

Association between remote dielectric sensing and transpulmonary thermodilution–derived lung water after cardiac surgery: a repeated- measures exploratory study

Weitao Duan

Sichuan University West China Hospital

Yan Ren

Sichuan University West China Hospital

Shouxing Hu

Sichuan University West China Hospital

Yi Zheng

Sichuan University West China Hospital

XinYang Chen

Sichuan University West China Hospital

Hui Yu

Sichuan University West China Hospital

Jingxiu Fan

236654994@qq.com

Sichuan University West China Hospital

Research Article

Keywords:

Posted Date: October 18th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11150061/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Background

Remote dielectric sensing (ReDS) is a non-invasive technology that estimates pulmonary fluid content and may provide a convenient approach for monitoring thoracic fluid status. However, its relationship with invasive transpulmonary thermodilution-derived measures of pulmonary fluid in patients after cardiac surgery remains uncertain. This exploratory study investigated the association between ReDS measurements and PiCCO-derived extravascular lung water (EVLW) and extravascular lung water indexed to predicted body weight (ELWI).

Methods

We conducted a single-centre observational study of patients after cardiac surgery who underwent paired ReDS and PiCCO measurements during intensive care unit stay. A total of 88 paired measurements from 29 patients were analysed, with repeated measurements clustered within patients. Linear mixed-effects models with a patient-specific random intercept were used to evaluate associations between ReDS and PiCCO-derived parameters. The primary analysis assessed the association between ReDS and ELWI, while the key secondary analysis evaluated the association between ReDS and absolute EVLW. Patient-level mean values and first-measurement analyses were performed as sensitivity analyses. Exploratory analyses examined whether central venous pressure (CVP) modified the association between ReDS and pulmonary fluid parameters.

Results

Across 29 patients, 88 paired ReDS–PiCCO measurements were available, with a median of 3 measurements per patient (IQR, 1–4). In the primary mixed-effects analysis, ReDS was not significantly associated with weight-indexed ELWI ($\beta = 0.129$ per 1% increase in ReDS; 95% CI, -0.066 to 0.324 ; $P = 0.195$). In contrast, ReDS was positively associated with absolute EVLW ($\beta = 16.41$ mL per 1% increase in ReDS; 95% CI, 6.45 – 26.36 ; $P = 0.001$). Patient-level sensitivity analyses showed similar patterns, with no significant association between mean ReDS and mean ELWI ($r = 0.073$, $P = 0.706$), whereas mean ReDS was positively correlated with mean EVLW ($r = 0.518$, $P = 0.004$). Unadjusted CVP-stratified analyses showed a stronger ReDS–ELWI correlation among measurements with CVP > 12 mmHg; however, the formal interaction analysis did not demonstrate statistically significant effect modification by CVP.

Conclusions

In this exploratory cohort of patients after cardiac surgery, ReDS was not significantly associated with weight-indexed ELWI but showed a significant positive association with absolute EVLW. These findings

suggest that ReDS may reflect aspects of overall thoracic fluid burden without being interchangeable with thermodilution-derived ELWI. Larger longitudinal studies focusing on within-patient changes and incorporating independent reference measures are warranted to determine the clinical utility of ReDS for postoperative pulmonary fluid monitoring.

1. Introduction

Pulmonary fluid accumulation is common after cardiac surgery and may arise from a combination of perioperative fluid administration, cardiopulmonary bypass-related inflammation, altered vascular permeability, impaired cardiac function, and changes in pulmonary and systemic fluid distribution[1]-[3]. Excess pulmonary fluid may contribute to impaired gas exchange, prolonged mechanical ventilation, and delayed recovery during the postoperative intensive care period[1][18]. Therefore, timely assessment of pulmonary fluid status is an important component of postoperative hemodynamic and respiratory management.

Transpulmonary thermodilution monitoring with the PiCCO system provides quantitative parameters that can be used to characterize pulmonary and systemic fluid status[4][21]. In particular, extravascular lung water (EVLW) represents the absolute volume of extravascular fluid in the lungs, whereas extravascular lung water indexed to predicted body weight (ELWI) provides a body-size-adjusted measure of pulmonary fluid accumulation[4][6][7]. These parameters have been used in critically ill patients to quantify pulmonary fluid burden and to support clinical assessment[5][8][9]. However, PiCCO monitoring requires invasive arterial and central venous catheterization and specialized equipment, which may limit its repeated use when continuous or frequent reassessment of pulmonary fluid status is desired.

Remote dielectric sensing (ReDS) is a non-invasive technology that estimates pulmonary fluid content using electromagnetic signals transmitted between sensors placed on the thorax[11]. The resulting signal is processed by a proprietary algorithm to generate a percentage-based estimate of lung fluid content[12][13]. In patients with heart failure, ReDS has been associated with invasively measured pulmonary artery wedge pressure[14]. ReDS-guided strategies have also been investigated for congestion monitoring and reduction of heart-failure readmissions[15][16]. These findings suggest that ReDS may provide a practical means of assessing thoracic fluid status without invasive monitoring. However, ReDS does not directly measure intrathoracic fluid volume, and the physiological compartment represented by its measurement may differ from that quantified by transpulmonary thermodilution[4][8].

This distinction may be particularly relevant after cardiac surgery. Postoperative changes in intravascular volume, pulmonary vascular permeability, interstitial fluid, atelectasis, pleural or mediastinal fluid, and cardiac filling pressures may occur simultaneously[1][2][3][18]. Consequently, a non-invasive thoracic fluid signal may not necessarily correspond directly to ELWI, which is an indexed thermodilution-derived estimate of extravascular pulmonary fluid[6][7]. Moreover, the relationship between ReDS and absolute EVLW may differ from its relationship with ELWI because these parameters represent related but not

identical measurements[4][8]. The extent to which ReDS reflects pulmonary fluid burden in this specific postoperative population therefore remains uncertain.

Accordingly, we conducted an exploratory observational study to investigate the association between ReDS measurements and PiCCO-derived pulmonary fluid parameters in patients after cardiac surgery. The primary objective was to evaluate the association between ReDS and ELWI while accounting for repeated measurements within patients. As a key secondary objective, we examined the association between ReDS and absolute EVLW. Additional exploratory analyses evaluated associations with other PiCCO-derived parameters and examined whether concurrent central venous pressure modified the relationship between ReDS and pulmonary fluid measures. Given the different physical principles and physiological constructs represented by ReDS and PiCCO, we considered the study hypothesis-generating rather than a formal validation of measurement equivalence.

2. Methods

2.1 Study design

This was a prospective, single-center observational study. The study was approved by the institutional ethics committee (Approval No. 2024 – 717) and was also registered with the Chinese Clinical Trial Registry(Trial registration number ChiCTR2500095200). Reporting was guided by the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations[19]. Written informed consent was obtained from patients or their legal representatives before the trial.

2.2 Study participants

This study was conducted in the Cardiac Surgery Intensive Care Unit (CSICU), West China Hospital, Sichuan University (WCHSU). All patients undergoing open-heart surgery who required PiCCO monitoring for clinical reasons were included in this study and concurrently received ReDS monitoring, unless they met any of the following exclusion criteria:

- PiCCO measurements were considered technically unreliable or clinically inconsistent with the overall patient assessment
- Severe pulmonary disease (with a confirmed prior diagnosis of pulmonary fibrosis, emphysema, or COPD) or abnormal anatomy of right lung
- Failure to meet the manufacturer's requirements for ReDS measurement, including predefined limits for body mass index, height, thoracic anatomy, or chest-wall configuration
- Severe spinal or thoracic deformity or any other reasons that precluded standardized sensor placement
- Declined to participate or were unable to cooperate with study procedures
- Previous participation in another clinical trial

All patients underwent median sternotomy for valve surgery or major aortic/vascular surgery and returned from the operating room with one pericardial and one mediastinal drain. The recruitment of post-surgery patients began in January 2025 and ended in May 2026.

2.3 Measurements

Invasive cardiac output and volumetric parameters were measured concurrently using the PiCCO system (Pulsion Medical Systems, Munich, Germany) [4][21]. A central venous catheter and a 5F thermistor-tipped arterial catheter (placed in the femoral or brachial artery) were utilized. Reported parameters included extravascular lung water (EVLW, mL), extravascular lung water index (ELWI, mL/kg), pulmonary vascular permeability index (PVPI), intrathoracic blood volume (ITBV), ITBV index (ITBVI), global end-diastolic volume index (GEDI), pulse-contour cardiac index (PCCI), and maximal left-ventricular pressure rise (dPmax). Central venous pressure (CVP) was recorded at the time of thermodilution.

Noninvasive lung fluid content was measured by the ReDS technology (Non-invasive lung fluid monitor - ReDS System, MITRASSIST Lifesciences Limited), which is registered as a class Ⅱ medical device in China (NMPA registration no. Anhui No.20232070067) [11][12]. The ReDS value was acquired immediately after completion of thermodilution calibration, with the sensor belt placed over the right mid-thoracic field per device instructions. Measurements were performed with patients in the semi-fowler position (30°-45° head-of-bed elevation) during standard end-expiratory pauses. Measurements were obtained approximately once daily while PiCCO monitoring remained clinically indicated; however, the exact postoperative time from surgery to each paired measurement was not systematically recorded.

2.4 Endpoints and definitions

The primary endpoint was the association between ReDS value (%) and ELWI (mL/kg), assessed using a linear mixed-effects model with a patient-specific random intercept. The key secondary endpoint was the association between ReDS value (%) and absolute EVLW (mL).

Exploratory analyses evaluated associations between ReDS and other PiCCO-derived parameters, including PVPI, ITBV, ITBVI, GEDI, PCCI, dPmax, and CVP. Effect modification by concurrent CVP was explored by categorizing measurements as $CVP \leq 12$ mmHg or > 12 mmHg and testing the ReDS $\times$ CVP stratum interaction.

An additional exploratory analysis evaluated the ability of ReDS to discriminate measurements with $ELWI > 12$ mL/kg using receiver-operating characteristic (ROC) analysis[10]. This analysis was considered descriptive and hypothesis-generating; no diagnostic threshold was prespecified or recommended.

2.5 Statistical analysis

Continuous variables are presented as mean $\pm$ standard deviation or median (IQR), as appropriate, and categorical variables as number (percentage). Patient-level baseline characteristics were summarized using one observation per patient.

Associations between ReDS and ELWI, EVLW, and other PiCCO-derived parameters were estimated using linear mixed-effects models with ReDS as a fixed effect and a patient-specific random intercept to account for repeated measurements within patients. Models were fitted using restricted maximum likelihood. The regression coefficient represents the estimated difference in the dependent variable associated with a 1-percentage-point increase in ReDS. These models estimate population-level associations while accounting for within-patient clustering and were not designed to explicitly decompose within-patient and between-patient associations.

For the exploratory CVP analysis, models included ReDS, CVP stratum, and the ReDS $\times$ CVP-high interaction term. The interaction term tested whether the slope of the association between ReDS and the outcome differed between CVP strata.

As sensitivity analyses, Pearson correlations were calculated using patient-wise mean ReDS and patient-wise mean PiCCO values, yielding one summary observation per patient ($n = 29$). A second sensitivity analysis was restricted to the first available paired measurement from each patient ($n = 29$).

ROC analyses were performed at the measurement level and were not used for primary inference or clinical decision thresholds because within-patient clustering was not accounted for. No imputation was performed for missing measurement-level data.

Two-sided P values < 0.05 were considered nominally statistically significant. No adjustment for multiple comparisons was performed because analyses beyond the primary endpoint were prespecified as secondary or exploratory and were interpreted accordingly. All analyses were performed using Python with SciPy and statsmodels.

3. Results

3.1 Patients and measurements

Twenty-nine patients contributed 88 paired ReDS–PiCCO measurements obtained approximately once daily while PiCCO monitoring remained clinically indicated (median, 3 measurements per patient; range, 1–10). Median age was 56.0 years [50.0–60.0]. Median CPB time was 194 min [140–232] and median aortic cross-clamp time 135 min [101–166].

The analytical dataset comprised 88 paired measurements nested within 29 patients. All primary mixed-effects analyses accounted for this within-patient dependence by including a patient-specific random intercept. Baseline characteristics are summarized in Table 1.

Table 1
Characteristics of the study population and paired measurements

Variable	Patients (n = 29)
Demographics	
Age (years)	56.0 [50.0, 60.0]
Male sex, n (%)	20 (69.0)
Height (cm)	165.0 [158.0, 169.0]
Weight (kg)	63.0 [56.0, 70.0]
BMI (kg/m ²)	23.1 [21.6, 24.6]
Surgical characteristics	
Median sternotomy, n (%)	29 (100)
Valve or major aortic/vascular surgery, n (%)	29 (100)
Pericardial + mediastinal drain, n (%)	29 (100)
CPB time (min)	194.0 [140.0, 232.0]
Aortic cross-clamp time (min)	135.0 [101.0, 166.0]
Severity and outcomes	
APACHE II score	18.0 [17.0, 18.0]
Mechanical ventilation duration (h)	68.0 [49.0, 144.2]
ICU length of stay (days)	7.0 [5.0, 9.5]
Hospital length of stay (days)	16.0 [13.5, 23.0]
Study measurements	
Paired ReDS–PiCCO measurements per patient	3.0 [1.0, 4.0]
Total paired measurements	88
Patient-mean ReDS (%)	29.0 [24.5, 33.0]
Patient-mean ELWI (mL/kg)	9.5 [8.0, 12.0]
Patient-mean EVLW (mL)	496.6 [430.5, 795.5]
Patient-mean CVP (mmHg)	9.3 [7.0, 11.3]

Values are median [IQR] or n (%). BMI = body mass index; CPB = cardiopulmonary bypass; APACHE = Acute Physiology and Chronic Health Evaluation; ICU = intensive care unit; ReDS = remote dielectric sensing; ELWI = extravascular lung water index; EVLW = extravascular lung water; CVP = central venous pressure.

Mechanical ventilation and length-of-stay data were unavailable for some patients. All patients underwent median sternotomy; ReDS was obtained immediately after PiCCO thermodilution calibration on each measurement day until catheter removal. Patient-mean values represent the arithmetic mean of all available paired measurements for each patient and are presented descriptively.

Of 88 measurements, 69 (78.4%) were obtained at CVP $\leq$ 12 mmHg and 19 (21.6%) at CVP > 12 mmHg. ELWI > 12 mL/kg was present in 23 measurements (26.1%), including 5 of 19 high-CVP measurements. Measurement-level distributions stratified by concurrent CVP are provided in Supplementary Table S1; high-CVP observations remained enriched for male sex and higher body mass index.

3.2 Primary and secondary associations

In the primary linear mixed-effects model with a random intercept for patient, ReDS was not significantly associated with ELWI. The estimated slope was 0.129 mL/kg per 1-percentage-point increase in ReDS (95% CI, - 0.066 to 0.324; P = 0.195) (Table 2, Fig. 1A).

In contrast, ReDS showed a positive fixed-effect association with absolute EVLW after accounting for patient-level clustering. Each 1-percentage-point increase in ReDS was associated with an estimated 16.4-mL higher EVLW (95% CI, 6.5–26.4; P = 0.001) (Table 2, Fig. 1B).

Thus, the primary mixed-effects analysis did not demonstrate a statistically significant association between ReDS and weight-indexed ELWI, whereas a positive fixed-effect association was observed between ReDS and absolute EVLW.

Table 2
Linear mixed-effects models for the primary and key secondary associations

Dependent variable	slope (per 1% ReDS)	95% CI	P value	Role
ELWI (mL/kg)	0.129	-0.066 to 0.324	0.195	Primary
EVLW (mL)	16.41	6.45 to 26.36	0.001	Key secondary

All models included ReDS as a fixed effect and a patient-specific random intercept.

Scatter plots of remote dielectric sensing (ReDS, %) versus (A) extravascular lung water index (ELWI, mL/kg) and (B) absolute extravascular lung water (EVLW, mL). Each point represents one paired measurement (n = 88 observations from 29 patients), with repeated measurements from the same patient connected by light lines. Solid black lines indicate the fixed-effect fit from linear mixed-effects models with a random intercept per patient; shaded bands indicate the approximate 95% confidence interval for the fixed-effect regression line. (A) Slope = 0.13 mL/kg per 1% ReDS (95% CI - 0.07 to 0.32; P = 0.195). (B) Slope = 16.4 mL per 1% ReDS (95% CI 6.5 to 26.4; P = 0.001).

3.3 Associations with other PiCCO parameters

Associations between ReDS and the remaining PiCCO-derived parameters are summarized in Table 3. No statistically significant mixed-effects associations were observed between ReDS and ITBV, ITBVI, GEDI, PCCI, dPmax, CVP, or PVPI. The estimated association with ITBV was 19.19 mL per 1 percentage-point increase in ReDS (95% CI, – 6.58 to 44.96; P = 0.144), whereas the association with ITBVI was 8.49 mL/m² per percentage point (95% CI, – 3.81 to 20.80; P = 0.176). The remaining exploratory associations were not statistically significant and are presented in Table 3.

Table 3
Linear mixed-effects associations between ReDS and all PiCCO-derived parameters.

Dependent variable	Slope (per 1% ReDS)	95% CI	P
ITBV (mL)	19.19	–6.58 to 44.96	0.144
ITBVI (mL/m ²)	8.49	–3.81 to 20.80	0.176
dPmax (mmHg/s)	–11.75	–32.84 to 9.34	0.275
CVP (mmHg)	0.05	–0.08 to 0.19	0.444
PCCI (L/min/m ²)	0.007	–0.019 to 0.033	0.599
PVPI	–0.009	–0.055 to 0.037	0.699
GEDI (mL/m ²)	0.40	–5.48 to 6.28	0.894

Linear mixed-effects models with a fixed effect of ReDS and a patient-specific random intercept (REML; 88 observations nested in 29 patients). The slope represents the estimated change in the dependent variable per 1 percentage-point increase in ReDS. Secondary endpoints were considered exploratory and were not adjusted for multiplicity. Models in which the patient-level random-intercept variance was estimated at or near the boundary were interpreted cautiously; these analyses were considered exploratory.

3.4 Sensitivity analyses

Patient-level sensitivity analyses showed directionally concordant findings (Table 4, Fig. 2). Using patient-wise mean values, mean ReDS was positively correlated with mean EVLW (r = 0.518, P = 0.004), whereas no correlation was observed between mean ReDS and mean ELWI (r = 0.073, P = 0.706). When the analysis was restricted to the first available measurement from each patient, the correlation between ReDS and EVLW remained positive (r = 0.511, P = 0.005), whereas the correlation between ReDS and ELWI remained negligible (r = 0.073, P = 0.708).

These patient-level analyses were directionally concordant with the primary mixed-effects findings and did not materially alter the overall interpretation.

Table 4
Patient-level sensitivity analyses of associations between ReDS and selected PiCCO parameters

Parameter	Patient means (n = 29) r (P)	First measurement (n = 29) r (P)
ELWI	0.073 (0.706)	0.073 (0.708)
EVLW	0.518 (0.004)	0.511 (0.005)

Values are Pearson correlation coefficients (P values). Patient-wise mean analyses used one mean value per patient. First-measurement analyses used the first available paired measurement from each patient. These analyses were performed as sensitivity analyses to assess the robustness of the primary and key secondary findings.

Figure 2. Figure 2. Patient-level sensitivity analysis. Pearson correlations using one summary value per patient. Each point represents the patient-wise mean of all available paired measurements. (A) Mean ReDS versus mean ELWI ($r = 0.073$, $P = 0.706$). (B) Mean ReDS versus mean EVLW ($r = 0.518$, $P = 0.004$). These patient-level analyses were directionally concordant with the primary mixed-effects analysis in Fig. 1.

3.5 Exploratory CVP stratification

At the measurement level, the unadjusted Pearson correlation between ReDS and ELWI was higher among measurements obtained at CVP > 12 mmHg ($r = 0.519$, $P = 0.023$; $n = 19$) than among those obtained at CVP ≤ 12 mmHg ($r = -0.096$, $P = 0.430$; $n = 69$). However, these analyses treated repeated measurements as independent observations.

In mixed-effects models accounting for within-patient clustering, the ReDS × CVP-stratum interaction was not statistically significant for ELWI (interaction $\beta = 0.271$; 95% CI, -0.114 to 0.657 ; $P = 0.167$) or EVLW (interaction $\beta = 16.81$; 95% CI, -7.09 to 40.70 ; $P = 0.168$). Thus, the measurement-level difference in the ReDS–ELWI correlation across CVP strata was not statistically supported by the cluster-adjusted interaction analysis.(Table 5)

Table 5
Exploratory analysis of effect modification by concurrent CVP

Model / term	Coefficient	95% CI	P	Unadjusted stratum-specific Pearson r	Naive P†
ELWI model					
ReDS (low CVP ref.)	0.033	−0.200 to 0.265	0.783	−0.096	0.430
ReDS × CVP_high	0.271	−0.114 to 0.657	0.167	0.519‡	0.023‡
EVLW model					
ReDS (low CVP ref.)	8.96	−5.56 to 23.47	0.226	0.361	0.002
ReDS × CVP_high	16.81	−7.09 to 40.70	0.168	0.612‡	0.005‡

†Naive Pearson within CVP stratum (measurements treated as independent). ‡High-CVP stratum (n = 19). Mixed models: N = 88 nested in 29 patients. Interaction terms were not significant after accounting for within-patient correlation.

3.6 Exploratory discrimination of ELWI > 12 mL/kg

At the measurement level, ReDS did not demonstrate evidence of discrimination for ELWI > 12 mL/kg across all 88 measurements (AUC, 0.492; approximate 95% CI, 0.35–0.64). The corresponding AUC was 0.368 (approximate 95% CI, 0.21–0.54) among measurements obtained at CVP ≤ 12 mmHg.

A higher AUC was observed in the CVP > 12 mmHg subgroup (AUC, 0.843; approximate 95% CI, 0.61–1.00), but this estimate was based on only 19 measurements and 5 events. Because the ROC analysis did not account for within-patient clustering and the high-CVP subgroup contained very few events, this estimate was considered unstable and hypothesis-generating. Overall, the exploratory measurement-level ROC analysis did not provide evidence to support a diagnostic role or threshold for ReDS in identifying ELWI > 12 mL/kg. (Supplementary Table S3 & Figure S3).

4. Discussion

4.1 Principal findings

In this prospective observational study, 29 patients after cardiac surgery contributed 88 paired ReDS–PiCCO measurements. By accounting for repeated measurements within patients, the analysis identified three principal findings.

First, ReDS was not significantly associated with weight-indexed ELWI in the primary mixed-effects model. This finding was consistent with patient-level analyses based on mean values and with an analysis restricted to the first measurement from each patient. Thus, the present data did not demonstrate a statistically significant linear association between ReDS and the weight-indexed measure of pulmonary extravascular water used in transpulmonary thermodilution.

Second, ReDS showed a positive fixed-effect association with absolute EVLW. The directionally concordant patient-level sensitivity analyses suggest that the positive association was not solely attributable to treating repeated measurements as independent observations. However, this finding should be interpreted as an association rather than evidence that ReDS quantitatively measures EVLW or is interchangeable with thermodilution-derived EVLW.

Third, the apparent increase in the measurement-level ReDS–ELWI correlation at higher CVP was not confirmed by the formal interaction analysis after accounting for patient-level clustering. Similarly, the apparently high AUC for $\text{ELWI} > 12 \text{ mL/kg}$ in the high-CVP subgroup was based on only five events and was insufficient to support a diagnostic or screening threshold.

Taken together, these findings suggest that ReDS may capture information related to postoperative thoracic fluid status, but the present data do not support using ReDS as a substitute for thermodilution-derived ELWI. The findings should not be interpreted as demonstrating that ReDS has no relationship with pulmonary fluid; rather, they indicate that the signal captured by ReDS may not correspond directly to the indexed pulmonary water measure generated by PiCCO.

4.2 Physiological interpretation

The distinction between ReDS, EVLW, and ELWI is central to interpreting the present findings. ReDS uses electromagnetic sensing to characterize dielectric properties within a defined thoracic measurement region and provides an indirect estimate of thoracic fluid content [11][12]. In contrast, EVLW is an absolute estimate of extravascular pulmonary water derived from transpulmonary thermodilution, whereas ELWI represents EVLW normalized to predicted body weight [4][6][7]. These parameters are related but represent different measurement constructs and should not be considered interchangeable.

The positive association observed between ReDS and absolute EVLW, together with the absence of a statistically significant association between ReDS and ELWI, may have several possible explanations. One possibility is that the normalization of EVLW to predicted body weight alters the relationship between a localized thoracic dielectric signal and the resulting indexed parameter. Differences in body size, thoracic geometry, and the distribution of fluid within the measurement field may also contribute [6][7]. However, the present study was not designed to determine which of these factors accounted for the observed pattern, and this interpretation should therefore be regarded as hypothesis-generating.

Postoperative cardiac surgery may further contribute to differences between these measurements. Cardiopulmonary bypass, fluid administration, transfusion, changes in vascular permeability, atelectasis, pleural or mediastinal fluid, and evolving intrathoracic fluid distribution may occur simultaneously during

the postoperative period[1][2][3][18]. Because the present study did not include an independent imaging reference or direct assessment of the spatial distribution of thoracic fluid, it cannot determine which anatomical or physiological components contributed to the ReDS signal[21]. Accordingly, the observed association with absolute EVLW should be interpreted as an empirical association rather than evidence that ReDS directly quantifies pulmonary extravascular water. Overall, the findings are more consistent with ReDS providing information related to thoracic fluid status than with ReDS serving as a direct surrogate for any single PiCCO-derived physiological variable.

4.3 Relation to prior ReDS literature

Previous studies have established the biological plausibility of ReDS as a non-invasive measure of thoracic lung fluid, but the reference standards and clinical settings used in those studies differ substantially from the present investigation. Measurement reliability has also been reported in trained users, although the available evidence is limited to small studies in healthy volunteers[28]. Early validation studies compared ReDS with high-resolution chest CT and demonstrated a strong relationship between ReDS-derived fluid estimates and CT-based measures of lung fluid[12][13]. Subsequent studies have also reported associations between ReDS and invasive haemodynamic measures such as pulmonary artery wedge pressure[14].

These findings provide important support for the physiological relevance of the ReDS signal, but they should not be interpreted as evidence that ReDS is interchangeable with PiCCO-derived ELWI. CT-based measures quantify lung density or high-attenuation areas, whereas PAWP reflects left-sided filling pressure; neither measurement is identical to thermodilution-derived EVLW or ELWI[4][8]. The different reference standards therefore address related but distinct physiological constructs.

Currently, Much of the published ReDS validation has been performed in patients with heart failure or other medical populations in whom pulmonary congestion is primarily related to changes in hydrostatic pressure and volume status[14][15]. In contrast, the present cohort consisted of patients in the early postoperative period after open cardiac surgery and CPB. In this setting, pulmonary fluid accumulation may result from several overlapping mechanisms, including hydrostatic pressure, endothelial injury, inflammatory permeability changes, fluid administration, transfusion, and impaired lymphatic clearance[1][2][3]. Thoracic dielectric measurements may consequently behave differently from measurements obtained in relatively stable heart-failure populations.

This distinction may help explain why findings from longitudinal congestion monitoring in heart failure may not directly translate to reproduction of a specific invasive ICU-derived lung-water index after cardiac surgery. Indeed, contemporary studies have explored ReDS as a tool for monitoring changes in congestion and guiding decongestion in heart failure, emphasizing its potential value for serial trend assessment rather than requiring it to reproduce every invasive haemodynamic variable[15][16].

The present study therefore adds a different perspective to the existing literature. Rather than testing whether ReDS detects clinically apparent congestion, it examined its relationship with multiple

components of the PiCCO-derived haemodynamic profile in a postoperative cardiac surgical population. The absence of a significant ReDS–ELWI association, despite a positive association with absolute EVLW, suggests that the relationship between ReDS and pulmonary fluid is context-dependent and may depend on how lung water is quantified and normalized.

Importantly, the present results do not invalidate previous ReDS validation studies. Instead, they highlight the distinction between demonstrating biological validity of a non-invasive thoracic fluid signal and demonstrating interchangeability with a particular invasive physiological index. ReDS may be sensitive to thoracic fluid while still being unsuitable as a direct substitute for ELWI in a heterogeneous postoperative population.

4.4 Clinical implications

The present findings do not support interpreting a single ReDS value as a direct estimate of ELWI after cardiac surgery. In particular, the observed association with absolute EVLW does not establish that a specific ReDS value corresponds to a specific degree of pulmonary extravascular water or that ReDS can be used interchangeably with PiCCO-derived measurements.

At the same time, the absence of a significant association with ELWI does not establish that ReDS has no clinical value for postoperative fluid monitoring. An important unanswered question is whether within-patient changes in ReDS correspond to clinically meaningful changes in pulmonary fluid over time. The present study was not designed to answer this question because exact postoperative measurement times were not systematically recorded and the primary mixed-effects models did not explicitly separate within-patient from between-patient associations.

Future longitudinal studies should therefore obtain synchronized ReDS and PiCCO measurements at predefined clinical time points or around clinically meaningful changes in fluid status. Such studies could directly evaluate whether within-patient changes in ReDS are associated with concurrent changes in EVLW or ELWI. Independent imaging measures, particularly lung ultrasound and, when clinically justified, chest CT, may also help characterize the anatomical and physiological components contributing to the ReDS signal after cardiac surgery [24, 26]. In addition, pleural effusion should be considered when interpreting ReDS measurements because it may affect the thoracic fluid signal[27]. Multimodal longitudinal studies incorporating ReDS, PiCCO, and clinically appropriate imaging may therefore help clarify which components of postoperative thoracic fluid status are captured by ReDS.

4.5 Limitations

This study has several limitations. First, the sample size was small, with 29 patients contributing 88 repeated measurements. Although the mixed-effects models accounted for within-patient dependence, the effective number of independent clusters remained 29. The study therefore had limited statistical power, particularly for interaction and subgroup analyses.

Second, the study was conducted at a single center and included only patients who underwent open cardiac surgery and required PiCCO monitoring. This introduces potential selection bias and limits generalizability to patients undergoing less invasive procedures, patients without an indication for invasive haemodynamic monitoring, or ambulatory populations with heart failure.

Third, the present study evaluated associations rather than agreement or interchangeability. A statistically significant association between ReDS and EVLW does not establish that the two measurements quantify the same physiological quantity or can be used interchangeably. No formal agreement analysis was prespecified, and the different units and measurement constructs of ReDS and EVLW further limit the interpretation of direct agreement.

Fourth, no concurrent imaging reference standard was available. Consequently, the study cannot determine whether ReDS was responding primarily to pulmonary parenchymal fluid, pleural fluid, atelectasis, intrathoracic blood volume, postoperative mediastinal changes, or a combination of these factors.

Fifth, the exact postoperative clock time of each ReDS–PiCCO pair was not retained. Although measurements were obtained approximately once daily and the sequence of PiCCO followed by ReDS was standardized, variation in the exact timing relative to surgery, extubation, fluid administration, diuretic therapy, and other clinical events could have introduced additional biological variability.

Sixth, body size and chest-wall characteristics may have influenced the ReDS measurement. Chest-wall thickness and other anatomical factors were not systematically recorded, and the high-CVP subgroup differed descriptively in sex and body size. These factors limit interpretation of the exploratory CVP-stratified findings.

Seventh, the exploratory ROC analyses were performed at the measurement level without adjustment for within-patient clustering. The high-CVP subgroup contained only five ELWI events, making the apparently high AUC particularly unstable. These analyses were therefore considered hypothesis-generating and should not be interpreted as evidence for a diagnostic threshold.

Finally, multiple secondary and exploratory associations were examined without adjustment for multiplicity, and some secondary mixed-effects models showed limited information for estimating between-patient variance. These results should therefore be interpreted as exploratory rather than confirmatory.

5. Conclusions

In this prospective repeated-measures exploratory study of patients after cardiac surgery, ReDS was positively associated with absolute EVLW but was not significantly associated with weight-indexed ELWI after accounting for repeated measurements within patients. These findings indicate that ReDS and PiCCO-derived lung-water parameters may capture related but non-equivalent aspects of postoperative

thoracic fluid status. Exploratory CVP stratification and measurement-level ROC analyses did not provide sufficient evidence to support a diagnostic role for ReDS in identifying elevated ELWI. Larger longitudinal studies incorporating predefined measurement time points, explicit within-patient change analyses, and independent reference measures are warranted to determine whether ReDS can provide clinically useful non-invasive monitoring of postoperative pulmonary fluid dynamics.

Declarations

Conflict of Interest

There were no financial or competing conflicts of interest in relation to this work.

Supplementary Material

See in the attached file list.

Funding

This study was supported by the Major Project of the Science and Technology Department in Sichuan province China (grant number 2024YFFK0138).

Author Contribution

Conceptualization: [JXF,HY]. Methodology: [WTD, RY]. Investigation and data curation: [RY,YZ,CXY]. Formal analysis: [WTD]. Writing—original draft: [WTD]. Writing—review and editing: [YR, JXF, HY,SXH]. Supervision: [JXF]. All authors read and approved the final manuscript.

Acknowledgement

We thank the nursing and medical staff of the Cardiac Surgery Intensive Care Unit, West China Hospital, Sichuan University, for their assistance with patient care and data collection.

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Tanner TG, Colvin MO. Pulmonary complications of cardiac surgery. *Lung*. 2020;198(6):889–96. 10.1007/s00408-020-00405-7.
2. Stephens RS, Shah AS, Whitman GJ. Lung injury and acute respiratory distress syndrome after cardiac surgery. *Ann Thorac Surg*. 2013;95(3):1122–9. 10.1016/j.athoracsur.2012.10.024.
3. Apostolakis E, Filos KS, Koletsis E, Dougenis D. Lung dysfunction following cardiopulmonary bypass. *J Card Surg*. 2010;25(1):47–55. 10.1111/j.1540-8191.2009.00823.x.
4. Sakka SG, Rühl CC, Pfeiffer UJ, Beale R, McLuckie A, Reinhart K, Meier-Hellmann A. Assessment of cardiac preload and extravascular lung water by single transpulmonary thermodilution. *Intensive Care Med*. 2000;26(2):180–7. 10.1007/s001340050043.
5. Sakka SG, Klein M, Reinhart K, Meier-Hellmann A. Prognostic value of extravascular lung water in critically ill patients. *Chest*. 2002;122(6):2080–6. 10.1378/chest.122.6.2080.
6. Phillips CR, Chesnutt MS, Smith SM. Extravascular lung water in sepsis-associated acute respiratory distress syndrome: indexing with predicted body weight improves correlation with severity of illness and survival. *Crit Care Med*. 2008;36(1):69–73. 10.1097/01.CCM.0000295314.01232.BE.
7. Huber W, Mair S, Götz SQ, Tschirdewahn J, Siegel J, Schmid RM, Saugel B. Extravascular lung water and its association with weight, height, age, and gender: a study in intensive care unit patients. *Intensive Care Med*. 2013;39(1):146–50. 10.1007/s00134-012-2745-3.
8. Jozwiak M, Teboul JL, Monnet X. Extravascular lung water in critical care: recent advances and clinical applications. *Ann Intensive Care*. 2015;5:38. 10.1186/s13613-015-0081-9.
9. Gavelli F, Shi R, Teboul JL, Azzolina D, Mercado P, Jozwiak M, Chew MS, Huber W, Kirov MY, Kuzkov VV, Lahmer T, Malbrain MLNG, Mallat J, Sakka SG, Tagami T, Pham T, Monnet X. Extravascular lung water levels are associated with mortality: a systematic review and meta-analysis. *Crit Care*. 2022;26(1):202. 10.1186/s13054-022-04061-6.
10. Tagami T, Ong MEH. Extravascular lung water measurements in acute respiratory distress syndrome: why, how, and when? *Curr Opin Crit Care*. 2018;24(3):209–15. 10.1097/MCC.0000000000000503.
11. Amir O, Rappaport D, Zafrir B, Abraham WT. A novel approach to monitoring pulmonary congestion in heart failure: initial animal and clinical experiences using remote dielectric sensing technology. *Congest Heart Fail*. 2013;19(3):149–55. 10.1111/chf.12021.
12. Amir O, Azzam ZS, Gaspar T, Faranesh-Abboud S, Andria N, Burkhoff D, Abbo A, Abraham WT. Validation of remote dielectric sensing (ReDS) technology for quantification of lung fluid status: comparison to high resolution chest computed tomography in patients with and without acute heart failure. *Int J Cardiol*. 2016;221:841–6. 10.1016/j.ijcard.2016.06.323.
13. Imamura T, Gono W, Hori M, Ueno Y, Narang N, Onoda H, Tanaka S, Nakamura M, Kataoka N, Ushijima R, Sobajima M, Fukuda N, Ueno H, Kinugawa K. Validation of noninvasive remote dielectric sensing system to quantify lung fluid levels. *J Clin Med*. 2022;11(1):164. 10.3390/jcm11010164.
14. Uriel N, Sayer G, Imamura T, Rodgers D, Kim G, Raikhelkar J, Sarswat N, Kalantari S, Chung B, Nguyen A, Burkhoff D, Abbo A. Relationship between noninvasive assessment of lung fluid volume and

- invasively measured cardiac hemodynamics. *J Am Heart Assoc.* 2018;7(22):e009175. 10.1161/JAHA.118.009175.
15. Amir O, Ben-Gal T, Weinstein JM, Schliamser J, Burkhoff D, Abbo A, Abraham WT. Evaluation of remote dielectric sensing (ReDS) technology-guided therapy for decreasing heart failure re-hospitalizations. *Int J Cardiol.* 2017;240:279–84. 10.1016/j.ijcard.2017.02.120.
 16. Alvarez-Garcia J, Lala A, Rivas-Lasarte M, De Rueda C, Brunjes D, Lozano-Jimenez S, Garcia-Sebastian C, Mitter S, Remior P, Jimenez-Blanco Bravo M, Del Prado S, Barghash M, González-Ferrer E, Ullman J, Cobo M, Segovia-Cubero J, Zamorano JL, Pinney SP, Mancini D. Remote Dielectric Sensing Before and After Discharge in Patients With ADHF: The ReDS-SAFE HF Trial. *JACC Heart Fail.* 2024;12(4):695–706. 10.1016/j.jchf.2024.01.002.
 17. Imamura T, Narang N, Kinugawa K. Clinical implications of remote dielectric sensing system to estimate lung fluid levels. *J Cardiol.* 2023;81(3):276–82. 10.1016/j.jjcc.2022.07.014.
 18. Weissman C. Pulmonary complications after cardiac surgery. *Semin Cardiothorac Vasc Anesth.* 2004;8(3):185–211. 10.1177/108925320400800303.
 19. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet.* 2007;370(9596):1453–7. 10.1016/S0140-6736(07)61602-X.
 20. Monnet X, Anguel N, Osman D, Hamzaoui O, Richard C, Teboul JL. Assessing pulmonary permeability by transpulmonary thermodilution allows differentiation of hydrostatic pulmonary edema from ALI/ARDS. *Intensive Care Med.* 2007;33(3):448–53. 10.1007/s00134-006-0498-6.
 21. Monnet X, Teboul JL. Transpulmonary thermodilution: advantages and limits. *Crit Care.* 2017;21(1):147. 10.1186/s13054-017-1739-5.
 22. Monnet X, Teboul JL. My patient has received fluid. How to assess its efficacy and side effects? *Ann Intensive Care.* 2018;8(1):54. 10.1186/s13613-018-0400-z.
 23. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. *Chest.* 2008;134(1):117–25.
 24. Touw HR, Parlevliet KL, Beerepoot M, Schober P, Vonk A, Twisk JW, Elbers PW, Boer C, Tuinman PR. Lung ultrasound compared with chest X-ray in diagnosing postoperative pulmonary complications following cardiothoracic surgery: a prospective observational study. *Anaesthesia.* 2018;73(8):946–54. 10.1111/anae.14243.
 25. Volpicelli G, Elbarbary M, Blaivas M, et al. International evidence-based recommendations for point-of-care lung ultrasound. *Intensive Care Med.* 2012;38(4):577–91.
 26. Agricola E, Bove T, Oppizzi M, Marino G, Zangrillo A, Margonato A, Picano E. Ultrasound comet-tail images: a marker of pulmonary edema: a comparative study with wedge pressure and extravascular lung water. *Chest.* 2005;127(5):1690–5. 10.1378/chest.127.5.1690.
 27. Imamura T, Izumida T, Yamamoto R, Nomoto Y, Aakao K, Kinugawa K. Presence of Pleural Effusion in the Assessment of Remote Dielectric Sensing. *J Clin Med.* 2023;12(13):4415.

Figures

Figure 1. ReDS versus thermodilution lung water after cardiac surgery

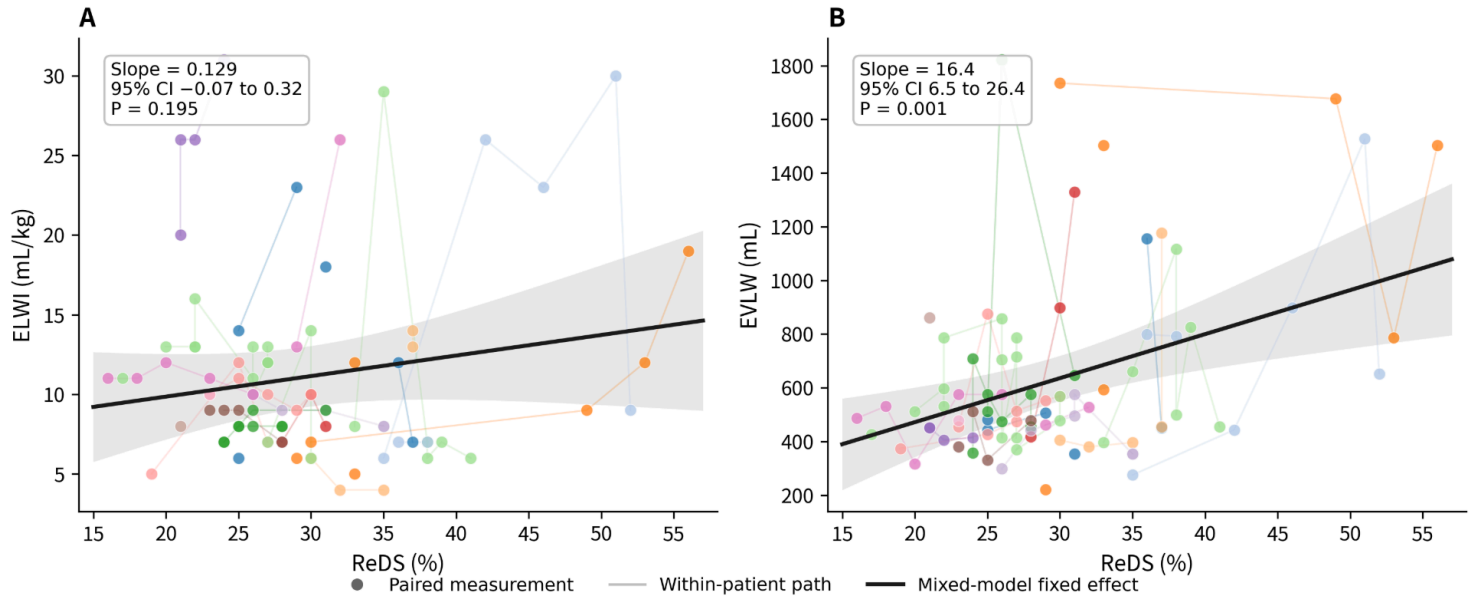


Figure 1

Association between ReDS and thermodilution lung-water parameters after cardiac surgery.

Scatter plots of remote dielectric sensing (ReDS, %) versus (A) extravascular lung water index (ELWI, mL/kg) and (B) absolute extravascular lung water (EVLW, mL). Each point represents one paired measurement ($n = 88$ observations from 29 patients), with repeated measurements from the same patient connected by light lines. Solid black lines indicate the fixed-effect fit from linear mixed-effects models with a random intercept per patient; shaded bands indicate the approximate 95% confidence interval for the fixed-effect regression line. (A) Slope = 0.13 mL/kg per 1% ReDS (95% CI -0.07 to 0.32; $P = 0.195$). (B) Slope = 16.4 mL per 1% ReDS (95% CI 6.5 to 26.4; $P = 0.001$).

Figure 2. Patient-level sensitivity analysis

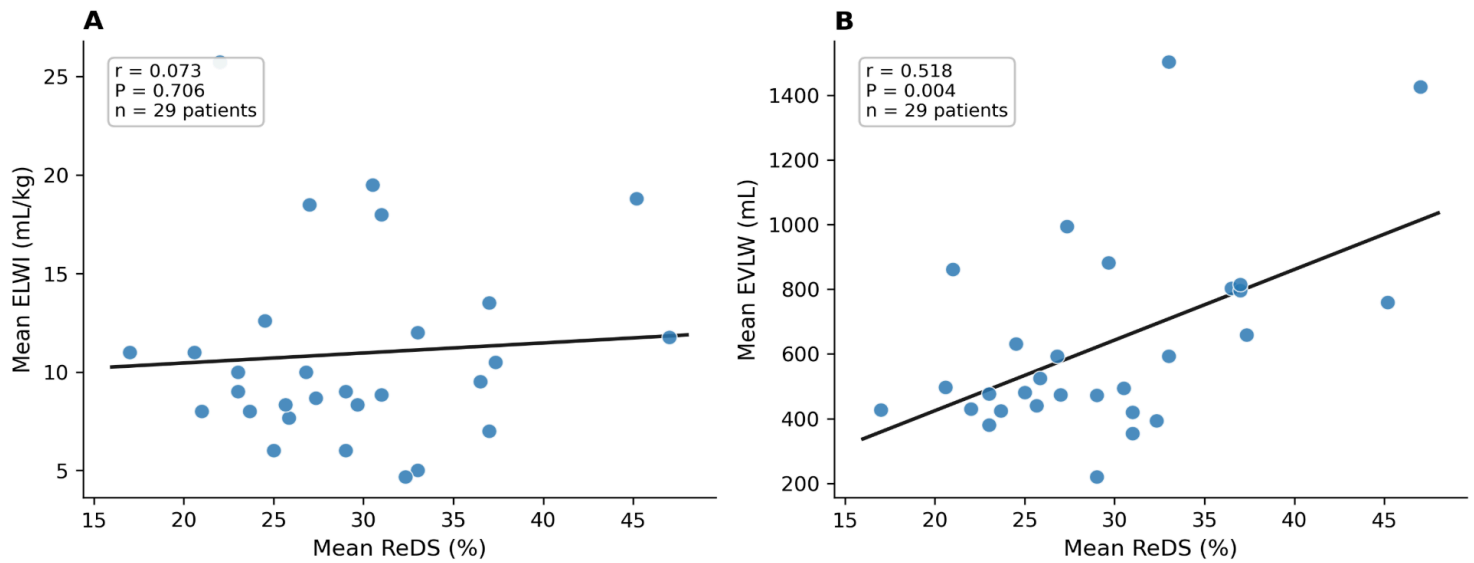


Figure 2

Patient-level sensitivity analysis. Pearson correlations using one summary value per patient. Each point represents the patient-wise mean of all available paired measurements. (A) Mean ReDS versus mean ELWI ($r = 0.073$, $P = 0.706$). (B) Mean ReDS versus mean EVLW ($r = 0.518$, $P = 0.004$). These patient-level analyses were directionally concordant with the primary mixed-effects analysis in Figure 1.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarymaterial.docx](#)