Computerized Lung Acoustic Monitoring Can Help to Differentiate between Various Chest Radiographic Densities in Critically Ill Patients

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Key Words

Chest radiography · Consolidation · Lung acoustic monitoring · Lung sound energy · Mechanical ventilation · Pneumonia · Vibration response imaging

Abstract

Background: Complementary bedside lung monitoring modalities are often sought in order to assist in the differentiation between several lung opacities in the intensive care unit (ICU). **Objectives:** To evaluate the use of computerized lung acoustic monitoring as a complementary approach in the differentiation between various chest radiographic densities in critically ill patients. **Methods:** Lung vibration intensity was assessed in 82 intensive care patients using vibration response imaging. Patients were classified according to their primary findings on chest radiography (CXR): consolidation (n = 35), congestion (n = 10), pleural effusion (n = 15), atelectasis/hypoinflation (n = 10) and normal findings (n = 12). Sixty patients were mechanically ventilated and 22 patients were spontaneously breathing. **Results:** Significantly elevated vibration intensity was detected in patients with consolidation, as opposed to pleural effusion, atelectasis and normal CXR (p < 0.01, Mann-Whitney U test). Vibration intensity was also increased for congestion, but this increase was not significant. The positive predictive value of CXR lung

opacity in combination with increased vibration intensity to detect consolidations and/or congestions was 95% (20/21). Furthermore, vibration intensity was significantly higher in mechanically ventilated patients compared to spontaneously breathing patients (p = 0.001, Mann-Whitney U test). Differences related to gender, age and body position were not significant. **Conclusions:** Computerized lung acoustic monitoring at the bedside was found to be a useful, readily available, noninvasive, adjunctive tool in the differentiation between various CXR densities in critically ill patients.

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Introduction

While a portable chest radiograph (CXR) remains the most commonly requested radiographic examination in the intensive care unit (ICU) [1], adjunctive bedside pulmonary monitoring methods are often sought to help differentiate between several lung opacities in critically ill patients [2]. Recently, electrical impedance tomography has gained acceptance as a valuable monitoring tool for the care of critical patients [3, 4]. While useful in the detection of alveolar collapse and recruitment [5] and the monitoring of the development of pneumothoraces [6, 7], the diagnostic capability of electrical impedance to-

mography is still not fully understood. Ultrasound, on the other hand, has been increasingly used as an adjunctive diagnostic tool in critically ill patients [8], taking a role in the management of airway [9] and thoracic diseases [10]. Recently, Lichtenstein et al. [11] used ultrasound to differentiate between pneumonia and resorptive atelectasis. The authors reported that a dynamic air bronchogram could be used as a sign of alveolar consolidation, ruling out atelectasis. Despite these promising developments, the need of high proficiency is one of the greatest challenges for wide adoption of ultrasound in the ICU [12] and therefore, there is still a need for interpretation-free modalities that could assist in the management of lung diseases. Lung sound monitoring [13–21] has been suggested as a potential tool to aid in the diagnosis of lung congestion [22] and as a method to assist in the differentiation between pneumonia and healthy controls [23–26]. While becoming readily available in clinical settings [27–30], computerized lung sound monitoring systems have only recently been introduced in critical care [31].

Vibration response imaging (VRI) is a monitoring system that produces a functional, dynamic image of lung sounds during the respiratory cycle [32, 33]. Its diagnostic capability has been described in non-critically ill patients, particularly in pneumonia [34], pleural effusion [35] and pneumothorax [36]. Experience in critical care includes assessment of asymmetric lung diseases [37] as well as the setting of mechanical ventilator parameters such as mode of ventilation [38] or positive end-expiratory pressure [39]. The aim of the present study was to evaluate the use of computerized lung acoustic monitoring as a complementary approach in the differentiation between various chest radiographic densities in critically ill patients.

Patients and Methods

Patients

The study was performed in the general ICU of the Rabin Medical Center in Petah-Tikva, Israel. The study protocol was approved by the institutional review board and informed consent was obtained from all patients or their next-of-kin. Vibration response measurements were investigated in a prospective trial.

Inclusion and Exclusion Criteria

Patients enrolled in the study were adults (18–85 years old) with a body mass index >20 to ensure good adherence of the array of sensors. Exclusion criteria included a body habitus or skin condition that would interfere with sensor placement; the presence of a cardiac pacemaker and pregnancy.

Study Design

Routine CXRs were scored by a board-certified radiologist blinded to the patients' clinical information. The radiologist was specifically asked to classify findings as primary, secondary and tertiary. Lung sound measurements recorded at the time of CXR were considered for analysis. Recording quality was assessed according to pre-determined criteria; recordings with an average vibration intensity level below a pre-defined threshold (<1 in the energy bar of the imaging display) were excluded [38]. Two patients were excluded from this study based on these criteria. Mode of mechanical ventilation, tidal volume, respiratory rate, fraction of inspired oxygen and pulse oximeter oxygen saturation were documented when applicable. To ensure that timing between spontaneous and controlled cycles did not affect the results, spontaneous breathing was maintained whenever available, including in synchronized intermittent mandatory ventilation mode.

Recording Procedure

The study setup is displayed in figure 1. The recordings were performed using a VRIxv™ device (Deep Breeze Ltd., Or-Akiva, Israel) with two arrays of 6 rows $\times$ 3 columns piezoelectric sensors or microphones similar to those used in digital stethoscopes. Earlier recordings were performed in sitting position ($n = 43$), using a low suction adherence mechanism. When the supine capability became available, the remainder of the patients ($n = 39$) were recorded in supine position with a bed angle between 30 and 45°. The sensors used in both arrays were identical. The arrays were positioned posterior to the patient's back. When recording with the supine array of sensors, a disposable positioning unit was used to help position the arrays and to reduce risk of cross-contamination. Morphological landmarks such as spine and scapula were used in order to ensure accurate and repeatable placement of the sensor arrays. Excessive secretions were removed by endotracheal and oral suctioning before recording. When applicable, airway pressure and flow waveforms were sampled from the ventilator using a proximal flow sensor inserted in the patient's circuit.

Measurement Output

Acoustic signals were recorded during 20 s of acquisition time, followed by 40 s of processing time, and were stored digitally on the system for later review and analysis. A band-pass filter between 150 and 250 Hz was applied to the data to remove heart and muscle sounds; median filtering was performed to suppress impulse noise, and truncation of samples above an automatically determined signal-to-noise threshold was carried out. A 64-multichannel analog-to-digital converter was used for data acquisition. The system included a 16-bit acquisition level and a sampling rate of 19.2 kHz. The resulting signal for each sensor was down-sampled to produce an envelope signal (vibration energy). The output was a gray-scale, two-dimensional dynamic image of the lungs created from a series of 118 still images or frames with each frame representing 0.17 s of vibration energy; 20-second recording included up to 10 respiratory cycles. High vibration was represented by dark colors (black) and low vibration by light color (light gray). Since the highest and lowest values were always determined as black or white, each recording was normalized to these values. Data from each sensor were collected separately, and the sums of vibration intensity expressed in arbitrary units (AU)

Fig. 1. Schematic diagram describing the elements of the system: patient with acoustic sensor array connected to the VRI system. For a mechanically ventilated patient, lung vibration intensity waveform obtained during a 20-second recording is synchronized with airway pressure and flow collected from the ventilator. For a spontaneously breathing patient, lung vibration intensity waveform is not synchronized.

in the right and left lungs, as well as the total vibration intensity in both lungs, were computed off-line. The analysis was performed on the data point corresponding to peak inspiratory flow, a specific time point of the respiratory cycle, as indicated in figure 2. In synchronized recordings, the representative data point was automatically selected by the system as the peak inspiratory point of lowest vibration intensity from the 20-second recording. This data point was referred to as synchronized maximum energy frame. If synchronization was not available, manual selection was performed based on similar criteria used by the automatic selection tool.

Statistical Analysis

Data are presented using descriptive statistics as means $\pm$ SD. Wilcoxon's signed-ranks test for paired data was used to analyze the data between lungs; the Mann-Whitney U test for unpaired data was employed to analyze the data between different clinical conditions. A p value <0.05 was considered significant. Data analyses were performed with statistics software (SPSS, version 11.5.1; SPSS, Chicago, Ill., USA; IFA Services Statistics, Amsterdam; GraphPad Software, San Diego, Calif., USA).

Results

A total of 82 ICU patients (57 males and 25 females; age 59 ± 19 years) were enrolled in the study between April 2007 and February 2008. Twenty-two patients were breathing spontaneously while 60 patients were mechanically ventilated using one of three ventilator types (Puritan Bennett 840; Tyco Healthcare, Mansfield, Mass., USA; Evita XL or Evita 4, Draeger, Lübeck, Germany; Engström Carestation, General Electric, Madison, Wisc., USA). The majority of the mechanically ventilated patients ($n = 42$; 70%) were on pressure support mode of ventilation with a level between 8 and 24 cm H₂O (mean 17 ± 5 cm H₂O). Sixteen patients (27%) were ventilated using synchronized intermittent mandatory ventilation and 2 patients (3%) were ventilated on pressure controlled mode. For mechanically ventilated patients, average tidal volume was 555 ± 152 ml, respiratory rate 21 ± 7 breaths/

Fig. 2. Example of acoustic data as displayed by the system: vibration response frame at peak inspiration (synchronized maximum energy frame; **a**) and synchronized vibration intensity graph with ventilator airway pressure and flow waveforms (**b**).

Table 1. Reason for ICU admission of the 82 patients

Reason for intubation	n	%
Pneumonia	17	21
Acute respiratory failure	10	12
Sepsis	9	11
Motor vehicle accident	8	10
Intoxication	3	4
Pancreatitis	3	4
HELLP syndrome and eclampsia	3	4
Cerebrovascular accident	3	4
Interstitial lung disease	2	2
Acute respiratory distress syndrome	2	2
Guillain-Barré syndrome	2	2
Pulmonary embolism	2	2
Acute renal failure	2	2
Others	16	20

Others include chronic obstructive pulmonary disease, facial burns, Legionnaire's disease, myocardial infarct, aspiration, spinal cord transection, fecal peritonitis, myasthenia gravis, colon resection, mesenteric ischemia, wound infection, acute supratitis, meningitis, diabetic ketoacidosis, cardiopulmonary resuscitation and stroke.

Table 2. Primary CXR findings

Primary finding	n	%	Uni-lateral	Bi-lateral
Consolidation	35	43	32	3
Congestion	10	12	5	5
Pleural effusion	15	18	11	4
Atelectasis/hypoinflation	10	12	7	3
Normal CXR	12	15		

min, oxygen saturation $96 \pm 4\%$ and fraction of inspired oxygen $58 \pm 25\%$. Patients were not deeply sedated and none was paralyzed. Reasons for ICU admission are described in table 1. No adverse event related to the measurement was registered.

As summarized in table 2, patients were divided into five groups according to their primary CXR finding: consolidation ($n = 35$), congestion ($n = 10$), pleural effusion ($n = 15$), atelectasis/hypoinflation ($n = 10$) and normal CXR ($n = 12$). Among the 70 patients with abnormal appearing findings, 55 had unilateral pathology (79%) and 15 had bilateral pathology (21%). Lung vibration intensities recorded from all the sensors at peak inspiration were calculated for each patient and are presented in figure 3. As revealed in figure 3, mean vibration intensity for patients with consolidation was significantly higher than for patients with pleural effusion, normal-appearing CXR and atelectasis ($p < 0.01$, Mann-Whitney U test). This difference was maintained when considering only the patients mechanically ventilated on pressure support-related modes ($n = 58$, $p = 0.03$, Mann-Whitney U test). A threshold, computed as the mean vibration intensity for normal-appearing CXR plus 5 times the standard deviation (threshold = 18×10^6 AU) was used to calculate the positive predictive value. The positive predictive value, defined as the proportion of patients with vibration intensity higher than this threshold that were actually diagnosed with consolidation and/or congestion, was 95% (20/21). Examples of the CXR and VRI image obtained for a patient with consolidation are presented in figure 4. As shown in figure 4, a localized area of high vibration intensity overlaps with the consolidation detected by CXR. Vibration intensity in 4 patients with pneumonia but without consolidation was lower than in 13 patients

Fig. 3. Individual vibration intensity in 82 ICU patients classified according to primary CXR findings: congestion (n = 10), consolidation (n = 35), pleural effusion (n = 15), atelectasis/hypoinflation (n = 10) and normal-appearing CXR (n = 12). Means $\pm$ SD are indicated as well as significant p values (Mann-Whitney U test). The suggested threshold for detection of consolidations at 18×10^6 AU is also specified.

Fig. 4. CXR and VRI at peak inspiration (synchronized maximum energy frame) of a patient with right consolidation. Increased vibration intensity area, represented with darker (black) colors in VRI, overlaps with the consolidation detected by CXR. Because of normalization, this high intensity overshadows the appearance of the left lung.

with pneumonia and consolidation (8 ± 14 vs. $22 \pm 29 \times 10^6$ AU). Finally, in patients with unilateral disease, less vibration intensity was recorded from the sick lung compared to the other lung, especially in 18 patients with pleural effusion or atelectasis (1 ± 2 vs. $2 \pm 5 \times 10^6$ AU, $p = 0.05$, Wilcoxon matched-pairs signed-ranks test).

The effect of gender, age and body position on vibration intensity was studied in homogeneous subgroups of patients. As shown in table 3, vibration intensity from spontaneously breathing patients ($n = 20$) was more than three times lower than for mechanically ventilated patients ($n = 17$). This difference was significant ($p = 0.001$, Mann-Whitney U test). Furthermore, the ratio between vibration intensity in apical and diaphragmatic areas was significantly higher in mechanically ventilated patients than in spontaneously breathing patients ($p = 0.006$, Mann-Whitney U test). As shown in table 3, differences related to gender, age, body position, oxygen saturation, tidal volume or respiratory rate were not significant.

Discussion

In this study, we used a VRI system in order to differentiate between various CXR densities in critically ill patients. Furthermore, we used homogeneous groups of patients to evaluate the effect of patient demographics, body position and ventilatory status on vibration intensity. Our results document the increase in vibration intensity in patients with consolidation and/or congestion as opposed to other lung pathologies such as atelectasis or pleural effusion. Furthermore, significantly higher energy was obtained in mechanically ventilated patients as opposed to spontaneously breathing patients.

The increased vibration intensity related to consolidation in our study on critically ill patients is compatible with results of Murphy et al. [26] comparing 50 non-critically ill patients diagnosed with pneumonia and 50 control subjects. In particular, the authors demonstrated that adventitious lung sounds were more common in pneu-

Table 3. Comparing lung vibration intensity and ratio between vibration intensity in the apical and diaphragmatic areas in different subgroups of patients classified according to ventilatory status, gender, age, body position, oxygen saturation, tidal volume and respiratory rate

Factor	Patient group used	Status	n	Vibration intensity $\times 10^6$ AU	p value	Ratio between vibration intensity in apical and diaphragmatic areas	p value
Ventilatory status	patients with pleural effusion, atelectasis or normal CXR	ventilated	20	5 ± 7	0.001	2.3 ± 1.9	0.006
		non-ventilated	17	1 ± 2		1.7 ± 1.4	
	patients with consolidation or congestion	ventilated	40	28 ± 33	NA	3.0 ± 4.8	NA
		non-ventilated	5	9 ± 14		2.6 ± 1.5	
Gender	all patients	male	57	15 ± 25	0.8	1.9 ± 1.4	0.7
		female	25	17 ± 30		2.3 ± 2.0	
Age	mechanically ventilated patients with consolidation	<60 years old	17	38 ± 40	0.2	2.6 ± 1.8	0.4
		≥ 60 years old	15	22 ± 30		2.2 ± 1.9	
Body position	mechanically ventilated patients with consolidation	supine	20	35 ± 34	0.2	2.2 ± 2.0	0.08
		sitting	12	24 ± 39		2.7 ± 1.6	
Oxygen saturation	mechanically ventilated patients with consolidation	<98%	16	32 ± 35	0.5	2.1 ± 1.3	1.0
		$\geq 98\%$	15	23 ± 30		2.6 ± 2.2	
Tidal volume	mechanically ventilated patients with consolidation	<550 ml	16	38 ± 40	0.6	2.8 ± 2.2	0.2
		>550 ml	15	25 ± 31		1.9 ± 1.3	
Respiratory rate	mechanically ventilated patients with consolidation	≤ 18 breaths/min	17	32 ± 39	0.8	2.0 ± 1.8	0.1
		>18 breaths/min	15	29 ± 33		2.8 ± 1.9	

p values are indicated (Mann-Whitney U test). Means $\pm$ SD. NA = Not applicable: p value not reliable because of the small sample of non-ventilated patients with consolidation or congestion.

monia patients than in normal subjects. Their acoustic data analysis revealed that 81% of the pneumonia patients had inspiratory crackles at a frequency of 309 ± 63 Hz. While most of this signal may be filtered by the band pass used in our analysis (150–250 Hz), residual adventitious sounds may contribute to the elevated lung vibration intensity in patients with consolidation. Another factor that may partly explain the increase in vibration intensity in this patient population is bronchial breathing. Indeed, Gross et al. [40] introduced computer-based detection of bronchial breathing as a useful part of quantitative monitoring of patients at risk to develop pneumonia. Finally, secretions may also contribute to this increase as the association between secretions and pneumonia was recently discussed [41, 42].

Our results also revealed elevated vibration intensity in mechanically ventilated patients when compared to spontaneously breathing patients. This difference may be the result of different ventilatory flow between these two modes. In our approach based on lung sounds generated

by airflow, it is indeed difficult to assess whether differences in sound recorded at the chest wall result from differing acoustic properties of the lung or differing airflow rates [43, 44]. In our study, however, differences in ventilatory status did not affect the diagnostic value of consolidations since significant differences were also obtained when limiting the comparison to mechanically ventilated patients in pressure support mode. Nonetheless, the threshold used in our study may need to be adjusted when recording patients in other ventilatory conditions, such as in modes of mechanical ventilation that may provide different baseline noise. Indeed, standardization of the source of noise may be necessary in order to minimize the effect of flow [45]. One possible option may be to compute the ratio between sound and flow. Alternatively, a different approach based on the injection of a known sound and recording of the sound transmitted to the chest wall [46, 47] may be applied, but this method may be less practical in critical care.

Automated lung sound analysis has been successfully compared to standard auscultation [48], with agreement reaching 84% in obstructive disease [49]. In some instances, discrepancies between the two techniques were explained by the increased sensitivity of digitalized breath sound measurement compared to a traditional stethoscope [50]. While the use of auscultation is controversial in critical care [51], digitalized lung sound analysis has gained increasing recognition as a practical complementary tool in critically ill patients, particularly during mechanical ventilation [52]. Despite being a priori more cumbersome to implement than a standard stethoscope, automated pulmonary acoustics provide a repeatable, more objective [53], less competency-dependent assessment which is easily archived, quantified and therefore comparable [54]. While it sometimes only confirms standard expected clinical findings of physical examination, computerized lung sound analysis is clinically relevant as it objectively documents reiterated examinations, and is therefore particularly useful during treatment follow-up in intensive care.

One of the limitations of our study is the elevated standard deviations detected in all the analyses related to vibration intensity. Lung sound intensity variability in normal men was previously reported by Dosani and Kraman [55] and, recently, by Torres-Jiménez et al. [56]. Moreover, similar dispersion of the data was accounted by Dellinger et al. [38] comparing patients ventilated with different

modes of mechanical ventilation. The authors reported that the vibration intensity varied between 10^4 and 10^8 AU and that the inter-patient variation was not found to be correlated with body mass index. This variability may be explained by the algorithm used to calculate lung vibration intensity as the sum of squared amplitudes in a 0.17-second window. Another limitation includes the fact that sound was filtered to a band pass of 150–250 Hz, which may have reduced the information available as lung sound characteristics are also contained in other frequency bands, especially >250 Hz. Finally, the protocol did not include a comparison of lung sound distribution with more appropriate tools, such as computerized tomography. This should be investigated in the future.

Despite these limitations, digitalized lung acoustic monitoring at the bedside may be a useful objective complementary modality to help differentiate between various lung opacities in critically ill patients. A randomized controlled study may be warranted in order to further validate the applicability of this methodology, particularly in the investigation of early pneumonia detection and during treatment follow-up.

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