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Original Article

Remote Dielectric Sensing Technology in Heart Failure: Correlating Lung-Fluid Volume Shifts with Postural Changes and Dyspnea Severity

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ABSTRACT

Background: Orthopnea, a common symptom in heart failure (HF), arises from elevated pulmonary pressures and interstitial edema due to positional shifts. Remote dielectric sensing (ReDS) offers a noninvasive method to quantify lung-fluid volume. This study evaluated ReDS system measurements in response to posture changes in HF patients, and the correlation of these measurements with dyspnea severity.

Methods: This prospective observational study included both healthy volunteers and HF patients. Lung-fluid volume was measured using the ReDS system, with the patients in 3 positions—sitting, supine, and supine with elevated legs. HF patients additionally reported dyspnea levels on a visual analog scale immediately before and after ReDS measurements were made.

Results: A total of 86 healthy volunteers and 20 HF patients were included in the study. In healthy volunteers, ReDS values modestly increased when patients changed from a sitting to a supine position (21% vs 22%; $P < 0.001$), and from being supine to supine with raised legs (22% vs 24%; $P < 0.001$). In contrast, HF patients showed significantly higher ReDS values across all positions (29%, 31%, and 34%, respectively), with more pronounced increases between positions compared to those of healthy subjects (P for interaction < 0.001). A strong correlation was observed between ReDS system measurements and dyspnea visual analog scale scores in HF patients following posture changes (Pearson's $r = 0.718$, $P < 0.001$).

RÉSUMÉ

Contexte : L'orthopnée, symptôme courant de l'insuffisance cardiaque (IC), résulte de pressions pulmonaires élevées et d'un œdème interstitiel dû à des changements de position. La détection diélectrique à distance (ReDS) offre une méthode non invasive pour quantifier le milieu liquide pulmonaire. Cette étude a évalué les mesures de ReDS en réponse à des changements de position chez des patients souffrant d'IC et leur corrélation avec la sévérité de la dyspnée.

Méthodes : Cette étude observationnelle prospective a porté sur des volontaires sains et des patients souffrant d'IC. La proportion de liquide pulmonaire a été mesurée dans trois positions - assis, en décubitus dorsal et en décubitus dorsal avec les jambes surélevées - à l'aide du système ReDS. Les patients atteints d'IC ont en outre signalé leur niveau de dyspnée sur une échelle visuelle analogique (EVA) immédiatement avant et après les mesures ReDS.

Résultats : Quatre-vingt-six volontaires sains et 20 patients souffrant d'IC ont été inclus dans l'étude. Chez les volontaires sains, les valeurs de ReDS ont légèrement augmenté de la position assise à la position couchée (21 % contre 22 % ; $p < 0{,}001$) et de la position couchée avec les jambes surélevées (22 % contre 24 % ; $p < 0{,}001$). En revanche, les patients atteints d'IC présentaient des valeurs de ReDS significativement plus élevées dans toutes les positions (29 %, 31 % et 34 %, respectivement), avec des augmentations plus prononcées entre les positions par rapport aux sujets sains (p pour l'interaction $< 0{,}001$).

Orthopnea, or difficulty breathing while lying flat, is a common symptom in heart failure (HF) patients[1]; however, its exact pathophysiology remains unclear. One hypothesis is that when a patient lies supine, blood volume shifts from the abdomen and lower extremities to the intrathoracic compartment, leading to increased pulmonary venous and capillary pressure.[2,3] In cases of HF, the heart is unable to

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Conclusions: The ReDS system effectively quantifies lung-fluid volume changes due to body-position shifts in HF patients. Its measurements correlate well with alterations in dyspnea severity, potentially offering an objective means to monitor HF symptoms. Further studies are needed to validate these findings in a larger cohort and over an extended period.

Une forte corrélation a été observée entre les mesures ReDS et les scores EVA de dyspnée chez les patients atteints d'IC à la suite de changements de posture (corrélation de Pearson r = 0,718, p <0,001).

Conclusions : Le système ReDS quantifie efficacement les variations du liquide pulmonaire dues aux changements de position du corps chez les patients atteints d'IC. Il présente une bonne corrélation avec les variations de la sévérité de la dyspnée, ce qui pourrait constituer un moyen objectif de surveiller les symptômes de l'IC. D'autres études sont nécessaires pour valider ces résultats dans une plus grande cohorte et sur une période prolongée.

manage this additional volume load, resulting in interstitial pulmonary edema, decreased pulmonary compliance, increased airway resistance, and consequently, dyspnea.[2,3] To alleviate orthopnea, patients typically adopt an upright sitting position, which reduces venous return and eases pulmonary congestion.

Although no gold standard exists for quantitatively assessing lung-fluid volume, cardiovascular magnetic resonance imaging (MRI) offers a direct, safe, and precise method for measuring lung-fluid density.[4] Studies have demonstrated that HF patients with a New York Heart Association class III or IV designation have significantly greater lung-fluid density, compared to that in healthy controls.[4] Moreover, elevated lung-fluid levels detected by cardiovascular MRI have been shown to predict 1-year outcomes in HF patients.[4] Chest ultrasound also has been used to indirectly examine the effects of body position on lung-fluid level in healthy individuals and patients with HF, nephrotic syndrome, and end-stage kidney disease.[5,6] In healthy subjects, a small but statistically significant reduction in extravascular lung-fluid level—indicated by a decrease in ultrasound B-lines—has been observed when patients shift from being in a supine position to a standing position.[6,7] This trend is more pronounced in patients with nephrotic syndrome and end-stage kidney disease.[6] Additionally, in patients with acute HF, chest ultrasound has revealed a significantly higher number of B-lines when they are in a supine position, compared to when they are sitting upright.[5]

The ReDS Pro System remote dielectric sensing (ReDS) system (Sensible Medical Innovations, Netanya, Israel) offers a novel, noninvasive method for rapidly quantifying lung-fluid volume.[8-11] Studies have demonstrated that the ReDS system is comparable to computed tomography in detecting lung fluid and is a valuable tool for managing HF patients.[9-12] Unlike cardiovascular MRI or chest ultrasound, the ReDS system offers an objective, reproducible, and quantitative assessment of lung fluid volume and is easy to operate at the bedside with minimal expertise. A recent pilot study also showed that the ReDS system can detect subtle changes in lung-fluid volume in healthy volunteers as they change their body position from sitting to supine or from supine to supine with their legs elevated.[13]

Increasing evidence supports use of the ReDS system to guide management of HF patients[14,15] and indicates the physiological and symptomatic effects that body position has on these patients.[16] Thus, understanding how changes in body position affect lung-fluid measurements using the ReDS system in HF patients is critical. This study aimed to first validate the impact of body position on ReDS system readings in a larger cohort of healthy individuals and then investigate ReDS system measurements in response to different body positions in HF patients. Lastly, we evaluated the correlation between changes in dyspnea severity and variations in ReDS system readings following position changes in HF patients.

Material and Methods

Study settings and subjects

This prospective observational study was conducted at the National Taiwan University Hospital in Taiwan. From July 2022 to May 2023, healthy volunteers were recruited through snowball sampling and were screened initially based on predefined inclusion criteria, including an age range of 20-75 years and the absence of a significant medical history. Eligible candidates then underwent a comprehensive evaluation, consisting of a detailed medical history review and a physical examination by a qualified physician, to confirm the absence of any underlying conditions that could influence lung-fluid dynamics. During the same period, adult patients admitted to a hospital ward specifically dedicated for inpatients from the emergency service, with a diagnosis of acute HF, also were screened for eligibility. Exclusion criteria included a body mass index of < 22 or > 38 kg/m^2, comorbid pulmonary diseases (such as lung cancer and interstitial lung disease), history of lung resection surgery, absence of an echocardiographic report within the past year, unwillingness to participate, and a concomitant diagnosis of pneumonia or acute kidney injury. Patients who either exhibited significant residual orthopnea after HF treatment or required oxygen therapy or noninvasive ventilatory support for hospital discharge also were excluded for safety reasons. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Research Ethics Committee of the National Taiwan University Hospital. All participants provided written informed consent prior to the commencement of study procedures.

Measurement using the ReDS system

The functionality of the ReDS system employed in this study has been described thoroughly in prior research.[8] In brief, the system utilizes 2 small, round sensors positioned on the right anterior and posterior thoracic walls, without the need for direct skin contact. These sensors transmit and receive electromagnetic signals as they pass through the pulmonary tissue. By analyzing the interaction of these signals, the system assesses the dielectric properties of the lung tissue. The dielectric coefficient, a complex number representing how a material interacts with electromagnetic energy—including its absorption, reflection, and transmission—is influenced by the tissue's fluid content. Given that fluid has a particularly high dielectric coefficient, the fluid content significantly impacts the dielectric properties of tissues. In the lungs, the dielectric coefficient is shaped by its various components—such as blood, air, and lung parenchyma—making it highly sensitive to fluid changes. This characteristic enables the ReDS system to detect and monitor pulmonary edema progression accurately over time.[8]

Measurement with the ReDS system is quick, taking approximately 45 seconds to complete, and the entire process can be done in < 5 minutes by trained personnel.[17] The manufacturer defines the normal range for the volume of lung fluid as 20% to 35%, and the system's display can show fluid-proportion values ranging from 15% to 60%.[11] A recent study demonstrated nearly perfect intra-rater reliability of the ReDS system, with an intraclass correlation ranging from 0.966 to 0.988.[18]

Dyspnea measurements

Patients reported their dyspnea using a 10-cm visual analog scale (VAS). Those with HF were asked to mark their current level of breathing difficulty on an uncalibrated 10-cm horizontal line. The left end of the line was labeled "I am not breathless at all," and the right end was labeled "I am the most breathless I have ever been." The distance from the left end to the patient's mark was measured to the nearest millimeter to determine their score. A score of 0 indicates they felt no breathlessness, whereas a score of 10 indicates the highest level of breathlessness the patient had ever experienced.[19]

Study protocol

The protocol is illustrated in Figure 1. Before any measurements were taken, participants were asked to sit for a 5-minute stabilization period. Following this, 2 consecutive ReDS system measurements were taken, and their readings were averaged for data analysis. Participants then lay supine and flat, and after another 5-minute rest period, 2 more ReDS system measurements were made. Finally, participants' legs were elevated 30 degrees from the bed, and they were maintained in this position for 5 minutes for stabilization, after which 2 additional ReDS system measurements were made. HF patients also were asked to report their dyspnea VAS scores immediately before the first ReDS system measurement was made and right after the final ReDS system measurement was made. All ReDS system measurements were made during when patients had regular tidal breathing, by a single operator who was certified by the manufacturer and blinded to the clinical information.

Data collection

Data were collected from electronic health records, hospital charts, and in-person interviews. For both healthy subjects and HF patients, their demographics and body habitus were recorded. Body mass index, calculated from height and weight, was used to estimate body habitus. Additionally, comorbidities and left ventricular ejection fraction from echocardiographic reports were documented for HF patients.

Statistical analysis

Numerical variables were expressed as means ± standard deviations, and categorical variables were presented as counts (percentages). To compare groups, we used the independent sample t test or the χ^2 test, depending on the data type. Within-group comparisons of values measured with the ReDS system across different body positions in both healthy volunteers and HF patients were evaluated using repeated-measures analysis of variance. If significant main effects were found, Bonferroni correction was applied for pairwise comparisons. The interaction term of subject group and body position was calculated using analysis of covariance to compare the trend of ReDS system reading changes between the 2 groups following position changes, taking age and body mass index into consideration. The paired t test assessed differences in dyspnea VAS scores in HF patients when they changed from a sitting to a supine position with raised legs. Pearson's correlation coefficient was used to evaluate the relationship between changes in dyspnea VAS scores and ReDS system values across different positions (ie, values while supine with raised legs minus values while sitting). All statistical analyses were performed using SPSS Statistics 20.0

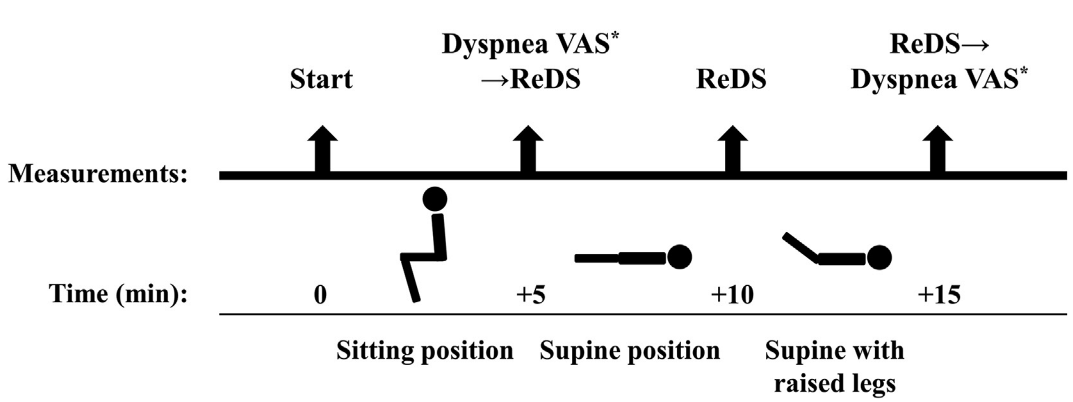

Figure 1. Scheme of the study protocol. ReDS, remote dielectric sensing; VAS, visual analog scale. *Evaluated in only patients with heart failure.

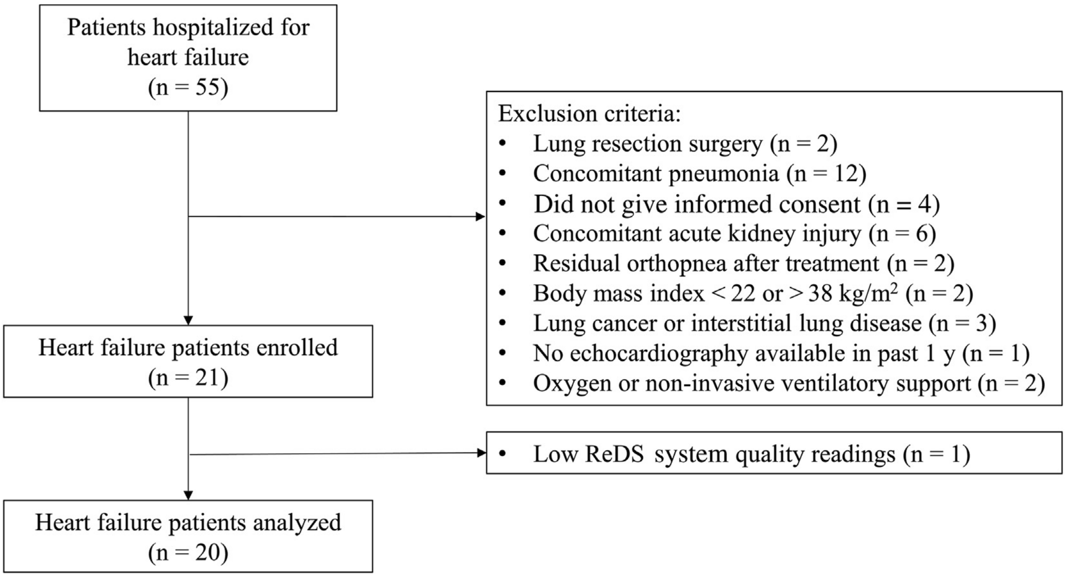

Figure 2. Study flow diagram. ReDS, remote dielectric sensing.

software (IBM, Armonk, NY), with 2-tailed *P*-values < 0.05 considered statistically significant.

Results

Study population

The study flow diagram is shown in Figure 2. A total of 86 healthy volunteers and 20 HF patients were included in the analysis (Table 1). HF patients were significantly older than healthy subjects (65 vs 41 years; $P < 0.001$) and tended to have a higher body mass index (25.6 vs 23.8 kg/m^2; $P = 0.097$). The average left ventricular ejection fraction for HF patients was 52% ± 12%.

ReDS system measurements across body positions

In healthy volunteers, all ReDS values fell within the normal range of 20%–35%, as recommended by the manufacturer, across the 3 body positions tested (Fig. 3). A significant increase in ReDS system readings was observed when patients changed from the sitting position to the supine position (21% ± 3% vs 22% ± 3%; $P < 0.001$), and from the supine position to the supine position with raised legs (22% ± 3% vs 24% ± 3%; $P < 0.001$). Compared to healthy subjects (Fig. 3), HF patients exhibited notably higher ReDS values in all 3 body positions (29% ± 6%, 31% ± 6%, and 34% ± 5% for the sitting, supine, and supine with raised legs positions, respectively; all $P < 0.001$ compared to the corresponding values for healthy volunteers). Similarly, ReDS system values in HF patients significantly increased when patients changed from the sitting to the supine position, and again when they changed to the supine with raised legs position (both $P < 0.001$; Fig. 3). However, the increase in ReDS system readings across these positions was more pronounced in HF patients, compared to that in healthy volunteers (*P* for interaction < 0.001).

Changes in dyspnea VAS vs ReDS system score

HF patients reported an average dyspnea VAS score of 2.2 ± 0.9 in the sitting position, which significantly increased to 4.5 ± 1.2 after they transitioned to the supine position with raised legs ($P < 0.001$; Fig. 4). None of the HF patients experienced intolerable orthopnea during the measurements. In the sitting position, patients' dyspnea VAS scores showed a moderate correlation with their ReDS system values (Pearson's $r = 0.507$; $P = 0.023$; Fig. 5A). Additionally, changes in dyspnea VAS scores following the posture change were correlated strongly with changes in ReDS system measurements (Pearson's $r = 0.718$; $P < 0.001$; Fig. 5B). However, in the supine position with raised legs, the dyspnea VAS scores were not correlated with the ReDS system readings (Pearson's $r = -0.054$; $P = 0.820$; Fig. 5C).

Discussion

This study contributes to the existing body of knowledge, first by validating the effectiveness of the ReDS in detecting changes in lung fluid proportion in response to body position

Table 1. Characteristics of study subjects

Variable	Healthy volunteers	Patients with HF	*P*
Patients, n	86	20	
Age, y	41 ± 12	65 ± 17	< 0.001
Male sex	34 (40)	11 (55)	0.208
Body mass index, kg/m^2	23.8 ± 4.0	25.6 ± 5.6	0.097
Comorbidity			
Diabetes mellitus	—	9 (45)	—
Hypertension	—	12 (60)	—
Hyperlipidemia	—	8 (40)	—
Chronic kidney disease	—	11 (55)	—
LVEF, %	—	52 ± 12	—

Values are mean ± standard deviation or n (%), unless otherwise indicated.

HF, heart failure; LVEF, left ventricular ejection fraction.

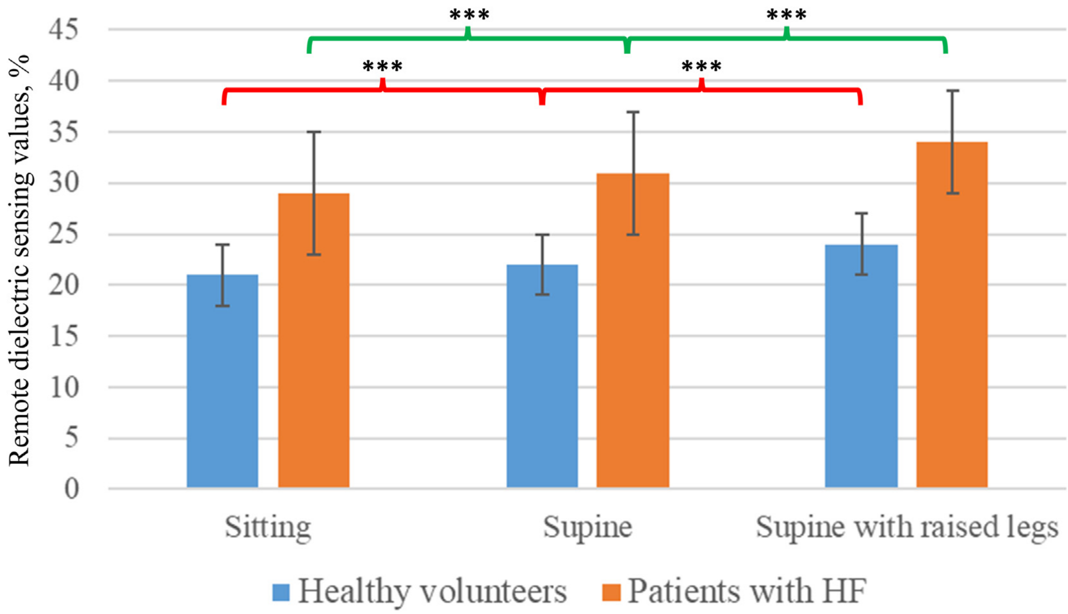

Figure 3. Remote dielectric sensing system measurements across various body positions in healthy volunteers and heart failure (HF) patients. The interaction between subject group and body position is significant, with $P < 0.001$. ***$P < 0.001$.

shifts in healthy individuals. Furthermore, an even more pronounced effect of position changes on ReDS system values was observed in patients with HF. Notably, the subjective experience of dyspnea severity in HF patients was correlated strongly with the ReDS system readings as the patients changed from a seated position to a supine position with their legs elevated. These findings demonstrate that the ReDS system can accurately quantify changes in fluid levels in the lungs due to posture changes, in both healthy individuals and HF patients. This finding underscores the importance of standardizing body position when using the ReDS system to make serial lung-fluid measurements in clinical settings. Additionally, the strong correlation between ReDS system values and changes in dyspnea severity highlights the potential of using the ReDS system as an objective tool to monitor symptom fluctuations in HF patients.

Consistent with prior research,[13] a small but noticeable increase in ReDS system readings, indicating lung-fluid proportion, was observed during positional changes in healthy individuals. The transition from a sitting to a supine position, or

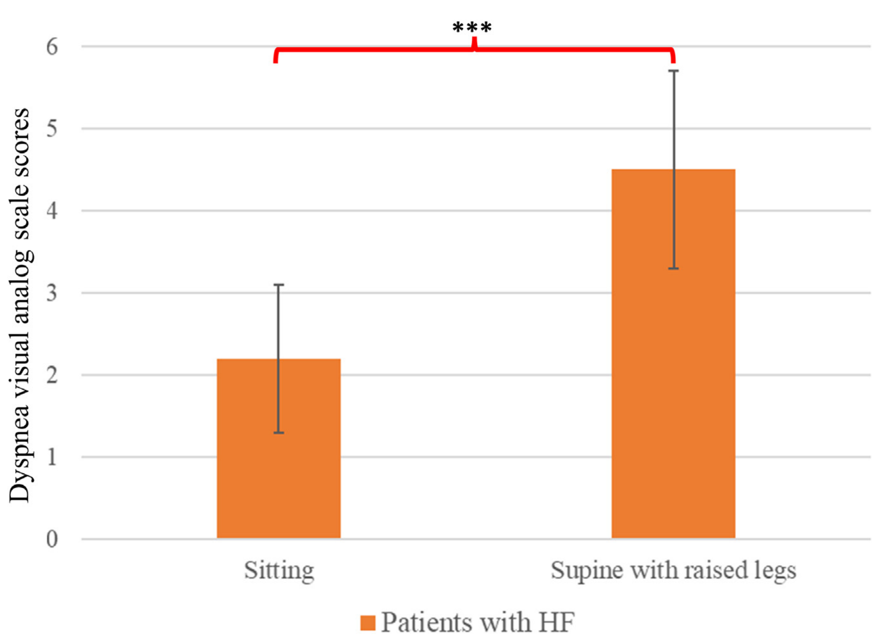

Figure 4. Assessment of dyspnea using the visual analog scale (VAS) in the sitting position and in the supine position with raised legs in heart failure (HF) patients. ***$P < 0.001$.

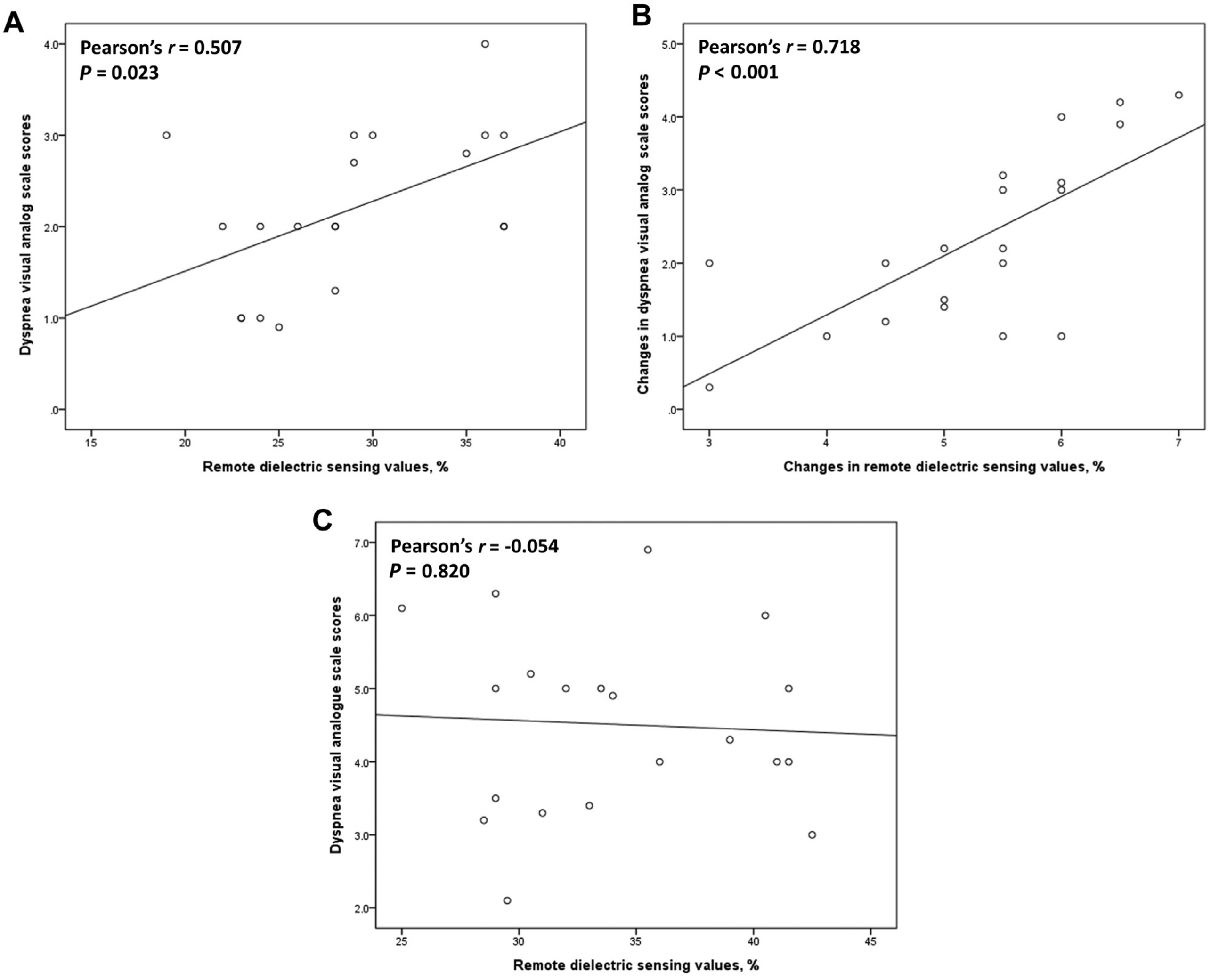

Figure 5. Scatterplot illustrating the dyspnea visual analog scale scores and remote dielectric sensing system values in heart failure patients, (**A**) in the sitting position, (**B**) transitioning from the sitting position to the supine position with raised legs, and (**C**) in the supine position with raised legs.

from a supine to a supine with raised legs position, redistributes several hundred milliliters of pooled blood from the splanchnic compartment and extremities to the thoracic cavity,[20-22] leading to a predictable increase in cardiac preload.[23] A normally functioning heart responds by increasing stroke volume and cardiac output.[24] Therefore, the detection of only a minor change in lung-fluid proportion due to posture change in our healthy subjects is physiologically plausible.

Notably, a recent MRI study did not observe the expected increase in total thoracic blood volume with supine positioning in healthy volunteers.[25] However, the study did report a significant increase in lung-fluid density associated with decreased lung volumes following supine positioning.[25] This finding suggests that interpreting ReDS system score alterations resulting from posture changes should be approached with caution. Nevertheless, the MRI study supports our results, reinforcing the ReDS system's capability to detect subtle changes in lung-fluid proportions in clinical practice.

According to the Frank-Starling law, a failing heart shifts the Frank-Starling curve downward and to the right, diminishing its ability to accommodate an increased preload due to body position changes.[26] In this context, excessive fluid redistribution from the splanchnic compartment may contribute to elevated cardiac filling pressures.[22] This elevation, in turn, increases pulmonary capillary hydrostatic pressure, leading to greater fluid transudation into the pulmonary interstitium and alveoli.[26] Consequently, our HF patients exhibited a significantly greater rise in ReDS system readings after they transitioned from sitting to being supine with raised legs, compared to healthy volunteers. The observed effect of body position on lung-fluid proportion provides further insight into why HF patients experience orthopnea.

Dyspnea is a primary reason for hospitalization in patients with acute HF, and it is often linked to fluid overload, manifesting as pulmonary congestion and peripheral edema.[27] In North America, the prevalence of dyspnea at rest in HF patients is around 38%, whereas in other regions, it exceeds 70%.[28] The severity of dyspnea at baseline and the inability to adequately alleviate it during hospitalization for acute HF have been associated with poorer patient outcomes.[29,30] Clearly, relieving dyspnea is a crucial goal for both patients and healthcare providers and serves as a key therapeutic target and endpoint in clinical trials.[31] Although the Likert scale and the VAS score are tools used commonly to assess dyspnea in trials,[32] they are subject to a degree of subjectivity. A point of interest is that our study revealed a strong correlation between dynamic changes in dyspnea scores and ReDS system measurements following posture changes, suggesting that the ReDS system may offer an objective surrogate for monitoring the progression or regression of dyspnea in HF patients in response to treatments or interventions. However, our analysis was limited to a short timeframe. Further studies are needed to validate these findings in a larger cohort and over an extended period.

The ReDS system's prompt response to postural changes in our study reinforces its viability as a feasible, point-of-care technology for daily patient management. Both our findings and those of earlier research demonstrate the ReDS system's capacity to detect subtle lung-fluid volume alterations,[13] highlighting its practical utility in monitoring the effects of interventions or therapies over short periods. In this context, our recent work indicates that an increase in ReDS system values exceeding 2% after a 6-minute walk test can help distinguish between chronic obstructive pulmonary disease patients with vs without comorbid HF.[33] This result suggests that the ReDS system can have an expanded diagnostic role in clinical settings. Moreover, a recent case report showed the ReDS system's potential for monitoring fluid levels before and after hemodialysis,[34] although definitive conclusions require further investigation. In summary, the growing body of evidence suggests that the ReDS system may see widespread clinical use across various conditions in the near future.

Limitations

Several limitations of this study are worth discussing. First, all ReDS system measurements were made by a single operator. Although previous research has demonstrated substantial interrater reliability for ReDS system measurements,[18] caution should still be exercised when interpreting results obtained by multiple operators. Second, we included only patients recovering from acute decompensated HF, excluding those with significant symptoms. Additionally, ReDS system measurements in our study were taken during regular tidal breathing, indicating that the readings reflect the average lung volume over the respiratory cycle. Given the documented variation in lung-fluid density with respiration[25] and the potential for ReDS system values to fluctuate with changes in the respiratory cycle,[35] its performance in HF patients with marked respiratory effort remains to be determined. Third, although we observed a strong correlation between dynamic changes in dyspnea and ReDS system readings over a short timeframe, the relationship over the longer course of the clinical trajectory requires validation in future studies. Fourth, examining ReDS system reading changes in response to patients being in a standing position would have been valuable, but such evaluation was not included in the current study design. Future research is needed to address this limitation. Finally, a significant proportion of HF patients were excluded from the study due to comorbidities or other concomitant conditions, limiting the generalizability of our findings to these specific patient populations.

Conclusions

Our findings highlight the potential of the ReDS system as an effective, noninvasive tool for quantifying and monitoring lung-fluid changes in response to body position shifts in both healthy individuals and HF patients. This technology can detect subtle fluid-volume variations, which may aid in the timely titration of diuretic therapy and the optimization of fluid management strategies. Furthermore, the strong correlation between ReDS system measurements and changes in dyspnea severity in HF patients suggests that treatment decisions could be tailored based on individualized fluid-status trends rather than solely subjective assessments.

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Ethics Statement

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Research Ethics Committee of the National Taiwan University Hospital.

Patient Consent

The authors confirm that patient consent forms have been obtained for this article.

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Disclosures

The authors have no conflicts of interest to disclose.

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