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Non-Invasive Assessment of Respiratory Mechanics Using Anatomical M-Mode Ultrasound in Acute Pulmonary Oedema With Impending Respiratory Failure: A Case Report

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ABSTRACT

Assessing respiratory mechanics in critically ill patients is crucial for diagnosis and treatment monitoring. The Lung Curtain Swing vs. Time (LCST) graph using Anatomical M-mode (AMM) ultrasound provides a novel non-invasive approach to evaluating lung excursion and respiratory dynamics. An 83-year-old male with end-stage kidney disease on peritoneal dialysis presented with dyspnea and desaturation. Initial evaluation indicated hypertensive crisis with acute pulmonary oedema. NIV therapy improved oxygenation and ventilation, with concurrent lung ultrasound assessments. The LCST graph demonstrated abnormal inspiratory and expiratory waveforms, suggesting respiratory muscle fatigue and bronchial oedema. NIV led to improved lung excursion and retraction speed, correlating with clinical recovery. The LCST graph using AMM ultrasound offers real-time, non-invasive assessment of respiratory mechanics in critical care. This case highlights its potential utility in diagnosing and monitoring respiratory failure, warranting further research.

1 | Introduction

Acute pulmonary oedema can lead to respiratory failure, necessitating prompt assessment and intervention. Evaluating respiratory mechanics in patients with respiratory failure is challenging, as they require oxygenation devices and are unsuitable for spirometry. Respiratory mechanics derived from ventilation parameters may be confounded by ventilation support, failing to accurately reflect the intrinsic respiratory function.

Lung ultrasound offers a real-time assessment of lung function without interfering with ongoing management. The Lung Curtain Swing vs. Time (LCST) graph, generated using Anatomical M-mode (AMM) ultrasound, introduces an innovative and non-invasive method [1] for evaluating lung excursion and respiratory dynamics. This allows clinicians to diagnose and monitor respiratory failure with improved precision and reliability.

2 | Case Report

An 83-year-old male with a history of end-stage kidney disease on peritoneal dialysis presented with shortness of breath.

His vital signs were: temperature of 36.1°C, blood pressure of 243/122 mmHg, heart rate of 105 beats per minute, respiratory rate of 23 breaths per minute, and oxygen saturation (SpO_2) of 94% on 4 L/min nasal cannula. Physical examination revealed respiratory distress (tachypnoic with accessory muscle usage) with expiratory rhonchi and basal crepitations. His initial arterial blood gas (ABG) showed pH 7.21, partial pressure of carbon dioxide (pCO_2) 51 mmHg, partial pressure of oxygen (pO_2) 92 mmHg, bicarbonate (HCO_3) 22 mmol/L, with a fraction of inspired oxygen (FiO_2) 40% (delivered via Venturi mask), and an SpO_2 95%. The initial clinical impression was hypertensive crisis with acute pulmonary oedema. He was treated with a glyceryl trinitrate (GTN) infusion (for 18 h) and non-invasive ventilation (NIV) via an oronasal mask in spontaneous/timed mode with inspiratory positive airway pressure of 15 cmH2O and expiratory positive airway pressure of 5 cmH2O. A repeat ABG performed 1 h after the initiation of NIV and GTN showed improvement—pH 7.29, pCO_2 40 mmHg, HCO_3 20 mmol/L, pO_2 137 mmHg, FiO_2 40% and SpO_2 99%. His respiratory pattern improved, and bilateral rhonchi resolved. Peritoneal dialysis was initiated with a total ultrafiltration of 2000 mL achieved. His symptoms resolved and a follow-up ABG on room air 2 days after showed normal values—pH 7.37, pCO_2 35 mmHg, pO_2 90 mmHg, HCO_3 20 mmol/L and SpO_2 96%.

2.1 | Ultrasound Evaluation

The Mindray MX7 ultrasound machine, equipped with a curvilinear transducer (C5-1s) in abdominal mode, was used. The transducer was positioned along the mid-axillary line at the level of the costophrenic angle (Figure 1A). AMM was activated to record the displacement of the pleural line tip along the sampling arrow, which translated into lung excursion, creating the LCST graph (Figure 1B). The *x*-axis represents time in milliseconds, and the *y*-axis represents the displacement of the pleural line of the lung curtain in centimetres (Figure 1C).

Lung excursion was assessed using this ultrasound technique concurrently with ABG before (Figure 2A) and 1 h after (Figure 2B) NIV application, and during quiet and deep breathing post-recovery (Figure 2C/D). The assessments took place with the patient in a seated position, with each assessment taking approximately 3–5 min.

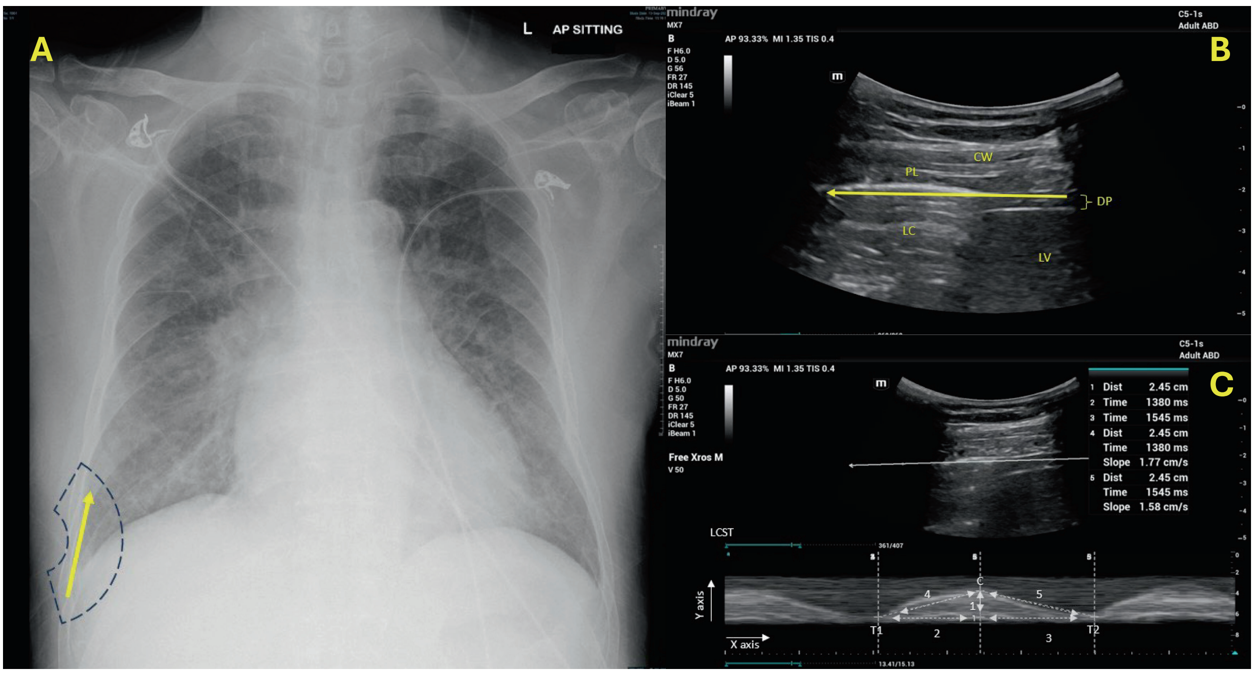

FIGURE 1 | (A) CXR of the patient upon presentation to the emergency department, demonstrating signs of acute pulmonary oedema. The dotted sector outlines the ultrasound view with the transducer placement at the right mid-axillary line at the level of the costophrenic angle. The yellow arrow represents the sampling arrow for the anatomical M-Mode, which was applied to this ultrasound view to assess lung curtain displacement. (B) Ultrasound view obtained from a healthy subject. This serves as a reference to illustrate anatomical structures observed in the patient's ultrasound. The hyperechoic pleural line (PL) is seen as a bright echogenic line marking the boundary between the lung and chest wall (CW). The lung curtain (LC) appears as a hyperechoic region below the PL. The peripheral diaphragm (PD) appears as a linear structure positioned between the CW and liver (LV). The yellow arrow in (B) represents the sampling arrow for anatomical M-Mode (AMM), corresponding to the yellow arrow in (A) and the white arrow in (C). (C) Ultrasound view with activated Anatomical M-Mode (AMM). The white sampling arrow of AMM is positioned between the CW and LV, projecting to the PL to assess lung movement. The lung excursion along the AMM sampling arrow, labelled '1', is visualised in the lung curtain swing vs. time (LCST) graph below. In the LCST graph, 'T1' marks the lowest point of lung excursion, representing the start of lung expansion. The peak 'C' corresponds to the end of inspiration and the beginning of lung retraction. 'T2' is the trough following 'C', representing the end of expiration. The vertical distance labelled '1' (T1 to C) represents the extent of lung excursion, measured at 2.45 cm. The horizontal duration labelled '2' represents the inspiratory time, measured at 1380 ms, while duration '3' represents the expiratory time, measured at 1545 ms. Slope '4', measured at 1.77 cm/s, indicates the speed of lung expansion from T1 to C, while slope '5', measured at 1.58 cm/s, represents the speed of lung retraction from C to T2.

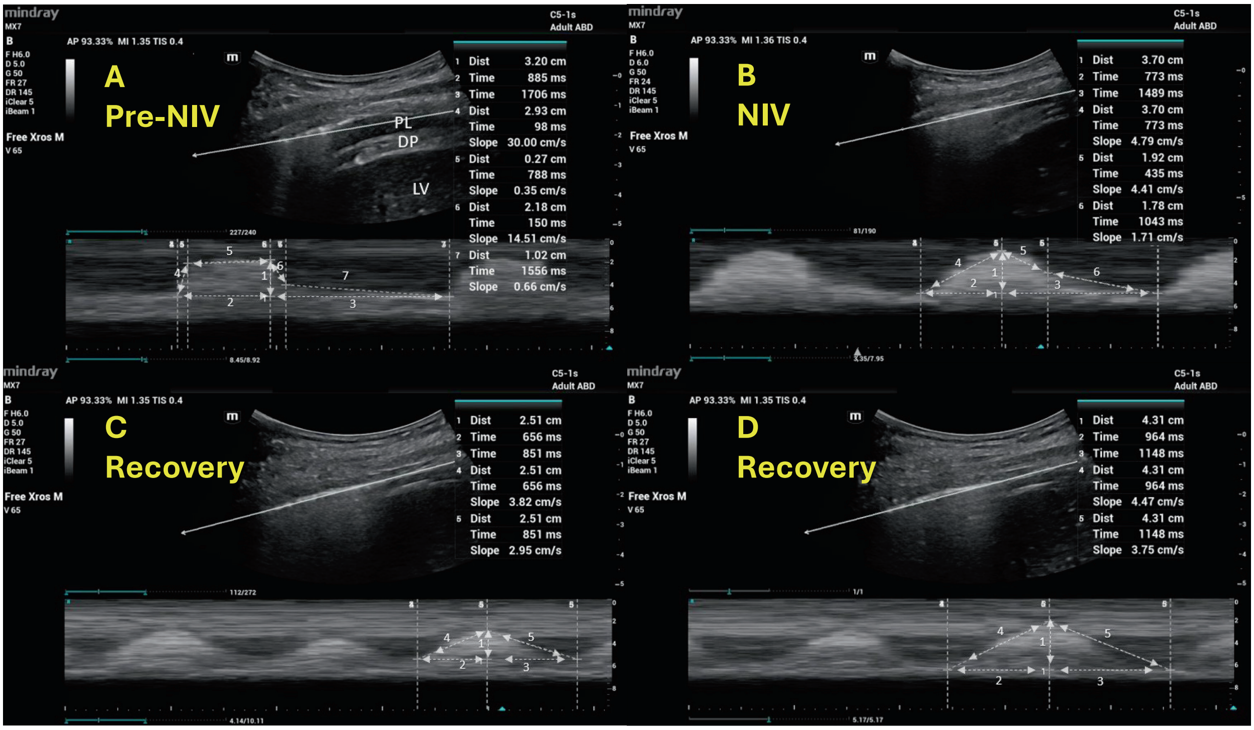

FIGURE 2 | (A) Anatomical M-mode ultrasound view and Lung Curtain Swing vs. Time (LCST) graph of the patient before the application of non-invasive ventilation (NIV). The ultrasound image shows minimal pleural effusion ('PL') and anatomical landmarks including the diaphragm ('DP') and liver ('LV'). The white arrow represents the anatomical M-mode sampling arrow. In the LCST graph below, '1' marks the extent of lung expansion (3.20 cm), '2' indicates the inspiratory time (885 ms), and '3' denotes the expiratory time (1706 ms). The slope '4' (30 cm/s) represents the speed of lung expansion during the early phase, while slope '5' (0.35 cm/s) corresponds to the speed in the late phase of lung expansion. Slope '6' (14.51 cm/s) indicates the speed of lung retraction during the early phase of expiration, and slope '7' (0.66 cm/s) reflects the speed of lung retraction during the late phase of expiration. (B) Anatomical M-mode ultrasound view and LCST graph of the patient under NIV. '1' marks the extent of lung expansion (3.70 cm), '2' indicates the inspiratory time (773 ms), and '3' denotes the expiratory time (1489 ms). The slope '4' (4.79 cm/s) represents the speed of lung expansion, while slope '5' (4.41 cm/s) corresponds to the speed of lung retraction during the early phase of expiration. Slope '6' (1.71 cm/s) reflects the speed of lung retraction during the late phase of expiration. (C) Anatomical M-mode ultrasound view and LCST graph of the patient during quiet breathing, taken 2 days after admission when pulmonary oedema had resolved. No pleural effusion is present. '1' marks the extent of lung expansion (2.51 cm), '2' indicates the inspiratory time (656 ms), and '3' denotes the expiratory time (851 ms). The slope '4' (3.82 cm/s) represents the speed of lung expansion, while slope '5' (2.95 cm/s) corresponds to the speed of lung retraction during expiration. (D) Anatomical M-mode ultrasound view and LCST graph of the patient during deep breathing, taken at the same time as (C). '1' marks the extent of lung expansion (4.31 cm), '2' indicates the inspiratory time (964 ms), and '3' denotes the expiratory time (1148 ms). The slope '4' (4.47 cm/s) represents the speed of lung expansion, while slope '5' (3.75 cm/s) corresponds to the speed of lung retraction during expiration.

3 | Discussion

As the lung curtain predominantly moves in the cranial–caudal direction [2], representing the primary vector of lung volume change during respiration, the measured extent of lung expansion serves as an indicator of lung volume change. The speeds of lung expansion and retraction (the slopes in the LCST graph) correspond to inspiratory and expiratory flows, respectively.

The patient's initial ABG indicated hypoxemic and hypercapnic respiratory failure. Unlike the characteristic hill-like pattern of the lung excursion waveforms observed in healthy subjects (Figure 1C) and in post-recovery breathing (Figure 2C/D), the initial LCST graph (Figure 2A) exhibited a convex inspiratory curve and a concave expiratory curve. The convex inspiratory limb consisted of a rapid initial lung expansion (Figure 2A, slope 4), followed by a near-plateau phase (Figure 2A, slope 5). Lung expansion (2.93 cm) occurred mostly within the first 98 ms of inspiration, while minimal further expansion (0.27 cm) occurred in the subsequent 788 ms. The late phase of inspiration showed impaired inspiratory effort, and the resultant lung expansion (Figure 2A, label '1' = 3.2 cm) was significantly smaller than the lung expansion capacity observed in deep breathing post-recovery (Figure 2D, label '1' = 4.31 cm). This ineffective inspiration suggests respiratory muscle fatigue, an indicator of impending respiratory failure [3].

The concave expiratory limb was consistent with the obstructive pattern observed in flow-volume graphs of obstructive lung disease [4]. It was characterised by an initial rapid lung retraction (Figure 2A, slope 6), followed by a nearly flat slope with minimal further retraction (Figure 2A, slope 7). This corresponds to early rapid expiratory flow, with restricted expiratory flow towards the end of expiration. This pattern was likely due to cardiogenic asthma secondary to bronchial oedema.

After NIV initiation, the LCST graph (Figure 2B) demonstrated improved lung expansion (Figure 2B, '1' = 3.7 cm). The previously convex inspiratory limb was transformed into a single ascending slope (Figure 2B, slope 4: 4.79 cm/s), surpassing the pre-NIV average expansion speed (3.62 cm/s: 3.2 cm/0.885 s). This improvement demonstrated the benefits of NIV in reducing breathing workload and increasing tidal volume [5].

In the expiratory limb, the average retraction speed (2.48 cm/s: 3.7 cm/1489 ms) was higher than in pre-NIV conditions (1.88 cm/s: 3.2 cm/1706 ms). The previously concave expiratory curve was smoothed due to the increased retraction speed in the late expiration phase (Figure 2B, slope 6). This enhanced retraction speed indicated improved expiratory flow facilitated by NIV. The ABG showed enhanced oxygenation and ventilation (PaO_2/FiO_2: 342), with resolution of respiratory acidosis.

Other quantitative measurements have been explored to assess lung sliding amplitude. The B mode technique detects B-lines or pleural defects, which may limit the examination of healthy lungs. Pulsed wave Doppler estimates the velocity of pleural sliding at specific points but cannot evaluate overall lung ventilation. Speckle tracking and tissue Doppler imaging measure focal pleural line sliding distance/velocity but are also limited in the analysis of the lung ventilation process. Diaphragm ultrasound quantitatively evaluates diaphragm function by measuring diaphragm thickness, thickening fraction and diaphragm excursion. However, these methods require the patient to be supine and may potentially interfere with diaphragm movement due to transducer pressure. The accuracy and reliability of measurements using AMM ultrasound can be limited by conditions such as pleural effusions or adhesions which may restrict lung curtain movement. Focal pulmonary lesions (e.g., bullae or masses) can affect lung swing dynamics. Hyperventilating patients may also have hyperinflated lungs displaced beyond the range of the ultrasound image and making assessment challenging.

Nevertheless, the LCST graph using AMM ultrasound offers real-time, non-invasive assessment of respiratory mechanics. The ability to identify respiratory failure and obstructive expiration patterns through convex inspiratory and concave expiratory curves in the LCST graph suggests a promising role for this technique in evaluating respiratory pathology, and for guiding treatment decisions.

Author Contributions

Timothy Kangwei Wong: investigation, writing, review and editing. **Albert Yick Hou Lim:** review and editing, supervision. **Chiao-Hao Lee:** conceptualisation, methodology, writing, supervision.

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Ethics Statement

The authors declare that written informed consent was obtained for the publication of this manuscript and accompanying images using the consent form provided by the Journal.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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