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Remote dielectric sensing predicts elevated left atrial pressure in patients with atrial fibrillation

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ABSTRACT

Background: There are currently no established non-invasive indices of echocardiography for elevated left atrial pressure (LAP) especially in patients with atrial fibrillation (AF). Remote dielectric sensing (ReDS) is a novel non-invasive electromagnetic energy-based technology that quantifies total lung fluid, enabling the monitoring of volume status in patients with heart failure. The utility of ReDS for estimating LAP in patients with AF remains unknown.

Methods: We prospectively investigated patients with AF in whom LAP was directly measured during catheter ablation for AF, and ReDS measurements were conducted the day before ablation. Elevated LAP was defined as LAP $\geq$ 15 mmHg.

Results: A total of 61 patients were included (median age 66 years, 38 % female). Among them, 26 patients had elevated LAP. There was a positive correlation between ReDS and LAP ($r = 0.363$, $P = 0.004$). Receiver operating characteristic curve analysis for the prediction of elevated LAP demonstrated that the best cut-off value of ReDS was 30 %, with a sensitivity of 65 %, specificity of 69 %, and an area under the curve of 0.703 (95 % confidence interval 0.568–0.837). Multivariate logistic regression analysis revealed that ReDS was an independent predictor of elevated LAP, among covariates including left ventricular ejection fraction, the ratio of early transmitral flow velocity to septal mitral annular early diastolic velocity, and left atrial volume index.

Conclusions: Our results suggest ReDS could be a valuable marker of elevated LAP even in patients with AF. Further studies are needed to elucidate the effectiveness of a ReDS-guided decongestive strategy in patients with heart failure.

1. Introduction

Elevation of left ventricular (LV) filling pressure is a diagnostic hallmark of heart failure (HF) and represents an adaptive mechanism aimed at maintaining cardiac output [1]. While both the mean left atrial pressure (LAP) and LV end-diastolic pressure serve as indicators of LV filling pressure, the former is considered to be more closely associated with pulmonary venous pressure and pulmonary congestion [2]. Although LAP can be estimated by pulmonary arterial wedge pressure (PAWP) obtained through right heart catheterization, this method is invasive and impractical for repeated measurements in routine clinical practice. Therefore, echocardiographic indices have been employed for estimating the LV filling pressure in most patients [3,4]; however, available indices for patients with atrial fibrillation (AF) are limited, and no established indices exist [5]. Thus, a need exists for novel non-invasive indices of LV filling pressure that can be easily measured and performed repeatedly in patients with AF.

Remote dielectric sensing (ReDS) is a non-invasive technology based on electromagnetic energy that enables the estimation of lung fluid content [6]. A previous proof-of-concept study of patients with and without acute decompensated HF demonstrated that ReDS was highly accurate for assessing lung fluid content, as measured by chest computed

Abbreviations: AF, atrial fibrillation; HF, heart failure; LAP, left atrial pressure; LV, left ventricular; PAWP, pulmonary arterial wedge pressure; ReDS, remote dielectric sensing.

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tomography [7]. The ReDS-measured lung fluid content also was strongly positively correlated with invasive PAWP in patients with HF [8]. However, it remains unknown how lung fluid content measured by ReDS relates to directly measured LAPs, which are rarely available but considered a more direct and accurate measure of LV filling pressure than PAWP [2,9]. Furthermore, the utility of ReDS for estimating LV filling pressure, even in patients with AF, remains to be elucidated. Accordingly, we aimed to clarify the utility of ReDS in estimating directly measured LAPs in patients undergoing catheter ablation for AF.

2. Methods

The authors declare that all supporting data are available within the article.

2.1. Study patients

This was a single-center prospective observational study. All consecutive patients scheduled and admitted for catheter ablation for AF were included in the study, with exclusion criteria comprising physical deformities of the thorax or lesions hindering ReDS measurement, presence of focal lung lesions like a history of pulmonary embolism or active pneumonia, or a pacemaker generator on the right side of the chest that would affect ReDS measurements. Additionally, patients for whom data on ReDS or LAP could not be obtained were excluded. This study was carried out in accordance with the principles outlined in the Declaration of Helsinki, and the institutional ethics committee approved the study protocol. Written informed consent was obtained from all participants prior to enrolment.

2.2. Data collection

We collected data on clinical variables, including age, sex, type of AF, $CHADS_2$ score, comorbidities, body mass index, systolic and diastolic blood pressures, heart rate, and oral medications on the day of admission. All patients underwent ReDS and direct LAP measurements, echocardiography, and venous blood sampling. The ReDS measurement was performed the day before ablation. Echocardiography was performed before admission according to standard techniques by a commercially available machine, as previously reported [10]. Approximately half of the patients had AF on the day of echocardiography; hence, mitral annular early diastolic velocity was measured at the septal mitral annulus [5]. In patients with AF on the day of echocardiography, early transmitral flow velocity and septal mitral annular early diastolic velocity were averaged from three nonconsecutive beats with cycle length within 10 % to 20 % of the average RR interval [11]. The patients with sinus rhythm with the ratio of early transmitral flow velocity to septal mitral annular early diastolic velocity (E/e') $>$ 15 and those with AF with E/e' $>$11 were judged to have high E/e' ratio [5,12]. Venous blood was drawn at admission. The estimated glomerular filtration rate was calculated with the use of the modified isotope-dilution mass-spectrometry traceable modification of diet in renal disease study equation with a Japanese coefficient [13]. The H_2FPEF score, which has been shown to predict LAP in patients with suspected HF and an LV ejection fraction of $\geq$ 50 %, was calculated from six clinical and echocardiographic variables: body mass index $>$ 30 kg/m^2 (2 points), a history of AF (3 points), age $>$ 60 years (1 point), treatment with $\geq$ 2 antihypertensives (1 point), E/e' $>$9 (1 point), and echocardiographic pulmonary artery systolic pressure $>$ 35 mmHg (1 point). Patients with an H_2FPEF score $\geq$ 6 were judged to have a high likelihood of heart failure with preserved ejection fraction (HFpEF) [14].

2.3. ReDS system

The ReDS system was previously described in detail [6–8,15,16]. Remote dielectric sensing utilizes low-power electromagnetic signals emitted between two sensors that are embedded in wearable devices. The sensors are positioned on the front and back of the patient's thorax without requiring direct skin contact, enabling measurement to be performed through light clothing (Fig. 1). The analyzed signal reflects the dielectric properties of lung tissue between the sensors. The dielectric coefficient of a material is expressed by a frequency-dependent complex number that describes the interaction of the material with electromagnetic energy. Since water has a high dielectric coefficient and air has a low dielectric constant, the dielectric coefficient of a tissue is predominantly determined by its fluid content. Remote dielectric sensing provides an estimate of the percentage of lung fluid content within a range of 15 %–60 %. A single measurement is completed in approximately 45 s. Measurements do not require rigorous training, allowing healthcare professionals at any level of experience to make accurate measurements. There is no risk associated with this measurement. While the reliability of a single examiner was not perfect, high interobserver reproducibility has been reported.

2.4. Measurement of LAP

At the beginning of the ablation procedure, patients were sedated with a continuous infusion of dexmedetomidine. An 8-F SL0 sheath (Abbott, St Paul, MN, USA) was inserted through the right femoral vein, and the Brockenbrough method was used to perform a trans-septal puncture to enable the sheath to enter the left atrium. The line for pressure measurement was connected to the side port of the sheath, and the LAP was directly measured through the sheath just before ablation in the presenting rhythm [17,18]. With the patient in the supine position, a zero reference point was set at the level of the right atrium, and positioned 5 cm below the surface of the anterior thorax.

The mean invasively measured LAP at the time of ablation served as an index of LV filling pressure [17]. The mean LAP was calculated from the waveforms obtained during a sampling time of 9 s with the use of a widely used polygraph (RMC-5000, Nihon Kohden, Tokyo, Japan). An elevated LAP was defined as LAP $\geq$ 15 mmHg [17,19].

2.5. Statistical analysis

Data are presented as medians and interquartile ranges (25th to 75th percentiles) for continuous variables and as percentages for categorical variables. The Mann-Whitney *U* test and the χ^2 test were used to compare differences in continuous and categorical variables, respectively. Correlations between variables were determined by the Pearson correlation coefficient. The predictive value of ReDS measurement or E/e' ratio for elevated LAP was assessed by receiver operating characteristic curve analysis. The results were expressed as areas under the curve and 95 % confidence intervals (CIs). Logistic regression analysis was performed to assess the association between ReDS values and elevated LAPs. Variables were selected a priori based on previous studies investigating determinants of elevated LV filling pressures [20–22]. Variables of $P < 0.05$ on univariate analysis were incorporated into a multivariate model to evaluate the independent association between ReDS values and elevated LAPs. For the comparison of predictability for elevated LAP between ReDS and the H_2FPEF score, variables including age, hypertension, body mass index, and E/e' ratio, which are components of the H_2FPEF score calculation, were excluded from the logistic regression analysis. Additionally, despite having univariate $P \geq 0.05$, both ReDS and the H_2FPEF score were included in the multivariate models to evaluate whether the predictive value of ReDS for elevated LAP is independent of the H_2FPEF score. The χ^2 test was performed to compare sensitivity, specificity, positive and negative predictive values, and predictive accuracy, which meant the proportion of all test results—both positive and negative—that were correct between ReDS and E/e' ratio for prediction of elevated LAP. Statistical significance was set at $P <$ 0.05. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), which is a graphical

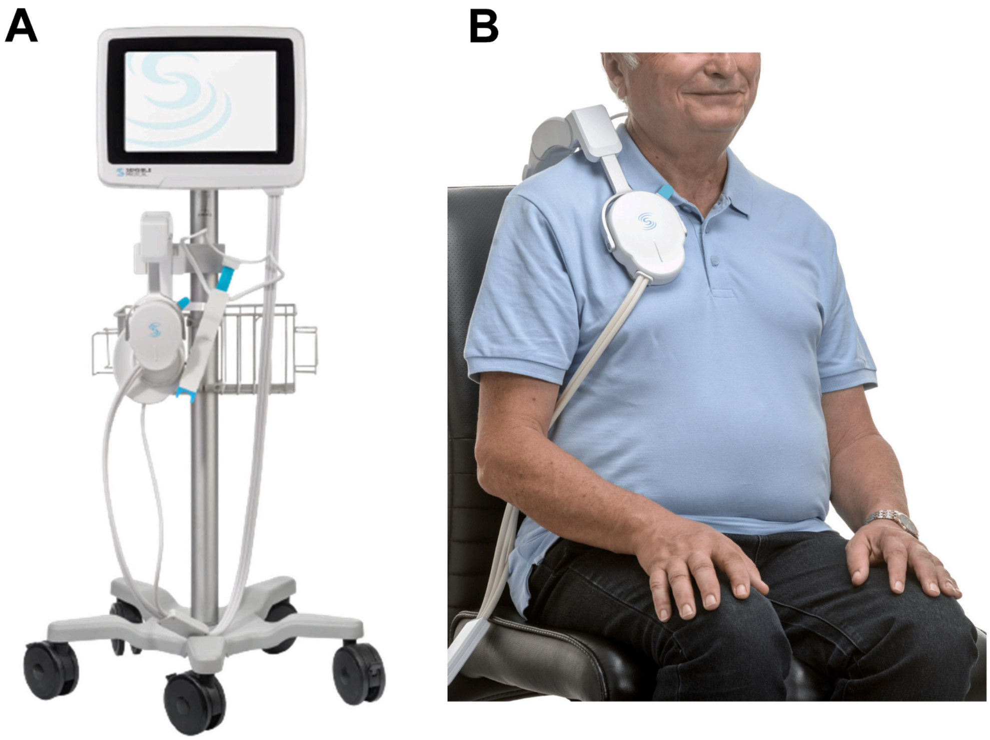

Fig. 1. ReDS system **A**, A wearable device and a monitor console to display data. **B**, A representative of actual measurement of ReDS value using the device.

user interface for R (The R Foundation for Statistical Computing, Vienna, Austria) [23].

3. Results

3.1. Baseline Characteristics

Between July and November 2023, we screened 67 patients, of whom 61 were enrolled in this study. Consent could not be obtained from three patients, and an additional three patients were excluded due to failure to obtain LAP data. The baseline characteristics of the patients are summarized in Table 1. The number of days between the dates of echocardiography and LAP measurement was 20 (14–32) days. Data on E/e' ratio could not be obtained in one patient. The median age was 66 (62–74) years, and 38 % of the patients were female. Among the patients, 52 % had persistent AF, and the majority presented with a low $CHADS_2$ score (median 1 [1–3]).

3.2. Association between ReDS and LAP

The correlation between ReDS values and the mean invasively measured LAPs is shown in Fig. 2. A modest but a statistically significant positive correlation was observed between ReDS values and LAPs (r = 0.363, P = 0.004). Receiver operating characteristic curve analysis for predicting elevated LAP demonstrated that the optimal cut-off value for ReDS was 30 %, yielding a sensitivity of 65 %, specificity of 69 %, and an area under the curve of 0.703 (95 % CI 0.568–0.837), which was larger than that of E/e' ratio (Fig. 3A). The LAP was significantly higher in patients with ReDS ≥ 30 % than in ReDS < 30 % (15 [11–20] vs 11 [8–15] mmHg, respectively, Fig. 3B). While age was significantly lower and body mass index was significantly higher in patients with ReDS ≥ 30 %, the differences between the other variables of patients with ReDS < 30 % and patients with ReDS ≥ 30 % were not significant (Table 1). The difference between the number of days between the dates of echocardiography and dates of LAP measurements of the two patient groups was not significant (ReDS < 30 %: 19 [13–32] days vs ReDS ≥ 30 %: 23 [14–31] days, P = 0.839).

3.3. ReDS as the predictor of elevated LAP

The results of the logistic regression analysis for predicting elevated LAP are shown in Table 2. The univariate analysis identified persistent AF, left atrial volume index, and ReDS as significant predictors of elevated LAP, with ReDS maintaining significance, regardless of being treated as a continuous or categorical variable. The multivariate analysis, even after adjusting for significant confounders, found that ReDS as either a continuous or categorical variable (Models 1 and 2, respectively) remained an independent predictor of elevated LAP.

The prediction of elevated LAP using ReDS and E/e' ratio is presented in Table 3. Sensitivity for the prediction of elevated LAP was higher with ReDS ≥ 30 % compared to the high E/e' ratio, while the specificity was lower, although these differences were not statistically significant. Predictive accuracy of ReDS ≥ 30 % and the high E/e' ratio was nearly identical.

3.4. Comparison of ReDS with H_2FPEF score

Among all study patients, the H_2FPEF score could be obtained and analyzed for 48 patients. Eight patients were excluded due to a LV ejection fraction < 50 %, and additional five patients were excluded because measurement of echocardiographic pulmonary artery systolic pressure was not feasible due to the absence of tricuspid regurgitation jet. Out of the 48 patients, 23 were judged to have a high likelihood of HFpEF. Receiver operating characteristic curve analysis for predicting elevated LAP demonstrated that the area under the curve of ReDS was larger than that of H_2FPEF score (0.696 [95 % CI 0.538–0.855] vs 0.597 [95 % CI 0.436–0.759]). The logistic regression analysis for predicting elevated LAP revealed that the predictive value of ReDS was independent of the H_2FPEF score (Table 4).

Table 1
Baseline Characteristics of Patients.

	Total	ReDS < 30 %	ReDS ≥ 30 %	
Characteristics	(n = 61)	(n = 33)	(n = 28)	*P*-value
Age, y	66 (62–74)	69 (65–74)	63 (58–68)	0.009
Female sex	38 %	48 %	25 %	0.105
Persistent atrial fibrillation	52 %	45 %	61 %	0.351
$CHADS_2$ score	1 (1–3)	1 (1–2)	2 (1–3)	0.687
Comorbidities				
Heart failure	31 %	24 %	39 %	0.324
Hypertension	67 %	73 %	61 %	0.470
Diabetes	39 %	36 %	43 %	0.799
Dyslipidemia	46 %	39 %	54 %	0.396
Stroke	10 %	9 %	11 %	1.000
Coronary artery disease	11 %	12 %	11 %	1.000
Chronic kidney disease	28 %	30 %	25 %	0.862
Body mass index, kg/m^2	24.5 (21.4–27.1)	23.7 (21.4–25.8)	26.0 (22.5–28.6)	0.047
Systolic blood pressure, mmHg	125 (111–139)	127 (115–141)	117 (106–131)	0.056
Diastolic blood pressure, mmHg	74 (64–82)	78 (67–83)	70 (64–82)	0.271
Heart rate, beats/min	73 (66–81)	70 (67–78)	73 (66–88)	0.465
Echocardiographic data				
LV end-diastolic diameter, mm	48 (43–51)	46 (43–49)	49 (45–52)	0.138
LV end-systolic diameter, mm	31 (28–33)	30 (29–31)	31 (28–36)	0.259
LV mass index, g/m^2	82 (72–96)	80 (69–96)	85 (75–95)	0.942
Relative wall thickness	0.37 (0.33–0.40)	0.36 (0.31–0.41)	0.37 (0.34–0.39)	0.942
LV ejection fraction, %	62 (55–65)	63 (59–65)	59 (52–65)	0.185
E, cm/s	71 (58–84)	71 (58–86)	72 (61–83)	0.923
e', cm/s	7 (6–8)	7 (5–8)	7 (6–8)	0.800
E/e' ratio	10.7 (8.6–12.5)	10.5 (8.6–12.0)	10.8 (8.4–13.0)	0.848
LA volume index, mL/m^2	41 (32–52)	41 (33–53)	40 (30–46)	0.553
Moderate/severe MR	10 %	12 %	7 %	0.826
TRPG, mmHg	21 (17–25)	23 (20–28)	21 (17–24)	0.474
Laboratory data				
Hemoglobin, g/dL	13.5 (12.7–15.0)	13.0 (12.6–14.0)	14.3 (13.0–15.5)	0.051
Sodium, mEq/L	141 (140–142)	141 (140–143)	141 (140–142)	0.154
Creatinine, mg/dL	0.9 (0.8–1.1)	0.9 (0.7–1.0)	0.9 (0.8–1.1)	0.447
BUN, mg/dL	18 (15–22)	17 (13–21)	19 (16–23)	0.212
eGFR, mL/min/1.73 m^2	59 (51–69)	59 (50–67)	62 (53–70)	0.496
BNP, pg/mL	51 (20–129)	57 (23–146)	44 (16–118)	0.405
Uric acid, mg/dL	5.7 (4.9–6.6)	5.7 (4.9–6.4)	5.8 (4.9–6.8)	0.482
Albumin, mg/dL	4.2 (4.0–4.4)	4.2 (4.0–4.4)	4.3 (4.0–4.5)	0.550
CRP, mg/dL	0.07 (0.03–0.13)	0.07 (0.04–0.18)	0.06 (0.03–0.08)	0.070
Oral medications				
ACE inhibitor/ARB	43 %	39 %	46 %	0.769
β-blocker	77 %	76 %	79 %	1.000
SGLT2 inhibitor	21 %	18 %	25 %	0.738
Statin	39 %	36 %	43 %	0.799
ARNI	11 %	12 %	11 %	1.000
Diuretic	23 %	15 %	32 %	0.205
Sodium channel blocker	16 %	24 %	7 %	0.147
Amiodarone	11 %	9 %	14 %	0.817

Values are presented as median (interquartile range) or %.

ACE, angiotensin-converting enzyme; ARB, angiotensin II type 1 receptor blocker; ARNI, angiotensin receptor-neprilysin inhibitor; BNP, B-type natriuretic peptide; BUN, blood urea nitrogen; CRP, C-reactive protein; E, early transmitral flow velocity; e', septal mitral annular early diastolic velocity; eGFR, estimated glomerular filtration rate; LA, left atrial; LV, left ventricular; MR, mitral regurgitation; SGLT2, sodium-glucose cotransporter type 2; TRPG, tricuspid regurgitation pressure gradient.

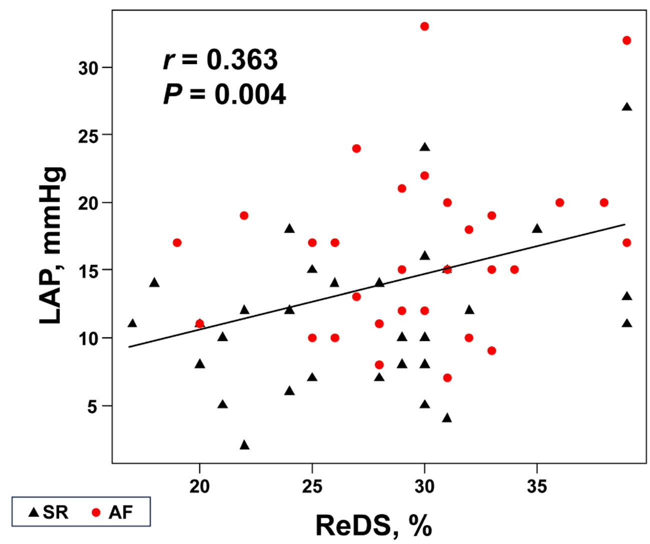

Fig. 2. Correlation between ReDS measurements and LAP Correlation between ReDS measurements and directly measured LAP is shown. AF, atrial fibrillation; LAP, left atrial pressure; ReDS, remote dielectric sensing; SR, sinus rhythm.

3.5. Influence of underlying rhythm on the predictability for elevated LAP

On the day of echocardiography, 31 out of a total of 61 patients (51 %) presented with AF. Receiver operating characteristic curve analysis for predicting elevated LAP using ReDS and E/e' ratio in each presenting rhythm is shown in Fig. 4. In patients with sinus rhythm, predictive value of ReDS for elevated LAP was almost the same as that of the E/e' ratio. On the other hand, ReDS had a higher predictive value for elevated LAP than the E/e' ratio in patients with AF.

4. Discussion

In this study, we found a significant positive correlation between ReDS values and directly measured LAP in patients with AF who underwent catheter ablation. Remote dielectric sensing showed a strong predictive value for elevated LAP, defined as LAP ≥ 15 mmHg. Additionally, in the multivariate logistic regression analysis, ReDS proved to be an independent predictor of elevated LAP, irrespective of being analyzed as either a continuous or categorical variable. To the best of our knowledge, this is the first report to demonstrate the utility of ReDS in estimating invasively measured LAP, which represents LV filling pressure, even in patients with AF.

Assessments of LV filling pressure are crucial for the clinical diagnosis of HF, especially in patients with HF with preserved LV ejection fraction [2]. Echocardiography has usually been the primary method for estimating the LV filling pressure in patients with HF. Recent guidelines have emphasized that an algorithm that is based on the combination of several echocardiographic parameters should be used to estimate the LV filling pressure [5]. The feasibility and accuracy of the algorithm, irrespective of LV ejection fraction, was confirmed in a large multicenter study [3]. However, evaluation of the diastolic function in patients with AF remains a clinical challenge because atrial activity is disorganized; the length of cycles varies; and there is LA enlargement, irrespective of filling pressures [11]. In fact, the reliability of the recommended

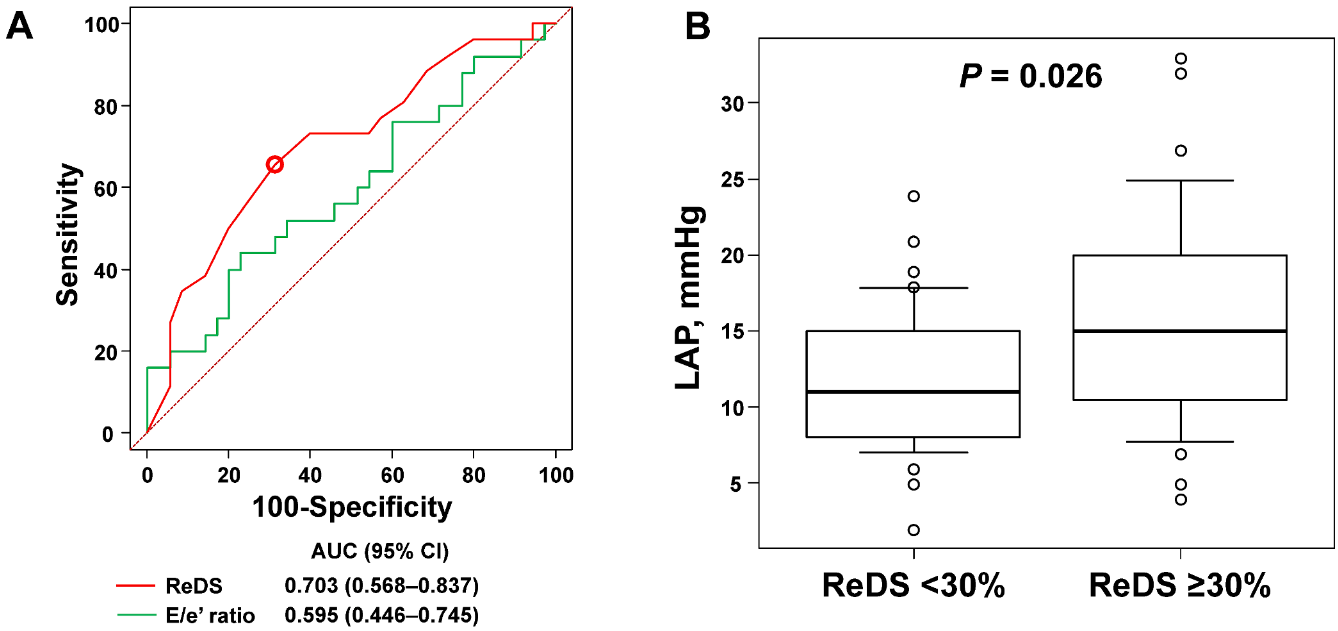

Fig. 3. Predictive value of ReDS measurement for elevated LAP **A**, Receiver operating characteristic curve analysis of ReDS values and E/e' ratio for the prediction of elevated LAP. **B**, LAP values of patients with ReDS ≥ 30 % vs patients with ReDS < 30 %. AUC, area under the curve; CI, confidence interval; E/e' ratio, the ratio of early transmitral flow velocity to septal mitral annular early diastolic velocity; LAP, left atrial pressure; ReDS, remote dielectric sensing.

Table 2
Logistic Regression Analysis for the Prediction of LAP ≥ 15 mmHg.

	Univariate		Multivariate (Model 1)		Multivariate (Model 2)	
Variable	Unadjusted OR(95 % CI)	*P* value	Adjusted OR(95 % CI)	*P* value	Adjusted OR(95 % CI)	*P* value
Age, y	0.99 (0.94–1.05)	0.833				
Female sex	0.79 (0.28–2.28)	0.668				
Persistent atrial fibrillation	3.37 (1.15–9.87)	**0.026**	1.65 (0.47–5.80)	0.438	2.23 (0.63–7.85)	0.211
Hypertension	1.60 (0.53–4.84)	0.402				
Diabetes	1.24 (0.44–3.50)	0.683				
Dyslipidemia	2.31 (0.82–6.51)	0.114				
Coronary artery disease	1.01 (0.21–4.94)	0.989				
Body mass index, kg/m^2	1.05 (0.92–1.20)	0.492				
Systolic blood pressure, mmHg	0.98 (0.95–1.01)	0.186				
Heart rate, beats/min	1.00 (0.97–1.03)	0.848				
LV mass index, g/m^2	0.99 (0.97–1.02)	0.653				
LV ejection fraction, %	0.95 (0.90–1.01)	0.079				
E/e' ratio	1.13 (0.97–1.31)	0.129				
LA volume index, mL/m^2	1.06 (1.02–1.10)	**0.004**	1.08 (1.02–1.13)	**0.005**	1.08 (1.03–1.13)	**0.003**
Moderate/severe MR	1.39 (0.26–7.52)	0.701				
Hemoglobin, g/dL	1.05 (0.77–1.43)	0.781				
eGFR, mL/min/1.73 m^2	0.99 (0.96–1.02)	0.485				
ReDS as a continuous variable						
ReDS, %	1.15 (1.03–1.28)	**0.013**	1.19 (1.04–1.37)	**0.013**		
ReDS as a categorical variable						
ReDS ≥ 30 %	4.12 (1.40–12.10)	**0.010**			7.37 (1.83–29.70)	**0.005**

Models 1 and 2 included ReDS as a continuous or a categorical variable, respectively.
CI, confidence interval; E, early transmitral flow velocity; e', septal mitral annular early diastolic velocity; eGFR, estimated glomerular filtration rate; LA, left atrial; LAP, left atrial pressure; LV, left ventricular; MR, mitral regurgitation; OR, odds ratio; ReDS, remote dielectric sensing.

algorithm for the prediction of elevated LV filling pressure was recently found to be suboptimal in a large cohort of patients with a history of AF [17]. Hence, there has been an urgent need to identify and verify a novel non-invasive method for predicting LV filling pressure in patients with AF.

Lung fluid content as measured by ReDS showed a significant association with invasive PAWP measurements in patients with HF [8]. Remote dielectric sensing was also reported to be useful for detecting or ruling out acute decompensated HF [24], and ReDS-guided therapy for patients with HF was shown to have potential for reducing the frequency of readmissions for HF in patients with HF who were recently discharged from the hospital [25,26]. Our data both support and expand on these studies by demonstrating the robust relationship between ReDS and directly measured LAP, which is closely associated with pulmonary venous pressure and lung congestion [2]. Furthermore, our results suggest that, in addition to conventional echocardiographic indices, ReDS might be a powerful non-invasive indicator of LV filling pressure, even in patients with AF. We determined the optimal cut-off value of ReDS as 30 %, based on the result of receiver operating characteristic curve analysis for predicting elevated LAP. Although this value is slightly lower than the manufacturer recommended cut-off of 35 %, its prognostic value has been reported in a recent study that included

Table 3
Prediction of LAP ≥ 15 mmHg.

	ReDS ≥ 30 %	High E/e' ratio
Sensitivity (%)	65 (17/26)	44 (11/25)
Specificity (%)	69 (24/35)	83 (29/35)
Positive predictive value (%)	61 (17/28)	65 (11/17)
Negative predictive value (%)	73 (24/33)	67 (29/43)
Predictive accuracy (%)	67 (41/61)	67 (40/60)

The numbers in parentheses are patient numbers. High E/e' ratio, E/e' ratio > 15 or > 11 in patients with sinus rhythm or atrial fibrillation, respectively. Note that data on E/e' ratio could not be obtained in one patient.
E, early transmitral flow velocity; e', septal mitral annular early diastolic velocity; ReDS, remote dielectric sensing.

Japanese patients undergoing transcatheter aortic valve replacement [27]. The relatively lower cut-off value of ReDS measurements in this study, compared to previous reports, may be attributed to difference in the reference LV filling pressure value or variations in the patient population studied. Our current study only included approximately 30 % of patients with HF. Given that even subclinical congestion could worsen clinical outcomes of patients with HF [28], we believe that it is clinically important that ReDS can detect mild hemodynamic congestion in hemodynamically stable patients.

Although it is possible to estimate LV filling pressure in patients with a history of AF using the algorithm recommended in the recent guidelines when the patient is in sinus rhythm, there is a risk of misjudgment due to the transient atrial mechanical dysfunction that can occur after the conversion of AF to sinus rhythm, affecting the ratio of early transmitral flow velocity to late transmitral flow velocity [29]. Therefore, strictly speaking, the algorithm cannot be reliably used even if the AF is paroxysmal. On the other hand, E/e' ratio can be used to estimate LV filling pressure in both patients with sinus rhythm and AF at the time of echocardiography, with respective cut-off values of > 15 and > 11 [5,12]. Accordingly, we selected E/e' ratio as an echocardiographic index estimating LV filling pressure in this study. Our results suggest that ReDS has superior predictive value for elevated LAP compared to E/e' ratio in patients with a history of AF. In patients with sinus rhythm on the day of echocardiography, the predictive value of ReDS was similar to that of E/e' ratio, while in patients with AF, the predictive value of ReDS was superior to that of E/e' ratio. However, we could not demonstrate incremental predictive value of using both indices in patients with sinus rhythm, nor could we show statistically significant predictive power of ReDS for elevated LAP in patients with AF, due to the small sample size. Theoretically, the results of ReDS measurement would not be affected by the presence or absence of AF, and our results suggest that ReDS might be superior to traditional echocardiographic index in predicting elevated LAP even in patients with AF. Further studies are needed to evaluate whether the patient's rhythm affects the predictive value of ReDS or E/e' ratio for elevated LAP in patients with a history of AF.

We found that ReDS has a higher predictive value for elevated LAP than H_2FPEF score, which has been reported to predict elevated LAP in patients with suspected HF and an LV ejection fraction of ≥ 50 % [14]. Although the difference in the duration between the dates of echocardiography and LAP measurements or the absence of a stress test might have caused the lower predictive value of H_2FPEF score compared to the previous report, our data suggested that, in addition to H_2FPEF score, ReDS can help refine the clinical diagnosis of HFpEF in patients with AF. Incremental value of ReDS for the diagnosis of HFpEF in patients with AF over the H_2FPEF score should be verified in future studies. Moreover, a very recent study revealed that ReDS-guided decongestion during hospitalization and early after discharge reduced the number of HF readmissions in patients with ADHF [30]. In that study, a substantial proportion of patients needed an increase in diuretics to sustain decongestion state, underlining the importance of dose and drug adjustment after hospital discharge. Remote monitoring has recently been proposed as a measure to improve post-discharge management of HF [31]. Considering that the required techniques are such that even patients can take reliable measurements [15], ReDS seems to be a useful tool for effective remote monitoring of congestion and might be beneficial for the management of HF at home.

5. Study limitations

This study has some limitations. First, the empirically chosen small sample size is a major limitation. Second, since we only included patients with a history of AF who underwent catheter ablation, comparisons between the diagnostic values of elevated LAPs in patients with and without AF remain unknown; and indices such as PAWP, LV end-diastolic pressure, and pre-A pressure could not be obtained. Third, there were gaps between the dates of echocardiography and the dates of LAP measurements. Therefore, a rigorous comparison between the diagnostic accuracies of ReDS values and the guideline-recommended algorithm that uses echocardiographic indices for identifying patients with elevated LAP could not be performed. In addition, ReDS

Table 4
Logistic Regression Analysis for the Prediction of LAP ≥ 15 mmHg including H_2FPEF score.

	Univariate		Multivariate (Model 1)		Multivariate (Model 2)	
Variable	Unadjusted OR(95 % CI)	*P* value	Adjusted OR(95 % CI)	*P* value	Adjusted OR(95 % CI)	*P* value
Female sex	0.97 (0.29–3.22)	0.959				
Persistent atrial fibrillation	2.87 (0.87–9.45)	0.083				
Diabetes	0.91 (0.26–3.13)	0.875				
Dyslipidemia	2.58 (0.79–8.44)	0.117				
Coronary artery disease	1.44 (0.19–11.20)	0.725				
Systolic blood pressure, mmHg	0.99 (0.96–1.03)	0.674				
Heart rate, beats/min	0.99 (0.96–1.03)	0.618				
LV mass index, g/m^2	1.00 (0.97–1.03)	0.872				
LV ejection fraction, %	0.90 (0.81–1.01)	0.076				
LA volume index, mL/m^2	1.05 (1.01–1.10)	**0.020**	1.07 (1.01–1.13)	**0.018**	1.08 (1.02–1.15)	**0.009**
Moderate/severe MR	0.68 (0.06–8.11)	0.764				
Hemoglobin, g/dL	1.06 (0.73–1.53)	0.775				
eGFR, mL/min/1.73 m^2	0.97 (0.94–1.01)	0.190				
H_2FPEF score	1.46 (0.81–2.62)	0.210	1.40 (0.71–2.76)	0.331	1.53 (0.74–3.14)	0.249
ReDS as a continuous variable						
ReDS, %	1.15 (1.02–1.30)	**0.025**	1.23 (1.06–1.43)	**0.008**		
ReDS as a categorical variable						
ReDS ≥ 30 %	3.17 (0.96–10.50)	0.059			10.40 (1.94–55.10)	**0.006**

Models 1 and 2 included ReDS as a continuous or a categorical variable, respectively.
CI, confidence interval; eGFR, estimated glomerular filtration rate; LA, left atrial; LAP, left atrial pressure; LV, left ventricular; MR, mitral regurgitation; OR, odds ratio; ReDS, remote dielectric sensing.

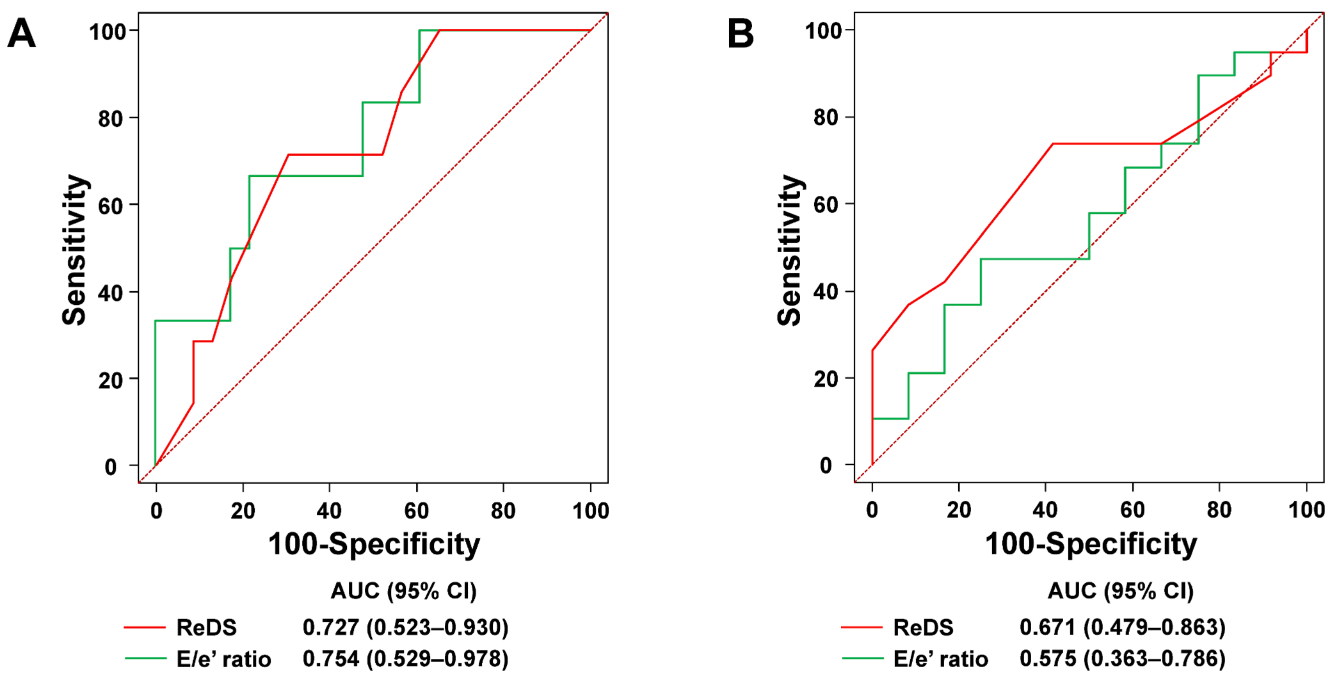

Fig. 4. Predictive value of ReDS measurement for elevated LAP according to underlying rhythm Receiver operating characteristic curve analysis of ReDS values and E/e' ratio for the prediction of elevated LAP in patients with sinus rhythm (**A**) and AF (**B**) on the day of echocardiography. AUC, area under the curve; CI, confidence interval; E/e' ratio, the ratio of early transmitral flow velocity to septal mitral annular early diastolic velocity; LAP, left atrial pressure; ReDS, remote dielectric sensing.

measurements could not be performed on the same day as LAP measurements, which might account for the relatively weak correlation between ReDS values and the index of LV filling pressure, compared to previous studies [8]. Finally, in this study, we focused on LAP as an indicator of LV filling pressure, which is closely associated with pulmonary congestion, and investigated its relationship with ReDS measurements. However, it is important to note that LAP is ultimately an indirect indicator of pulmonary congestion. Thus, failure to include data from lung ultrasonography, which has recently been demonstrated to be useful for the evaluation of pulmonary congestion in patients with HF [32], is a major limitation. Further investigation is required to determine the correlation between the degree of pulmonary congestion and ReDS measurements in hemodynamically stable AF patients with mild hemodynamic congestion, as in this study.

6. Conclusions

This prospective observational study showed that ReDS is a useful indicator of elevated LAP that can even be used in patients with AF. Additional larger studies are warranted to investigate the impact of ReDS-guided decongestive therapy on patients with HF.

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CRediT authorship contribution statement

Shunsuke Tamaki: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Katsuji Inoue:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Hiroshi Kawakami:** Data curation, Investigation, Supervision, Validation, Writing – review & editing. **Tomoki Fujisawa:** Data curation, Investigation, Validation. **Ryo Miyabe:** Investigation. **Yasuhisa Nakao:** Investigation. **Shigehiro Miyazaki:** Investigation. **Yusuke Akazawa:** Investigation. **Toru Miyoshi:** Investigation. **Akinori Higaki:** Investigation. **Fumiyasu Seike:** Investigation. **Haruhiko Higashi:** Investigation. **Kazuhisa Nishimura:** Methodology, Supervision. **Shuntaro Ikeda:** Supervision. **Osamu Yamaguchi:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] F.H. Verbrugge, M. Guazzi, J.M. Testani, B.A. Borlaug, Altered hemodynamics and end-organ damage in heart failure: impact on the lung and kidney, Circulation 142 (2020) 998–1012.
[2] O.A. Smiseth, D.A. Morris, N. Cardim, M. Cikes, V. Delgado, E. Donal, et al., Multimodality imaging in patients with heart failure and preserved ejection fraction: an expert consensus document of the European association of cardiovascular imaging, Eur. Heart J. Cardiovasc. Imaging 23 (2022) e34–e61.
[3] O.S. Andersen, O.A. Smiseth, H. Dokainish, M.M. Abudiab, R.C. Schutt, A. Kumar, et al., Estimating left ventricular filling pressure by echocardiography, J. Am. Coll. Cardiol. 69 (2017) 1937–1948.
[4] K. Inoue, F.H. Khan, E.W. Remme, N. Ohte, E. Garcia-Izquierdo, M. Chetrit, et al., Determinants of left atrial reservoir and pump strain and use of atrial strain for evaluation of left ventricular filling pressure, Eur. Heart J. Cardiovasc. Imaging 23 (2021) 61–70.
[5] S.F. Nagueh, O.A. Smiseth, C.P. Appleton, B.F. Byrd 3rd, H. Dokainish, T. Edvardsen, et al., Recommendations for the evaluation of left ventricular diastolic function by echocardiography: an update from the american society of echocardiography and the European association of cardiovascular imaging, J. Am. Soc. Echocardiogr. 29 (2016) 277–314.
[6] O. Amir, D. Rappaport, B. Zafrir, W.T. Abraham, A novel approach to monitoring pulmonary congestion in heart failure: initial animal and clinical experiences using remote dielectric sensing technology, Congest. Heart Fail. 19 (2013) 149–155.
[7] O. Amir, Z.S. Azzam, T. Gaspar, S. Faranesh-Abboud, N. Andria, D. Burkhoff, et al., 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. 221 (2016) 841–846.
[8] N. Uriel, G. Sayer, T. Imamura, D. Rodgers, G. Kim, J. Raikhelkar, et al., Relationship between noninvasive assessment of lung fluid volume and invasively measured cardiac hemodynamics, J. Am. Heart Assoc. 7 (2018) e009175.
[9] J. Mascherbauer, C. Zotter-Tufaro, F. Duca, C. Binder, M. Koschutnik, A. A. Kammerlander, et al., Wedge pressure rather than left ventricular end-diastolic pressure predicts outcome in heart failure with preserved ejection fraction, JACC Heart Fail. 5 (2017) 795–801.
[10] H. Higashi, K. Inoue, S. Inaba, Y. Nakao, M. Kinoshita, S. Miyazaki, et al., Restricted left atrial dilatation can visually differentiate cardiac amyloidosis from hypertrophic cardiomyopathy, ESC Heart Fail. 8 (2021) 3198–3205.
[11] N. Chan, T.K.M. Wang, C. Anthony, O.A. Hassan, M. Chetrit, A. Dillenbeck, et al., Echocardiographic evaluation of diastolic function in special populations, Am. J. Cardiol. 202 (2023) 131–143.
[12] S.S. Mitter, S.J. Shah, J.D. Thomas, A test in context: E/A and E/e' to assess diastolic dysfunction and LV filling pressure, J. Am. Coll. Cardiol. 69 (2017) 1451–1464.
[13] S. Matsuo, E. Imai, M. Horio, Y. Yasuda, K. Tomita, K. Nitta, et al., Revised equations for estimated GFR from serum creatinine in Japan, Am. J. Kidney Dis. 53 (2009) 982–992.
[14] Y.N.V. Reddy, R.E. Carter, M. Obokata, M.M. Redfield, B.A. Borlaug, A simple, evidence-based approach to help guide diagnosis of heart failure with preserved ejection fraction, Circulation 138 (2018) 861–870.
[15] W.T. Abraham, D. Bensimhon, S.P. Pinney, S.C. Feitell, W.F. Peacock, O. Amir, et al., Patient monitoring across the spectrum of heart failure disease management 10 years after the CHAMPION trial, ESC Heart Fail. 8 (2021) 3472–3482.
[16] M. Hori, T. Imamura, A. Fukuo, T. Fukui, T. Koi, Y. Ueno, et al., Validation of inter-rater and intra-rater reliability of remote dielectric sensing measurement, Int. Heart J. 63 (2022) 73–76.
[17] M. Pak, T. Kitai, A. Kobori, Y. Sasaki, T. Okada, R. Murai, et al., Diagnostic accuracy of the 2016 guideline-based echocardiographic algorithm to estimate invasively-measured left atrial pressure by direct atrial cannulation, J. Am. Coll. Cardiol. Img. 15 (2022) 1683–1691.
[18] Y. Mukai, K. Nakanishi, M. Daimon, K. Iwama, Y. Yoshida, K. Hirose, et al., Prevalence, associated factors, and echocardiographic estimation of left atrial hypertension in patients with atrial fibrillation, J. Am. Heart Assoc. 12 (2023) e030325.
[19] T.A. McDonagh, M. Metra, M. Adamo, R.S. Gardner, A. Baumbach, M. Bohm, et al., 2021 ESC guidelines for the diagnosis and treatment of acute and chronic heart failure, Eur. Heart J. 42 (2021) 3599–3726.
[20] A.Y. Wang, M. Wang, C.W. Lam, I.H. Chan, Y. Zhang, J.E. Sanderson, Left ventricular filling pressure by Doppler echocardiography in patients with end-stage renal disease, Hypertension 52 (2008) 107–114.
[21] M. Murayama, H. Iwano, H. Nishino, S. Tsujinaga, M. Nakabachi, S. Yokoyama, et al., Simple two-dimensional echocardiographic scoring system for the estimation of left ventricular filling pressure, J. Am. Soc. Echocardiogr. 34 (2021) 723–734.
[22] C. Gerges, A.M. Pistritto, M. Gerges, R. Friewald, V. Hartig, T.M. Hofbauer, et al., Left ventricular filling pressure in chronic thromboembolic pulmonary hypertension, J. Am. Coll. Cardiol. 81 (2023) 653–664.
[23] Y. Kanda, Investigation of the freely available easy-to-use software 'EZR' for medical statistics, Bone Marrow Transplant. 48 (2013) 452–458.
[24] A.S.O. Olesen, K. Miger, A. Fabricius-Bjerre, K.D. Sandvang, I.E. Kjesbu, A. Sajadieh, et al., Remote dielectric sensing to detect acute heart failure in patients with dyspnoea: a prospective observational study in the emergency department, Eur. Heart J. Open. 2 (2022) oeac073.
[25] O. Amir, T. Ben-Gal, J.M. Weinstein, J. Schliamser, D. Burkhoff, A. Abbo, et al., Evaluation of remote dielectric sensing (ReDS) technology-guided therapy for decreasing heart failure re-hospitalizations, Int. J. Cardiol. 240 (2017) 279–284.
[26] A. Lala, M.H. Barghash, G. Giustino, J. Alvarez-Garcia, S. Konje, A. Parikh, et al., Early use of remote dielectric sensing after hospitalization to reduce heart failure readmissions, ESC Heart Fail. 8 (2021) 1047–1054.
[27] T. Imamura, T. Izumida, H. Onoda, S. Tanaka, R. Ushijima, M. Sobajima, et al., Prognostic impact of remote dielectric sensing value following TAVR, Heart Vessels 38 (2023) 1468–1475.
[28] A.P. Ambrosy, P.S. Pang, S. Khan, M.A. Konstam, G.C. Fonarow, B. Traver, et al., Clinical course and predictive value of congestion during hospitalization in patients admitted for worsening signs and symptoms of heart failure with reduced ejection fraction: findings from the EVEREST trial, Eur. Heart J. 34 (2013) 835–843.
[29] O. Yokoseki, K. Tsutsumi, C. Obinata, Y. Toba, Transient atrial mechanical dysfunction assessed in acute phase of embolic stroke of undetermined source, J. Stroke Cerebrovasc. Dis. 29 (2020) 105032.
[30] J. Alvarez-Garcia, A. Lala, M. Rivas-Lasarte, C. De Rueda, D. Brunjes, S. Lozano-Jimenez, et al., Remote dielectric sensing before and after discharge in patients with ADHF: the ReDS-SAFE HF trial, JACC Heart Fail. 12 (2024) 695–706.
[31] L.W. Stevenson, H.J. Ross, L.D. Rathman, J.P. Boehmer, Remote monitoring for heart failure management at home, J. Am. Coll. Cardiol. 81 (2023) 2272–2291.
[32] S. Coiro, P. Rossignol, G. Ambrosio, E. Carluccio, G. Alunni, A. Murrone, et al., Prognostic value of residual pulmonary congestion at discharge assessed by lung ultrasound imaging in heart failure, Eur. J. Heart Fail. 17 (2015) 1172–1181.