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The Role of Thoracic Fluid Content by Electrical Cardiometry and Diaphragmatic Ultrasound in Predicting Weaning Success in Patients with Pulmonary Congestion

Shawky M. El- Shaer, Ahmed M. Abd El-Hamid, Enas W. Mahdy, Samar R. Amin

Anesthesiology and Intensive Care Department, Faculty of Medicine Benha University, Egypt.

Corresponding to:
Shawky M. El- Shaer.
Anesthesiology and Intensive Care Department, Faculty of Medicine Benha University, Egypt.

Email:
elshaershawky@gmail.com

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Abstract:

Background: Mechanical ventilation weaning is a fundamental aspect of managing patients diagnosed with respiratory failure. Failure to wean successfully can lead to prolonged ventilation, increased morbidity, extended hospital stays, and higher mortality. Identifying reliable predictors of weaning success is therefore essential. Diaphragmatic ultrasound allows for direct assessment of diaphragmatic function and has been associated with improved weaning outcomes. Thoracic fluid content (TFC), a hemodynamic parameter measured by electrical cardiometry, reflects thoracic fluid status and inversely correlates with thoracic impedance. Elevated TFC has been linked to lung congestion and may serve as an early predictor of weaning failure. Objective: This review article aims to evaluate the predictive value of TFC measured by electrical cardiometry in combination with diaphragmatic excursion assessed by ultrasound for forecasting weaning success in patients with signs of pulmonary congestion. **Methods:** A literature search was conducted through PubMed, Scopus, and Google Scholar using keywords including "Thoracic fluid content", "Electrical cardiometry", "Diaphragmatic excursion", "Ultrasound", and "Weaning from MV". Articles published in English from 2000 to 2024 that investigated non-invasive predictors of weaning outcomes were reviewed. Conclusion: TFC provides a non-invasive estimate of extravascular lung water, making it a potentially valuable tool in assessing readiness for ventilator weaning. When combined with diaphragmatic ultrasound, these measures may offer a more accurate and individualized approach to predict weaning success, particularly in patients with lung congestion.

Keywords: Thoracic Fluid Content; Electrical Cardiometry; Diaphragmatic Ultrasound; Weaning Success; Pulmonary Congestion.

Introduction

Weaning patients from mechanical ventilation (MV) remains a complex challenge, particularly after cardiac surgery, where timing is critical. Both premature and delayed extubation are linked to increased morbidity, mortality, prolonged ventilation, and extended ICU stay. One of the main contributors to weaning failure is left ventricular dysfunction, which may result from prolonged cardiopulmonary bypass (CPB), inadequate intraoperative cardiac protection, or myocardial ischemia. Recent focus has shifted toward cardiac-related factors such as pulmonary congestion and hypervolemia. Traditional indicators like B-type natriuretic peptide or echocardiography require invasive testing or specialized expertise, limiting their routine use [1].

Left ventricular dysfunction is one of the common causes of failed ventilator-weaning following cardiac surgeries. Prolonged CPB, insufficient cardiac protection during operation, and the presence of myocardial ischemia are accompanied by an increased incidence of postoperative cardiac dysfunction. A great interest was directed to cardiac factors, including pulmonary congestion and hypervolemia, as essential factors with a significant role in weaning failure. Most of the previously used measures for cardiac factors as predictors of weaning outcomes from mechanical ventilators necessitate frequent blood sampling like B-type natriuretic peptide, or professional operators in echocardiography [2].

Thoracic fluid content (TFC), measured by electrical cardiometry, offers a non-invasive, real-time assessment of intrathoracic fluid status. TFC inversely correlates with thoracic impedance and reflects both intravascular and extravascular lung water. Its dynamic nature makes it a promising predictor of weaning outcomes. Similarly, diaphragmatic excursion assessed by ultrasound provides valuable information on diaphragmatic function during spontaneous breathing [3]. Comparing these two methods—TFC and diaphragmatic excursion—may enhance the ability to predict successful weaning from MV, offering a more comprehensive and accessible approach for clinical decision-making [4].

This review article aims to compare the predictive ability of TFC, as measured by electrical cardiometry, with diaphragmatic excursion, as assessed by ultrasound, in evaluating weaning success in patients with signs of lung congestion.

Methods

A comprehensive narrative review was conducted to assess the predictive value of thoracic fluid content (TFC), measured by electrical cardiometry, and diaphragmatic excursion (DE), evaluated via ultrasound, in determining weaning outcomes from invasive mechanical ventilation. The literature search aimed to identify studies examining these non-invasive parameters either individually or in combination, particularly in patients with evidence of pulmonary congestion.

Searches were performed in three major electronic databases: PubMed, Scopus, and Google Scholar, covering literature published between January 2000 and March 2024. The search strategy utilized a combination of medical subject headings (MeSH) and free-text keywords, including: “thoracic fluid content,” “electrical cardiometry,” “diaphragmatic excursion,” “diaphragm ultrasound,” “mechanical ventilation,” and “weaning.” Boolean operators such as “AND” and “OR” were used to refine the search and retrieve the most relevant articles. Additional references were identified through manual screening of the bibliographies of eligible studies**.**

The inclusion criteria for this review were as follows:

Studies involving adult human patients (≥18 years old) receiving invasive mechanical ventilation;

Investigations assessing the role of TFC and/or diaphragmatic ultrasound (DE or DTF) in predicting weaning success or failure;

Original research articles, clinical trials, observational studies, and systematic reviews/meta-analyses;

Articles published in English.

Exclusion criteria included:

Non-English language publications;

Case reports, editorials, narrative commentaries, and expert opinions without original data;

- Studies exclusively focused on neonatal or paediatric populations;
- Studies where TFC or diaphragmatic parameters were not clearly linked to weaning outcomes.
- The selection process was conducted in two stages. First, titles and abstracts were screened for relevance. In the second stage, full-text articles of selected studies were thoroughly reviewed to assess eligibility based on the inclusion and exclusion criteria. Any discrepancies during selection were resolved through discussion among the authors**.**

Results

A total of (9) studies were included in this review after screening titles, abstracts, and full texts. These studies examined the predictive role of thoracic fluid content (TFC) measured via electrical cardiometry and diaphragmatic ultrasound parameters, primarily diaphragmatic excursion (DE) and diaphragmatic thickening fraction (DTF), in weaning patients from mechanical ventilation.

1. Thoracic Fluid Content (TFC)

Several studies reported that elevated TFC was significantly associated with weaning failure, particularly in patients with underlying cardiac dysfunction or fluid overload.

- Fathy et al. reported a moderate predictive ability of TFC in surgical ICU patients (AUC = 0.69), which improved in patients with impaired ejection fraction (AUC = 0.93) **[5]** .
- Elbagoury et al. observed high predictive accuracy in post-cardiac surgery patients (AUC = 0.97 at 30 minutes into SBT, cutoff <45 kΩ^{-1}) **[2]**.
- Sumbel L et al. TFC Measurement predicts Outcomes in Critically Ill Children with respiratory failure and/or shock, TFC did not correlate with conventional measures of fluid balance [FIMO (Fluid Intake Minus Output) and AFIMO (Adjusted Fluid Intake Minus Output)], but a significant proportion of patients with high TFC had pulmonary plethora on chest x-ray. Both initial and peak TFC predicted outcomes in critically ill children **[3]**
- Studies in neonates also confirmed the utility of TFC for predicting extubation success, suggesting its broader applicability across age groups **[6]** .

Overall, TFC was most predictive in cardiac patients, likely due to the close association between intrathoracic fluid shifts and cardiac performance during weaning.

2. Diaphragmatic Excursion (DE)

The predictive value of DE for weaning outcomes varied among studies. While several studies showed that lower DE was associated with failed weaning, its diagnostic performance was generally moderate and often influenced by operator technique and patient cooperation.

- Saravanan et al. found that DE to be significantly decreased in the group who failed weaning , (AUC = 0.809 , cut-off values were DE >1.21 cm , sensitivity 94%, specificity 71%) [7] .
- Sabetian et al**.** found that the group who failed weaning had significantly lower right diaphragmatic excursion compared to the success group [8] .

3. Diaphragmatic Thickening Fraction (DTF)

DTF consistently showed strong predictive performance across most studies.

- A systematic review found DTF to have high pooled AUC values (>0.85), outperforming DE in terms of both sensitivity and specificity [9] .
- Parada-Gereda et al. and Llamas-Álvarez et al . reported DTF cutoffs between 30–36% to be most accurate for predicting weaning success [10] .
- DTF maintained high predictive value in both cardiac and non-cardiac patients, suggesting its robustness as a functional index of diaphragmatic activity.

4. Comparative Trends

Most studies that assessed both cardiopulmonary and diaphragmatic indices concluded that:

- TFC was more predictive in patients with cardiac-related pulmonary congestion, especially in early SBT phases.
- DTF was a more universally reliable marker across patient subgroups.
- DE alone showed moderate utility, often improved when combined with other parameters.

Discussion

Lung Ultrasound

Lung ultrasound (LUS) has increasingly been utilized in the diagnostic evaluation of a range of pulmonary conditions, including ARDS, pneumonia, pulmonary embolism, asthma, pneumothorax, COPD, and interstitial pulmonary fibrosis. Notably, the presence of LUS B-lines may suggest pulmonary congestion in patients with pulmonary oedema, ARDS, and pneumonia [11].

LUS is typically conducted by trained professionals holding nationally recognized certification. Examinations should be carried out with the patient in a supine position. B-lines may be assessed using 4-, 6-, 8-, or 28-point scanning protocols targeting the anterior and lateral chest regions, with the transducer aligned parallel to the ribs. Within each intercostal space, B-lines should be identified and counted individually in real time. Additionally, offline image interpretation may be performed through video analysis by two investigators experienced in LUS evaluation. The region exhibiting the highest number of B-lines should be selected for assessment [11].

- ❖ **Weaning and Predictors of Weaning from Mechanical Ventilation**

Weaning from MV: is a methodical approach to decreasing ventilatory support over time, intended to facilitate extubation in patients recovering from the initial insult that necessitated MV [12].

Weaning success: it is characterized by patient extubation and the maintenance of spontaneous breathing without the need for ventilatory support for a minimum of 48 hours thereafter [13].

- ❖ **Initiation of weaning from MV**

Clinical evaluation and predictive parameters: Patients are eligible for weaning from MV when they meet essential criteria, including resolution or stabilization of the initial illness, sufficient gas exchange, hemodynamic stability, and the ability to breathe spontaneously. If these conditions are satisfied, a spontaneous breathing trial

(SBT) should be initiated. However, in the presence of unfavourable clinical findings, weaning indices lose their utility, as evaluating predictive parameters is unwarranted when the precipitating cause for MV has not improved [14]

Spontaneous Breathing Trial (SBT)

Spontaneous breathing trials (SBTs) are essential steps in assessing a patient's readiness for extubation, and several techniques are available. A T-piece trial involves disconnecting the patient from the ventilator while supplying supplemental oxygen. In contrast, pressure support ventilation (PSV) maintains patient connection to the ventilator with minimal support (PS 5–8 cm H_2O, PEEP ≤5 cm H_2O, FIO_2 ≤0.4–0.5). Another method, automated tube compensation (ATC), mimics natural breathing by compensating for pressure loss across the endotracheal tube, improving comfort and reducing the work of breathing. A successful 30–120-minute SBT typically indicates readiness for extubation, while failure requires identifying reversible causes and reattempting SBTs every 24 hours, ideally alongside spontaneous awakening trials [15].

- **Weaning failure definition and pathophysiology**

The term 'weaning failure' refers to either failure to tolerate a spontaneous breathing trial or the necessity for reintubation within 48 hours post-extubation, most commonly resulting from a mismatch between respiratory muscle strength and ventilatory demand [16] .Contributing factors include central inhibition, phrenic nerve dysfunction, neuromuscular diseases, and general muscle weakness. Increased respiratory demands from sepsis, fever, pain, or reduced lung compliance also play a role. Neurological, metabolic, endocrine, and psychological disorders further complicate the weaning process. Identifying and addressing the specific cause of failure is critical to tailoring the approach and achieving successful ventilator liberation [16].

- **Predictive parameters for MV weaning**

1. Diaphragmatic Function and Its Role in Weaning

As the principal inspiratory muscle, the diaphragm plays a vital role in respiration, and its dysfunction serves as both an indicator of disease severity and a predictor of unfavourable outcomes in critically ill patients. Diaphragm dysfunction has been clearly linked to increased mortality and prolonged dependence on MV in the ICU [17].

Diaphragm dysfunction is common during weaning from MV, with reported prevalence up to 80%. Although assessed using phrenic nerve stimulation, many patients with reduced diaphragm strength ($P_{tr,stim} < 11$ cm H_2O) can still be successfully weaned. While dysfunction may affect exercise capacity, its direct impact on weaning success is limited. Respiratory muscle weakness overall may influence long-term outcomes, but diaphragm dysfunction alone should not discourage weaning attempts [18].

- **Diaphragmatic Excursion**

Accounting for nearly 75% of lung ventilation, the diaphragm plays a central role in respiratory mechanics. Imaging of the diaphragm is crucial for detecting dysfunction or paralysis, and normal diaphragmatic excursion values serve as a benchmark for diagnosing disease-related impairments **(Figure 1)** [19].

Reference values for diaphragmatic excursion are essential for identifying both hypokinesia and hyperkinesia. During tidal breathing, normal diaphragmatic excursion has been reported to range between 1 and 2.5

cm [19]. The procedure is conducted by instructing the patient to exhale fully and hold their breath. The clinician then percusses along the intercostal spaces of the posterior thorax, beginning just below the scapula. Percussion over bony structures yields a dull sound, whereas the lung fields produce a resonant tone. The point at which the percussion notes changes from resonant to dull is marked, indicating the lower border of the lung. The patient is then asked to take a deep breath and hold it, after which percussion is repeated in the same manner. The new point where the sound again shifts from resonant to dull is marked, corresponding to the expanded lower lung margin [20].

Diaphragmatic thickness fraction (DTF)

The diaphragmatic thickening fraction (DTF) %, indicative of the intensity of diaphragmatic contraction, may serve as a predictive marker for successful weaning from MV. Ultrasound facilitates evaluation of diaphragmatic function through parameters such as DTF, diaphragmatic excursion (DE), and time to peak inspiratory amplitude (TPIA). Evidence from several studies supports the superiority of DTF over DE in forecasting weaning success, citing enhanced sensitivity and specificity **[21]**. Diaphragmatic thickness (DT) was measured at the zone of apposition, which corresponds to the region where the diaphragm is in contact with the rib cage, typically between the eighth and tenth intercostal spaces. Measurements were obtained at both end-inspiration and end-expiration using a 6–13 MHz linear ultrasound transducer in M-mode. The diaphragmatic thickening fraction (DTF) percentage was calculated using the following formula: (DT at end-inspiration − DT at end-expiration) / DT at end-expiration × 100 **[22]**.

2. Thoracic Fluid Content and Electrical Cardiometry

Cardiac output (CO) is calculated as the product of heart rate (HR) and stroke volume (SV), and is typically expressed in litters per minute (L/min). Clinically, CO is valuable in the evaluation of cardiovascular conditions, particularly in patients with coronary artery disease and congestive heart failure **[23]**. Accurate measurement of CO has traditionally relied on invasive techniques, such as thermodilution using a pulmonary artery catheter (PAC), which has long been considered the clinical gold standard for hemodynamic assessment. However, these invasive methods carry significant risks, including increased mortality in critically ill patients, procedural complexity, and the requirement for highly trained personnel. Consequently, there is a growing interest in the adoption of minimally invasive or non-invasive modalities to overcome these limitations **[24]**.

- **Fundamental Basis of Impedance Cardiography**

Impedance cardiography measurements

Impedance cardiography is a non-invasive method used to measure changes in thoracic electrical impedance, offering real-time insights into the cardiovascular system. It works by applying a constant, high-frequency, low-amplitude alternating current (typically 1–5 mA, 20–100 kHz) through two outer electrodes, while the voltage is measured by two inner electrodes. This technique helps assess the electrical properties of thoracic tissues, making it useful in monitoring cardiac output and fluid status **[25]**.

One of the most common configurations is the tetrapolar-band setup, where electrodes are placed around the neck and upper abdomen to detect impedance changes during the cardiac cycle. An injected current of around 4 mA at 100 kHz is typically used. For more practical use, spot electrodes have replaced band electrodes. In this setup, outer electrodes are placed on the forehead and near the heart, while inner electrodes are positioned on the left chest between them, using a 1 mA current at 30 kHz to measure voltage changes **(Figure 2)** [26]Figure .

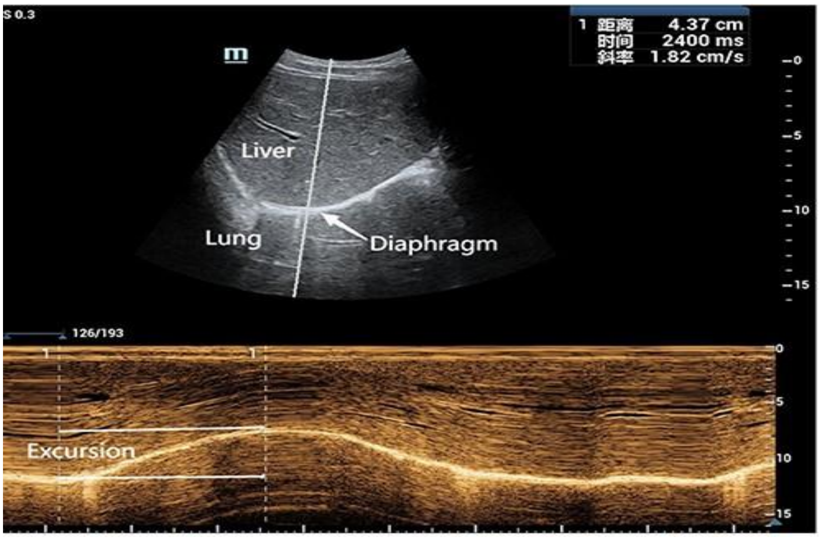

Figure 1: Diaphragmatic Excursion [19]

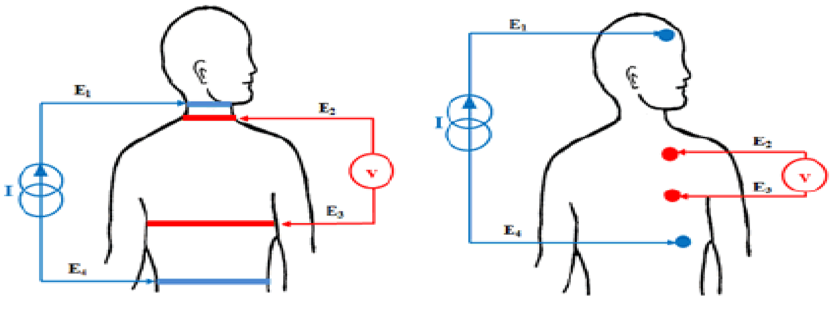

Figure 2: Electrode configurations for the impedance cardiography ICG signal measurements: (a) Tetrapolar-band electrodes, (b) Tetrapolar-spot electrodes [26]

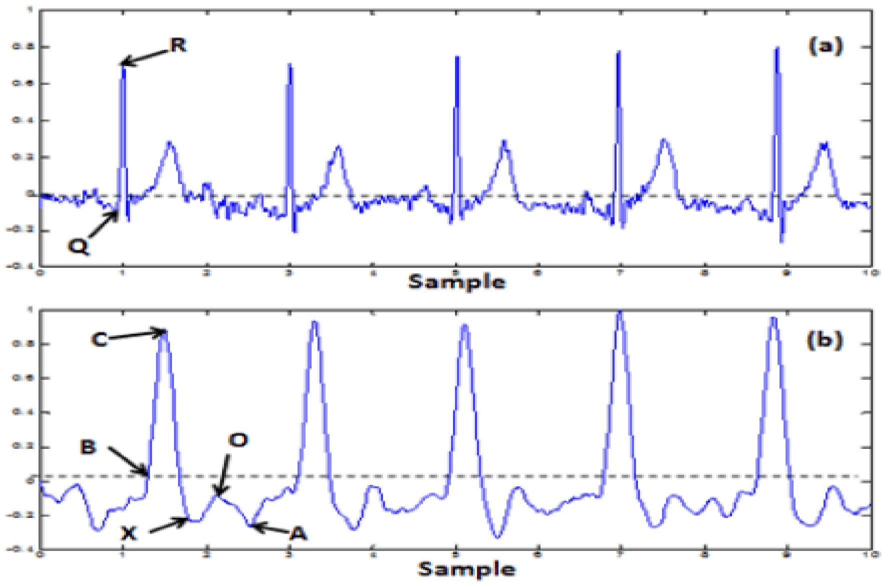

Figure 3: (a) ECG tracing, (b) Characteristic points in the impedance cardiography ICG tracing [28]

Impedance cardiography recording

The voltage acquired during impedance cardiography is proportional to the variation in thoracic impedance (ΔZ), and impedance (Z) is calculated using Ohm's law as the ratio of voltage (V) to known current (I). The resulting signal, represented as dZ/dt, is the first derivative of ΔZ and reflects changes in blood volume during the cardiac cycle. Key waveform points—A, B, C, X, and O—correlate with distinct physiological events and are essential for accurate interpretation of cardiac function [27].

Point A marks the onset of electromechanical systole, linked to atrial contraction. Point B signifies the start of aortic valve opening and ejection, crucial for calculating stroke volume (SV) and cardiac output (CO), though its exact location may vary along the ascending dZ/dt slope. Point C (dZ/dt max) reflects peak ventricular contraction. Point X, the lowest point after C, indicates aortic valve closure and systole's end, while point O corresponds to diastolic filling and mitral valve opening. Accurate identification of these points ensures reliable SV and CO estimation **(Figure 3)** [28].

Impedance cardiography (ICG), when synchronized with electrocardiography (ECG), enables measurement of key systolic time intervals (STIs) that reflect left ventricular function. The most commonly used STIs are the pre-ejection period (PEP) and the left ventricular ejection time (LVET). PEP is the interval from the Q wave on the ECG to the B point on the ICG trace, representing the isovolumetric contraction phase. LVET spans from the B to the X point on the ICG and corresponds to mechanical systole, offering a basis for estimating stroke volume (SV) and cardiac output (CO) [29].

Another important interval is the initial systolic time interval (ISTI), measured from the R peak on the ECG to the C point on the ICG. This interval reflects the delay between electrical activation and mechanical contraction, aligning with the maximum expansion of the aortic arch. Accurate detection of these time intervals relies on precise identification of ICG waveform points. Advanced signal processing algorithms have been developed to enhance the accuracy and consistency of these measurements, ultimately improving hemodynamic assessments [30].

❖ **TFC in Lung Congestion**

A recently introduced parameter, TFC, serves as an indicator of the total fluid volume within the thoracic cavity, including intravascular, extravascular, and intrapleural components. Higher TFC values are indicative of increased thoracic fluid accumulation and are considered a surrogate measure of pulmonary congestion or hypervolemia congestion [5] .

Conclusion

TFC provides a non-invasive estimate of extravascular lung water, making it a potentially valuable tool in assessing readiness for ventilator weaning. When combined with diaphragmatic ultrasound, these measures may offer a more accurate and individualized approach to predict weaning success, particularly in patients with lung congestion.

Limitations:

- Current evidence on thoracic fluid content (TFC) as a weaning predictor remains limited, with most studies being single-center and underpowered, reducing reliability.
- Significant heterogeneity exists in study populations, underlying conditions (e.g., cardiac vs. non-cardiac), and weaning assessment protocols, hindering direct comparisons.
- Variations in ultrasound techniques, operator skill, and cut-off values for diaphragmatic parameters (DE/DTF) further challenge standardization.
- Most studies were observational, with few RCTs, restricting causal conclusions.

Recommendations

- Encouragement for using TFC and diaphragmatic us assessment (DE and DTF) together with standard parameters of weaning criteria to increase rate of success of weaning and improve outcome in patient with lung congestion

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