B-lines, and finally to a tissue-like pattern, reflected progressive loss of aeration. Semi-quantitative assessment of aeration loss was based on the Lung Ultrasound Score (LUS) **[Lee, 10],** which identifies four stages of aeration:

Score 0: Normal aeration (A-lines or ≤2 B-lines),Score 1: Moderate loss of aeration (≥3 well-spaced B-lines),Score 2: Severe loss of aeration (coalescent B-lines),Score 3: Complete loss of aeration (tissue-like

pattern).The presence of two or more regions with small consolidations, or at least one consolidation area showing a dynamic arborescent or linear air bronchogram, was considered suggestive of pneumonia. A dynamic air bronchogram was identified by centrifugal movement exceeding 1 mm during inspiration, differentiating it from static bronchograms that indicate atelectasis. In addition, deep tracheal aspirate samples were collected from all patients for Gram stain, culture, and sensitivity testing. The diagnosis of ventilator-associated pneumonia was established based on the presence of purulent sputum, positive microbiological findings, and ultrasound evidence of pulmonary consolidation, upon which targeted antimicrobial therapy was initiated.

Patient Management:

In the intensive care unit (ICU), a defined VAP prevention and treatment procedure was followed in the management of every patient. A closed suction system, a cuffed endotracheal tube with subglottic suction, dental care every six hours, stress ulcer prevention, and keeping the head of the bed raised by at least 30 degrees were among the preventive measures. In order to encourage spontaneous breathing trials and lessen ventilator dependency, daily sedation interruption was also implemented. Empirical broad-spectrum antibiotic therapy was initiated at the discretion of the attending physician, guided by the unit's antibiogram and local resistance patterns. Antibiotic de-escalation or modification was performed as soon as the culture and sensitivity results became available to ensure appropriate antimicrobial stewardship. With ventilator settings tailored to each patient's unique respiratory mechanics and gas exchange needs, all patients were ventilated in assist/control volume-targeted mode. To lessen difficulties and enhance results, non-invasive post-extubating ventilation was used for patients who were thought to be at high risk of re-intubation.

Outcomes:

The primary outcome of the study was to determine the diagnostic validity of lung ultrasound (LUS) in predicting and detecting the development of ventilator-associated pneumonia compared with the conventional diagnostic approach.

The secondary outcomes included duration of antibiotic therapy, changes in the SOFA score, total number of VFDs, length of ICU stay (until death or discharge), and ICU mortality. These outcome measures were used to assess both clinical effectiveness and patient-centered results.

Ventilator-Free Days (VFDs):

The number of days in the first 28 days following the onset of VAP that a patient remained alive and breathing for at least 48 hours straight without the use of a ventilator was known as "ventilator-free days." If the patient died before extubating within this 28-day period, the VFD value was recorded as zero. Any episodes of re-intubation or mechanical ventilation recurrence within this timeframe were also considered in the calculation of total ventilator-free days [11].

Statistical analysis

The statistical analysis was conducted using SPSS version 26 (IBM Inc., Armonk, NY, USA). The two groups were compared using the unpaired Student's t-test, and quantitative measures were presented as mean ± standard deviation (SD). The qualitative variables, expressed as frequency and percentage (%), were evaluated using the Chi-square test. The diagnostic performance of lung ultrasonography was evaluated by calculating diagnostic sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) using standard formulas. Logistic regression analysis was also used to evaluate the relationship between the dependent variable and one (univariate) or more (multivariate) independent variables. A two-tailed p-value of less than 0.05 was considered statistically significant.

RESULTS

In this study, 153 patients in total were first evaluated for eligibility. Eight of these patients chose not to participate, and 19 of them did not fit the inclusion requirements. Two equal groups of 60 volunteers each were randomly selected from the remaining 126 patients. Following up, all 126 patients were included in the statistical analysis **(Figure 1).**

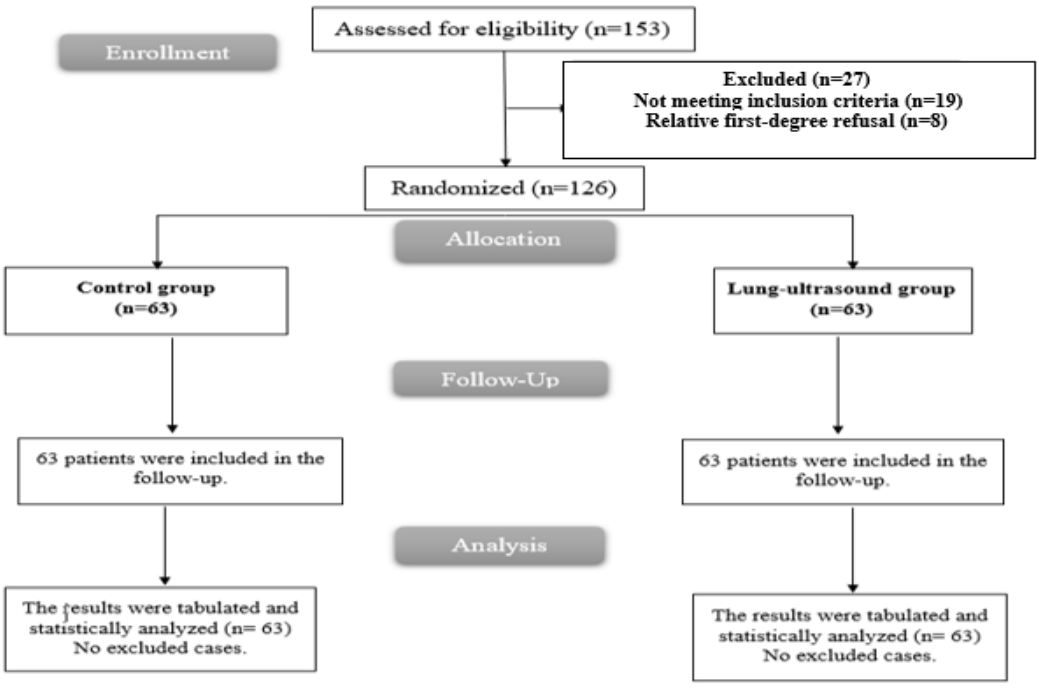

Figure 1: CONSORT flowchart of the studied patients

Age, sex distribution, weight, height, body mass index (BMI), and vasopressor use did not change statistically significantly between the two groups ($p > 0.05$), as indicated in **Table 1.** The control group's mean age was 45.3 ± 11.42 years, while the lung ultrasound group's was 47.03 ± 10.58 years. Adequate randomization and group homogeneity were confirmed by the comparable baseline anthropometric and clinical characteristics. The prevalence of pre-existing comorbidities, such as ischemic heart disease (IHD), chronic kidney disease (CKD), chronic obstructive pulmonary disease (COPD), stroke, diabetes mellitus (DM), hypertension (HTN), and dyslipidemia, did not differ significantly between the two study arms ($p > 0.05$). This suggests that the baseline medical characteristics of the two groups

were similar. Furthermore, there was no significant difference between the two groups in admission temperature, heart rate (HR), systolic blood pressure (SBP), or diastolic blood pressure (DBP) ($p > 0.05$).The period from ICU admission to VAP diagnosis was significantly shorter for the lung ultrasonography group (5.08±1.6 days) than for the control group (6.35±1.8 days) ($p < 0.001$), as shown in **Table 2.** The time interval between the start of mechanical ventilation and the diagnosis of VAP, however, did not differ statistically significantly between the two groups (6.98±2.43 days vs. 6.22±2.42 days; $p = 0.081$). There was no significant difference between the two groups in auscultatory findings or higher oxygen demand ($p > 0.05$). In the control group, chest radiography findings (Table 3) revealed progressive abnormalities over time. While all patients showed no findings on admission, opacities were observed in 48% at 48 hours, 71.2% at 72 hours, and 79.3% during follow-up ($p < 0.001$). Pleural effusion was also noted in 21%, 28.7%, and 31.7% of cases, respectively ($p < 0.001$). In the lung ultrasound group, B-line artifacts were detected in 48% of patients at 48 hours and in 55.6% at both 72 hours and follow-up. Air bronchograms were identified in 21% at 48 hours and increased to 26.9% at follow-up, while pleural effusion appeared in 17%, 20.6%, and 23.8%, respectively. All ultrasound findings changed significantly over time ($p < 0.001$), indicating dynamic disease progression. There was no discernible difference between the two groups' SOFA scores on the day of the VAP diagnosis (9.24 ± 1.93 vs. 9.29 ± 2.07; $p = 0.894$) (Table 4). However, analysis of PaO_2/FiO_2 ratios on the day of diagnosis demonstrated a significant difference between groups ($p = 0.031$). A higher proportion of patients in the lung ultrasound group had moderate oxygenation impairment (PaO_2/FiO_2 = 200–300), whereas those in the control group more frequently had severe impairment (PaO_2/FiO_2 = 100–200). ZAs presented in Table 5, the type and number of isolated organisms, as well as the rates of antibiotic resistance, were not significantly different between both groups ($p > 0.05$). The most commonly isolated pathogens were Klebsiella spp., Acinetobacter spp., and Pseudomonas spp. Similarly, empirical antibiotic regimens were comparable between groups, with no significant difference in the type of antibiotics used or the appropriateness of initial therapy ($p = 0.370$).Regarding the secondary outcomes Table 6, patients in the lung ultrasound group demonstrated significantly higher ventilator-free days (11.86 ± 3.3 vs. 5.48 ± 2.27, $p < 0.001$), lower SOFA Compared to the control group, they had lower ICU stays (18.38±5.48 vs. 26.33±8.99 days, $p<0.001$) and scores one week following VAP diagnosis (5.62 ± 2.28 vs. 7.16 ± 2.16, $p<0.001$). There were no significant differences between groups in 28-day mortality, antibiotic duration, or causes of death ($p > 0.05$). As illustrated in Table S1, the conventional radiological method (CXR and CT) demonstrated 76.9% sensitivity, 54.2% specificity, and 68.3% overall diagnostic accuracy, whereas the lung ultrasound method showed 84.6% sensitivity, 66.7% specificity, and 77.8% overall diagnostic accuracy. Although lung ultrasound achieved numerically higher values in all diagnostic indices, the difference between the two modalities was not statistically significant ($p = 0.676$). Univariate logistic regression analysis table 8 revealed that several imaging findings were associated with increased mortality risk, including opacity on chest radiography at 72 hours and pleural effusion on lung ultrasound at both 48 and 72 hours ($p < 0.05$). In the multivariate model, only opacity on chest radiography at 72 hours and pleural effusion on ultrasound at 72 hours remained significant independent predictors of mortality ($p < 0.05$).

Table 1: Baseline characteristics and comorbidities of the studied groups

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
Age (years)	Mean± SD	**45.3± 11.42**	**47.03± 10.58**	**0.379**
	Range	**26-64**	**25-65**	
Sex	Male	**34 (53.97%)**	**31 (49.21%)**	**0.592**
	Female	**29 (46.03%)**	**32 (50.79%)**	
Weight (kg)	Mean± SD	**75.41± 8.41**	**74.83± 8.25**	**0.693**
	Range	**59-91**	**60-90**	
Height (m)	Mean± SD	**1.67± 0.05**	**1.66± 0.05**	**0.206**
	Range	**1.6-1.75**	**1.59-1.74**	
BMI (kg/m^2)	Mean± SD	**26.94± 3.17**	**27.06± 3.11**	**0.825**
	Range	**20.42-33.98**	**21.11-33.62**	
Vasopressor use		**6 (9.52%)**	**4 (6.35%)**	**0.509**
Comorbidities				
HTN		**26 (41.27%)**	**20 (31.75%)**	**0.266**
DM		**21 (33.33%)**	**25 (39.68%)**	**0.459**
Dyslipidemia		**30 (47.62%)**	**36 (57.14%)**	**0.284**
IHD		**1 (1.59%)**	**2 (3.17%)**	**0.559**
CKD		**6 (9.52%)**	**4 (6.35%)**	**0.509**
COPD		**8(12.7%)**	**6(9.52%)**	**0.57**
Stroke		**1(1.59%)**	**3(4.76%)**	**0.309**
Vital signs				
HR (beat/min)	**Mean± SD**	**90.27± 9.67**	**91.02± 10.09**	**0.673**
	Range	**76-108**	**75-109**	
SBP (mmHg)	**Mean± SD**	**138.57± 8.4**	**139.21± 11.95**	**0.731**
	Range	**130-150**	**120-160**	
DBP (mmHg)	**Mean± SD**	**75.08± 9.82**	**75.71± 9.62**	**0.715**
	Range	**60-90**	**60-100**	
Temperature (^{o} c)	**Mean± SD**	**38.31± 0.49**	**38.42± 0.44**	**0.171**
	Range	**37.5-39.3**	**37.6-39.2**	

BMI: body mass index, Chi square test was used for comparison of qualitative data (%) and student T-test was used for quantitative data (mean ± SD).HTN: hypertension, DM: diabetes mellitus, IHD: Ischemic heart disease, CKD: Chronic kidney disease, COPD: Chronic obstructive pulmonary disease. Chi square test or fissure exact test (when appropriate) was used for comparison of qualitative data (%) and student T-test was used for quantitative data (mean±SD).

Table 2: Clinical course and diagnostic findings of ventilator-associated pneumonia in the studied groups

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
Time from ICU admission to VAP diagnosis (days)	**Mean± SD**	**6.35± 1.8**	**5.08± 1.6**	**<0.001***
	Range	**4-9**	**3-7**	
Time from start of MV to VAP diagnosis (days)	**Mean± SD**	**6.98± 2.43**	**6.22± 2.42**	**0.081**
	Range	**3-9**	**3-8**	
Presence of auscultatory findings	**41 (65.08%)**	**34 (53.96%)**	**0.203**	
Presence of increased oxygen requirement	**42 (66.67%)**	**37 (58.73%)**	**0.357**	

ICU: intensive care unit, MV: mechanical ventilation, VAP: ventilator associated pneumonia, student T-test was used for quantitative data (mean ± SD), *: statistically significant as p value <0.05.MV: mechanical ventilation, VAP: ventilator associated pneumonia, Student T-test was used for quantitative data (mean ± SD). *: statistically significant as p value <0.05. Chi square test was used for comparison of qualitative data (%)

Table 3. Comparison of radiological and lung ultrasound findings during follow-up

Chest radiography	On admission	48 h	72 h	Follow up	P value
No finding	**63 (100%)**	**26 (14%)**	**0 (0%)**	**0 (0%)**	**<0.001***
Opacity	**0 (0%)**	**28 (48%)**	**45 (71.24%)**	**50 (79.36%)**	**<0.001***
Effusion	**0 (0%)**	**13 (21%)**	**18 (28.71%)**	**20 (31.76%)**	**<0.001***
Chest ultrasound					
No finding	**63 (100%)**	**9 (14%)**	**0 (0%)**	**0 (0%)**	**<0.001***
B lines	**0 (0%)**	**30 (48%)**	**35 (55.56%)**	**35 (55.56%)**	**<0.001***
Air bronchogram	**0 (0%)**	**13 (21%)**	**15 (23.80%)**	**17 (26.98%)**	**<0.001***
Pleural effusion	**0 (0%)**	**11 (17%)**	**13 (20.63%)**	**15 (23.80%)**	**<0.001***

Chi square test was used for comparison of qualitative data (%), *: statistically significant as p value <0.05.

Table 4. SOFA score and oxygenation parameters at the time of VAP diagnosis

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
SOFA score on the day of VAP diagnosis	**Mean± SD**	9.24± 1.93	9.29± 2.07	0.894
	Range	6-12	6-12	
PaO_2 /FIO_2 on the day of diagnosis of VAP	**>400**	3 (4.76%)	4 (6.35%)	0.031*
	200–300	10 (15.87%)	24 (38.1%)	
	100–200	41 (65.08%)	27 (42.86%)	
	<100	9 (14.29%)	8 (12.7%)	

SOFA: Sequential organ failure assessment, student T-test was used for quantitative data (mean ± SD).PaO2: partial pressure of oxygen, FIO2: Fraction of inspired oxygen, MV: mechanical ventilation, Chi square test was used for comparison of qualitative data (%), *: statistically significant as p value <0.05.

Table 5: Microbiological profile and empirical antibiotic use in the studied groups

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
Number of isolated organisms	Single	34 (53.97%)	37 (58.73%)	0.857
	Multiple	23 (36.51%)	21 (33.33%)	
	No	6 (9.52%)	5 (7.94%)	
Organisms	Acinetobacter sp.	12 (19.05%)	17 (26.98%)	0.862
	Klebsiella sp.	20 (31.75%)	26 (41.27%)	
	Pseudomonas sp.	4 (6.35%)	5 (7.94%)	
	E. coli	6 (9.52%)	4 (6.35%)	
	Acinetobacter	4 (6.35%)	3 (4.76%)	
	Staphylococcus aureus	3 (4.76%)	2 (3.17%)	
Antibiotic resistance	Yes	50 (79.37%)	44 (69.84%)	0.219
	No	13 (20.63%)	19 (30.16%)	
Empirical antibiotic				
Antibiotics	Imipenem	4 (6.35%)	5 (7.94%)	
	Levofloxacin	6 (9.52%)	3 (4.76%)	
	Meropenem	15 (23.81%)	20 (31.75%)	
	Piperacillin/ tazobactam	13 (20.63%)	18 (28.57%)	
	Colistin	8 (12.7%)	3 (4.76%)	0.468
	Teicoplanin	3 (4.76%)	1 (1.59%)	
	Vancomycin	2 (3.17%)	4 (6.35%)	
	Others	2 (3.17%)	3 (4.76%)	
Use of appropriate empirical antibiotic		32 (50.79%)	27 (42.86%)	0.370

Chi square test was used for comparison of qualitative data (%).

Table 6: Secondary outcome of the studied groups

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
VFD	Mean± SD	5.48± 2.27	11.86± 3.3	<0.001*
	Range	2-9	7-18	
SOFA score after one week of VAP diagnosis	Mean± SD	7.16± 2.16	5.62± 2.28	<0.001*
	Range	3-11	1-10	
Length of ICU stay (days)	Mean± SD	26.33± 8.99	18.38± 5.48	<0.001*
	Range	10-39	10-27	
Antibiotic duration (days)	Mean± SD	13.02± 2.11	12.81± 2.03	0.577
	Range	10-17	10-16	
28 days mortality		27 (42.86%)	18 (28.57%)	0.094
Cause of death	Sepsis	6 (9.52%)	5 (7.94%)	0.389
	VAP	14 (22.22%)	6 (9.52%)	

		Control group (n=63)	Lung-ultrasound group (n=63)	P value
	Renal failure	**6 (9.52%)**	**4 (6.35%)**	
	Others	**1 (1.59%)**	**3 (4.76%)**	

VFD: ventilator-free day, VAP: Ventilator-associated pneumonia, SOFA: Sequential organ failure assessment, ICU: intensive care unit, Chi square test was used for comparison of qualitative data (%) and student T-test was used for quantitative data (mean ± SD), *: statistically significant as p value <0.05.

DISCUSSION

The results of this study showed that the lung ultrasonography group's time from ICU admission to VAP diagnosis was significantly shorter than that of the control group ($p < 0.001$). These findings align with those published by Mongodi et al. [12] and Wang et al. [13], who found that LUS can detect VAP at earlier stages, enabling faster clinical decision-making. Similarly, Mohamed et al. [14] confirmed that LUS reduces the diagnostic delay between ICU admission and the onset of VAP. In the current study the chest radiography findings showed opacity in 28 (48%) patients at 48 h, in 45 (71.24%) patients at 72 h and in 50 (79.36%) patients at follow up and showed effusion in 13 (21%) patients at 48 h, in 18 (28.71%) patients at 72 h and in 20(31.76%) patients at follow up. In addition, the chest ultrasound finding showed B lines in 30 (48%) patients at 48 h, in 35 (55.56%) patients at 72 h and in 35 (55.56%) at follow up, showed air bronchogram in 13 (21%) patients at 48 h, in 15 (23.80%) patients at 72 h and in 17 (26.98%) patients at follow up and showed pleural effusion in 11 (17%) patients at 48 h, in 13 (20.63%) patients at 72 h and in 15 (23.80%) patients at follow up. In alignment with our study, Charles et al. and Papazian et al reported that patients with VAP, chest radiograph after 48 hour after admission showed opacity and effusion [15,16]. Furthermore, El-shinnawy et al discovered in 74 MV patients, of whom 20 had a low risk of VAP and 54 had a high likelihood, as determined by a Clinical Pulmonary Infection Score (CPIS) of ≥ 6 points. Within 24 hours of this, a transthoracic ultrasound (TTUS) was carried out. B lines, subpleural or lobar consolidations, a linear air bronchogram, and pleural effusion were specifically found during the examination [17].In terms of PaO2/FIO2 on the day of VAP diagnosis, our findings indicate a significant difference between the two groups (P=0.031). The number of patients with PaO2/FIO2 200–300 was significantly higher in the lung-ultrasound group than in the control group, while the number of patients with PaO2/FIO2 100–200 was significantly higher in the control group than in the lung-ultrasound group. This could be because LUS offers early VAP diagnosis, which enables early treatment and improved results [18]. Regarding the secondary outcome, the VFD were significantly higher in lung-ultrasound group compared to control group (P<0.001). SOFA score after one week of VAP diagnosis and length of ICU stay were significantly lower in lung-ultrasound group compared to control group (P<0.001, <0.001).Wang et al. were on our side as they stated that usage of lung ultrasound could benefit for early detection of VAP and better SOFA score

and less ICU stay and ventilation[13].Additionally, Mohamed et al A highly statistically significant rise in the serial detection of chest ultrasonography abnormalities (B lines, air bronchogram, and pleural effusion) within the first 72 hours of the patient's hospitalization is required for the diagnosis of VAP (P=0.001 for all). This was associated with the results; in the first 48 hours, serial chest ultrasonography showed a large statistically significant increase in pleural effusion and air bronchogram in mortality patients (P=0.003, 0.002, respectively) [14].In our study, the conventional method (CXR and CT chest) had 64.10% sensitivity, 54.17% specificity, 69.44% PPV, 48.15% NPV and diagnostic accuracy of 60.32% in the diagnosis of VAP .In the early diagnosis of VAP, the lung-ultrasound group had 84.62% sensitivity, 66.67% specificity, 80.49% PPV, 72.73% NPV, and a diagnostic accuracy of 77.78%. When compared to the traditional approach (CXR and CT chest), the lung ultrasound demonstrated significantly greater sensitivity, specificity, PPV, NPV, and accuracy (P<0.001).These findings are in line with those of Lichtenstein et al., who reported that LUS had a sensitivity of 90% and a specificity of 98% in identifying lung consolidation, with CT serving as the gold standard[19].Furthermore, El-Helbawy et al demonstrated the better sensitivity (96.7%) and accuracy (97.5%) of CPIS in conjunction with LUS for early VAP diagnosis [20]. Additionally, Ibrahim et al. examined the sensitivity, specificity, positive predictive value, and negative predictive value of chest ultrasound in diagnosing VAP [21]. Additionally, Uguen and colleagues showed in fifty-seven cases. Of the children, 19 (33%) developed a VAP. When linked with clinical symptoms, B-Lines and consolidations were highly specific (95.5 [92–98]% and 98 [95–99]%, respectively) and sensitive (100 [79–100]% and 88 [62–98]%, respectively) in VAP patients [22]. In contrast to our findings, Zagli et al. conducted a retrospective analysis of the precision of alveolar consolidation in a comprehensive LUS examination. The specificity of sonographic consolidation was 84 and the sensitivity was 59% [23]. 42 ICU patients on mechanical ventilation participated in the Xirouchaki et al. trial. Chest X-rays are used to diagnose pleural effusion, interstitial syndrome, consolidation, and pneumothorax, lung ultrasonography, and CT scans were performed. Consolidations by lung ultrasound showed 100% sensitivity and 78% specificity, while those by chest X-ray showed 38% sensitivity and 89% specificity. This study agrees with ours in that the lung ultrasound had a high sensitivity and the chest X-ray had a low sensitivity, but it disagrees with ours in that the chest X-ray had a high specificity and was higher than the lung ultrasound [24].The univariate logistic regression analysis showed that no finding and opacity by chest radiograph (48 h), air bronchogram and pleural effusion by chest ultrasound (48 h), and pleural effusion by chest ultrasound (72 h) were significant predictors for mortality. The multivariate logistic regression analysis showed that pleural effusion by chest ultrasound (72 h) was significant predictors for mortality. Similarly, Sosa et al. [25] conducted a study on 59 patients who underwent at

least two lung ultrasound (LUS) assessments using the LUS score (range: 0–42) on the day of admission, the fifth day, and the tenth day. The mean LUS scores were 20.8 ± 6.1 at admission, 27.6 ± 5.5 on day 5, and 29.4 ± 5.3 on day 10 (P = 0.007). A significant positive correlation (r = 0.52, P < 0.001) was observed between increasing LUS scores and worsening clinical condition. Mortality among patients with higher LUS scores on day 5 was 76%, compared to 33% among those with lower scores (OR = 6.29, 95% CI = 2.01–19.65, P = 0.003); a similar difference persisted on day 10. The LUS score demonstrated good diagnostic performance on day 5, with 75% sensitivity, 78% specificity, an AUC of 0.80, and an optimal cutoff value of 27 [25]. In another study, Sun et al. [26] examined 402 patients and found that 318 (79.1%) had abnormal lung ultrasound findings. Non-survivors (n = 42) exhibited significantly more B2 lines, pleural line irregularities, pulmonary consolidations, and pleural effusions than survivors (n = 360) (all P < 0.05). Both the global and anterolateral LUS scores were markedly higher in non-survivors. Receiver operating characteristic analysis revealed AUCs of 0.936 and 0.913 for the global and anterolateral scores, respectively. A global LUS cutoff of 15 yielded 92.9% sensitivity and 85.3% specificity, while an anterolateral cutoff of 9 achieved 88.1% sensitivity and 83.3% specificity for mortality prediction. Kaplan–Meier analysis confirmed that both scores were strong predictors of mortality (P < 0.001). Furthermore, multivariate Cox regression identified the global LUS score as an independent predictor of death (HR = 1.08; 95% CI = 1.01–1.16; P = 0.03). All things considered, the current study's findings provide credence to the use of lung ultrasonography as a quick, accurate, and non-invasive diagnostic method for the early identification and tracking of VAP. It has definite benefits in terms of sensitivity, bedside applicability, and the capacity to direct prompt therapeutic measures, all of which eventually lead to better patient outcomes and shorter lengths of stay in the intensive care unit.

Limitations

It is important to recognize the various limitations of this study. The analysis's statistical power was unavoidably diminished by the very small sample size, which also made it more difficult to identify minute variations across groups. The results of this single-center study might not be entirely transferable to other intensive care units with distinct clinical protocols, technology, and patient demographics. Additionally, lung ultrasound (LUS) is not suitable for certain conditions such as subcutaneous emphysema, morbid obesity, or the presence of thoracic dressings, which can interfere with optimal image acquisition and interpretation. Finally, A little bias in the evaluation of respiratory mechanics may have been introduced by tracking static compliance in sedated individuals who were not receiving neuromuscular blockade, which could have affected the final findings.

CONCLUSIONS

The current study demonstrated that LUS is a reliable bedside imaging tool for the early diagnosis of VAP, with a sensitivity of 84.62%, specificity of 66.67%, positive predictive value (PPV) of 80.49%, negative predictive value NPV of 72.73%,

and overall diagnostic accuracy of 77.78%. Air bronchogram and pleural effusion on lung ultrasound at 48 hours, pleural effusion on ultrasound at 72 hours, and the lack of abnormalities and opacity on chest radiography at 48 hours were all found to be significant predictors of mortality by univariate logistic regression analysis. Pleural effusion found by lung ultrasonography at 72 hours was an independent predictor of death, according to multivariate analysis.

Recommendations

Future research should include larger, multicenter studies to confirm the diagnostic value of lung ultrasound across different ICU settings. Expanding the sample size and stratifying patients by risk and comorbidities would enhance statistical power and allow for more precise estimation of the diagnostic accuracy and prognostic value of lung ultrasound in ventilator-associated pneumonia.

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Table S1: Diagnostic accuracy of conventional radiology and lung ultrasound for early diagnosis of VAP

	Control group (n=63)	Lung-ultrasound group (n=63)
TP	**30**	**33**
TN	**13**	**16**
FP	**11**	**8**
FN	**9**	**6**
Sensitivity	**76.92%**	**84.62%**
Specificity	**54.17%**	**66.67%**
PPV	**73.17%**	**80.49%**
NPV	**59.09%**	**72.73%**
Accuracy	**68.25%**	**77.78%**
P value	**0.676**	

TP: true positive, TN: true negative, FP: false positive, FN: false negative, PPV: positive predictive value, NPV: negative predictive value.

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