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Temporal Association Between Intrathoracic Impedance and Tachyarrhythmia Occurrence

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ABSTRACT

Background: This study examined whether daily intrathoracic impedance is temporally associated with the occurrence of atrial fibrillation (AF) and ventricular tachycardia (VT).

Methods: This retrospective cohort study included 117 patients with cardiac implantable devices, followed for a median of 668 days, corresponding to 89 637 person-days. Recurrent AF occurred in 28% of patients (mean AF burden 0.27), while 773 VT episodes occurred in 15% of patients. Daily intrathoracic impedance, expressed relative to a reference impedance, was analyzed to identify events of impedance decrease and increase. The temporal association between impedance events and tachyarrhythmia burden was quantified using a patient-specific relational strength measure (γ), which compares post-event and pre-event tachyarrhythmia burden.

Results: For impedance decreases, event-related γ for AF was higher than control γ computed for randomly placed events (median 0.68 vs. 0.48, $p = 0.04$). For VT, event-related γ did not differ significantly from control γ (six patients; median 0.52 vs. 0.21, $p = 0.82$). No significant differences were observed for impedance increases in either the AF or VT analysis. In the pooled episode-level analysis, an impedance decrease was associated with a shorter time to VT occurrence than an impedance increase (median 4 vs. 7 days, $p < 0.001$), with 48% of VT episodes occurring within 3 days after an impedance decrease.

Conclusion: A decrease in intrathoracic impedance is temporally associated with subsequent AF occurrence and, at the episode level, with a shorter time to VT. These findings suggest that daily intrathoracic impedance may provide information on short-term changes preceding tachyarrhythmia occurrence.

1 | Introduction

Thoracic fluid accumulation may be reflected by a decrease in intrathoracic impedance [1–3]. In patients with implantable cardiac devices, intrathoracic impedance is commonly summarized using a fluid index, which integrates impedance

deviations from a patient-specific reference impedance [1]. Several studies have reported an association between crossing a predefined fluid index threshold and an increased occurrence of tachyarrhythmias, including atrial fibrillation (AF) and ventricular tachycardia (VT) [4–8].

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Because the fluid index was developed as a tool for monitoring heart failure and is cumulative by design, a threshold crossing occurs only after a sufficient deviation has accumulated over a period of time. Consequently, analyses based on this index typically use long time windows, such as 30 days [5, 6]. The threshold crossing may therefore occur days after the initial impedance decrease. When the duration of a tachyarrhythmia episode is shorter than this delay, it may begin and end before the threshold is reached, precluding assessment of its temporal association with the initial impedance change.

The aim of this study was to examine whether daily intrathoracic impedance is temporally associated with recurrent AF and VT. To address this question, we employed the relational strength measure [9, 10] to quantify, separately for each patient, whether tachyarrhythmia burden increased after recurrent impedance events relative to pre-event periods and randomly placed control events over a multi-year observation period. Since the analysis is based on daily impedance events rather than cumulative threshold crossings, the proposed approach can be used to assess temporal associations involving tachyarrhythmia episodes of any duration, subject to the detection criteria and temporal resolution of the available device data. Characterizing patient-specific associations may help identify patients who warrant closer assessment of fluid status and tachyarrhythmia occurrence.

2 | Methods

2.1 | Patient Population

This retrospective cohort study was performed using data collected from patients with a cardiac implantable electronic device (CIED) at a tertiary care hospital in Sweden between January 2015 and December 2020 [11]. Only patients with a CIED capable of measuring intrathoracic impedance were included. Daily intrathoracic impedance, reference impedance, fluid index, time spent in AF, and the daily number of VT episodes were retrieved using the CareLink software platform (Medtronic Inc., Minneapolis, MN).

AF occurrence was assessed in patients with a CIED capable of detecting atrial arrhythmias; therefore, patients without an atrial lead were not included in the AF analysis. The AF cohort included patients with recurrent device-detected AF. The device provided the total time spent in AF per day, which was converted to daily AF burden, defined as the proportion of the day spent in AF. Patients with continuous AF throughout the entire observation period were excluded. The no-AF subgroup consisted of patients without device-detected AF.

VT occurrence was assessed in patients with a CIED capable of detecting VT and delivering VT therapies; therefore, patients with cardiac resynchronization therapy pacemaker systems without implantable cardioverter-defibrillator functionality were excluded from the VT analysis. The VT cohort included patients with device-detected VT episodes, irrespective of therapy delivery. Self-terminating episodes for which no therapy was delivered were also included. VT occurrence was quantified as the daily number of episodes. Device-detected VT episodes

were independently adjudicated by two experienced electrophysiologists who were blinded to the daily impedance, reference impedance, and fluid index values. The no-VT subgroup consisted of patients without device-detected VT.

Data gaps in daily recordings were identified in 8 of 117 patients (6.8%); the median gap duration was 1 day (range 1–195). Seven of these patients had neither AF nor VT and were therefore not included in the relational strength analyses. Only one patient with AF had a single gap of 30 consecutive days.

2.2 | Assessment of Temporal Association

The relational strength measure γ was used to determine whether an impedance decrease or increase, hereafter referred to as an impedance event, was temporally associated with tachyarrhythmia occurrence. This patient-specific approach quantifies the extent to which the post-event tachyarrhythmia burden $B_{1,n}$ exceeds the pre-event burden $B_{0,n}$ for the n :th event. The relational strength is defined by [9, 10]:

$$\gamma = \sum_{n=1}^{N_t} \frac{B_{1,n}}{1 + B_{0,n}} H(B_{1,n} - B_{0,n}), \quad (1)$$

where N_t denotes the number of events within the observation period, and T represents the analysis time window used to compute $B_{1,n}$ and $B_{0,n}$. The Heaviside step function $H(\cdot)$ sets the contribution to zero when $B_{0,n} > B_{1,n}$, since such events do not indicate an increase in tachyarrhythmia burden after the impedance event.

Days with AF burden < 0.001 were considered non-AF days to reduce the impact of short detections, whereas days with AF burden > 0.999 were considered days of continuous AF. For VT, only the daily number of detected episodes was available. Therefore, daily VT occurrence was represented by a binary variable indicating the presence of VT when one or more episodes occurred and its absence when no episode occurred on that day.

T was set to 3 days, corresponding to the shortest window at which impedance-based γ stabilized in the window-length analysis shown in Figure 3. After an event was identified, no subsequent event was sought within the following $2T$ window to prevent overlap. Impedance events overlapping a data gap in the $2T$ window were excluded from the analysis. The computation of event-related γ is illustrated in Figure 1.

2.3 | Statistical Analysis

The Shapiro–Wilk test was used to assess data normality. Because the data were not normally distributed, nonparametric tests were used. The Mann–Whitney U test was used to compare independent groups, whereas the Wilcoxon signed-rank test was used for paired comparisons. For analyses involving multiple episodes per patient, a mixed-effects model with patient as a random effect was used to account for within-patient correlation.

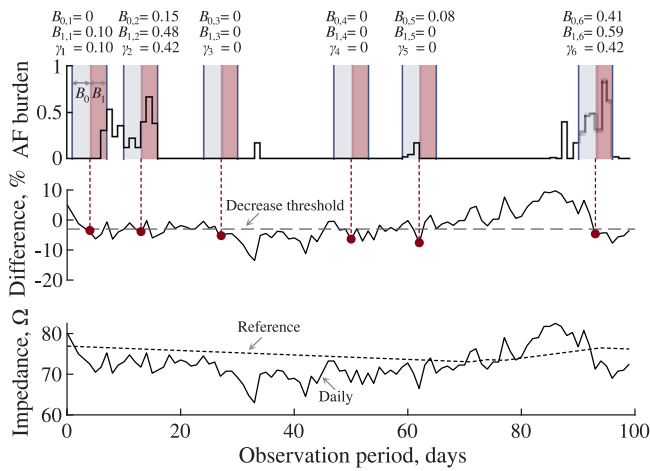


FIGURE 1 | Illustration of the computation of the temporal relational strength γ for a patient with recurrent AF. The top panel shows the daily AF burden; the middle panel shows detected impedance events (red circles); and the bottom panel shows daily (solid line) and reference (dashed line) impedance. The AF burden before ($B_{0,n}$, blue shading) and after ($B_{1,n}$, red shading) each event is computed over a 3-day window, yielding individual γ_n values and an overall $\gamma = 0.94$.

The medians of the distributions of daily impedance increases and decreases relative to the patient-specific reference were used to define the corresponding event thresholds.

To assess the stability of the relational strength across T values from 1 to 30 days, event-related γ was computed using impedance decrease events and fluid index events; the latter defined by a threshold crossing of 60 Ω -days [1, 4, 5, 12]. Stability across window lengths was quantified using the quartile coefficient of variation.

To obtain a patient-specific value expected by chance, control γ was computed using randomly placed control events equal in number to the identified events. To ensure robustness, the control γ was estimated using 100 random initializations [10]. Patients for whom both event-related and control γ values were zero were excluded. Comparisons between event-related and control γ values are presented using boxplots, with connected dots indicating individual paired differences.

To account for multiple comparisons, the Holm method was applied separately within predefined sets of related hypotheses. AF and VT were treated as separate outcomes because they were evaluated in different cohorts and using different definitions of tachyarrhythmia burden. In the relational strength analysis, each set included the decrease-related versus control and increase-related versus control comparisons for the corresponding tachyarrhythmia. A Holm-adjusted $p < 0.05$ was considered statistically significant.

The time between impedance events and tachyarrhythmia occurrence was summarized using empirical survivor functions. Data were pooled across patients within the AF cohort for AF analysis and within the VT cohort for VT analysis.

3 | Results

In total, 117 patients were included in the study, of whom 79% were men, and the mean age was 69 years (Table 1). Median follow-up was 668 days (range 4–2192), corresponding to 89 637 person-days. Recurrent device-detected AF occurred in 33 (28%) patients with a mean AF burden of 0.27 over the entire observation period. VT occurred in 18 (15%) patients, resulting in 773 adjudicated, device-detected VT episodes. Six patients had both AF and VT episodes.

3.1 | Impedance Distributions

Figure 2 shows distributions of daily intrathoracic impedance decreases and increases relative to the patient-specific reference. The median magnitudes of impedance decreases and increases were 3.3% and 1.7%, respectively. These values were used as thresholds for defining impedance events in the subsequent analyses.

3.2 | Influence of the Analysis Time Window

Figure 3 shows the normalized γ for impedance decrease and fluid index events across analysis window lengths T ranging from 1 to 30 days. The impedance-based γ was more stable across window lengths than the fluid index-based γ , with quartile coefficients of variation of 0.27 and 0.99, respectively. This finding indicates that the impedance-based γ is less sensitive to the choice of T , supporting its use for short-term temporal association analysis.

3.3 | Impedance Characteristics

Intrathoracic impedance characteristics are summarized in Table 2. Median impedance over the entire observation period did not differ significantly between patients with and without AF ($p = 0.14$) or between patients with and without VT ($p = 0.89$). In patients with AF, impedance decreases were more frequent than impedance increases, with 86 versus 57 events per patient, respectively. A similar tendency was observed in patients with VT, with 80 versus 52 events per patient, respectively. Impedance decrease events also lasted longer in the VT cohort than in the no-VT subgroup (median 2.0 vs. 1.0 days, $p = 0.01$), whereas no other between-group differences were significant.

3.4 | Temporal Association

Figure 4 compares event-related γ with control γ derived from randomly placed events. For impedance decreases, event-related γ exceeded control γ in 17 of 26 patients in the AF cohort, with median values of 0.68 and 0.48, respectively ($p = 0.02$; Holm-adjusted $p = 0.04$). Only six patients had non-zero values for both event-related and control γ and were included in the VT analysis. Event-related γ was higher than control γ in four of these patients, but the difference was not statistically significant (median 0.52 vs. 0.21; $p = 0.47$; Holm-adjusted $p = 0.82$). For impedance increases, no significant

TABLE 1 | Clinical characteristics of the study population and the AF and VT cohorts.

	All patients (<i>n</i> = 117)	AF cohort (<i>n</i> = 33)	VT cohort (<i>n</i> = 18)
Age, years (SD)	69 (11)	69 (10)	66 (11)
Male sex, <i>n</i> (%)	92 (79)	27 (82)	17 (94)
ICD, <i>n</i> (%)			
Primary prevention	75 (64)	20 (61)	12 (67)
Secondary prevention	28 (24)	10 (30)	6 (33)
No ICD	14 (12)	3 (9)	0 (0)
Congestive heart failure, <i>n</i> (%)	109 (93)	33 (100)	18 (100)
Hypertension, <i>n</i> (%)	66 (56)	19 (58)	7 (39)
Ischemic cardiomyopathy, <i>n</i> (%)	48 (41)	17 (52)	6 (33)
History of AF, <i>n</i> (%)			
Recurrent	33 (28)	25 (76)	6 (33)
Permanent	30 (26)	0 (0)	6 (33)
VT, <i>n</i> (%)	18 (15)	6 (18)	18 (100)
Kidney failure, <i>n</i> (%)	44 (38)	15 (46)	8 (44)
Left ventricular ejection fraction, <i>n</i> (%)			
> 50%	7 (6)	0 (0)	0 (0)
40%–49%	14 (12)	8 (24)	1 (6)
30%–39%	31 (27)	4 (12)	2 (11)
< 30%	62 (53)	20 (61)	15 (83)
Missing	3 (3)	1 (3)	0 (0)
Cardiac medications, <i>n</i> (%)			
Beta-blockers	110 (94)	32 (97)	18 (100)
ACE-i/ARB/Nepr	103 (88)	28 (85)	18 (100)
MRA	71 (61)	18 (55)	11 (61)
Diuretics	78 (67)	22 (67)	12 (67)
SGLT2 inhibitors	4 (3)	0 (0)	0 (0)
Statins	70 (60)	20 (61)	10 (56)

Abbreviations: ICD, implantable cardioverter defibrillator; MRA, mineralocorticoid receptor antagonist; SGLT2, sodium–glucose cotransporter 2.

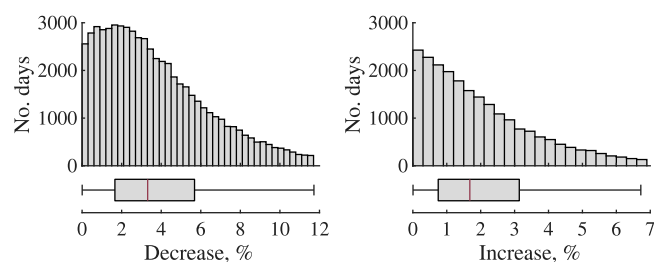


FIGURE 2 | Histograms of intrathoracic impedance decreases (left) and increases (right) relative to the patient-specific reference impedance. Values exceeding the upper quartile by more than 1.5 times the interquartile range are not shown.

differences between event-related and control γ were observed for either AF or VT.

3.5 | Time to Tachyarrhythmia

Figure 5 shows the empirical survivor functions of the time between impedance events and tachyarrhythmia occurrence.

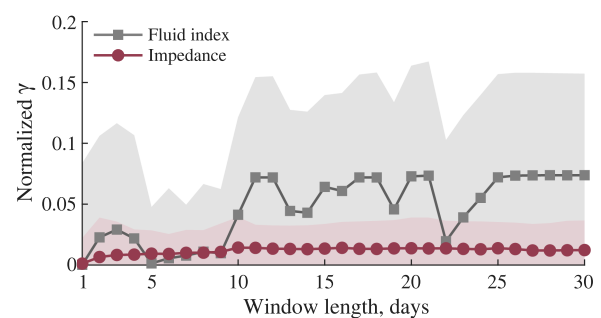


FIGURE 3 | Median event-related γ in the AF cohort as a function of window length T for fluid index and intrathoracic impedance decrease events. Shaded areas indicate the interquartile range. *Note:* For each patient, γ was normalized by the number of detected events to account for differences in event frequency between the impedance-based and fluid index-based definitions.

No significant difference in time to AF was observed between impedance decreases and increases (median 2 vs. 3 days, $p = 0.23$). In contrast, an impedance decrease was associated with a shorter time to VT than an impedance increase (median

TABLE 2 | Intrathoracic impedance characteristics in subgroups of patients with and without AF or VT.

	No-AF cohort (n = 33)	No-AF (n = 74)	p value (AF vs. no-AF)	VT cohort (n = 18)	no-VT (n = 85)	p value (VT vs. no-VT)
Median impedance, Ω	77	72	0.14	74	72	0.89
Impedance decrease						
Median number per patient	86	72	0.26	80	79	0.77
Median duration, days	1.5	1.5	0.89	2.0	1.0	0.01
Impedance increase						
Median number per patient	57	49	0.45	52	52	0.61
Median duration, days	1.0	1.0	0.41	1.0	1.0	0.78

4 vs. 7 days, $p < 0.001$). After an impedance decrease, 48% of VT episodes occurred within 3 days, compared with 29% after an impedance increase.

4 | Discussion

The main finding of this study is a temporal association between decreases in intrathoracic impedance and subsequent AF occurrence. This finding complements fluid index studies, which have reported increased AF occurrence both before and after threshold crossing [5, 6, 13]. Studies evaluating intrathoracic impedance have reported a higher likelihood of VT following an impedance decrease [14, 15]. Consistent with these findings, the episode-level analysis in the present study showed a shorter time to VT after an impedance decrease. However, the complementary patient-level relational strength analysis did not show a statistically significant difference between event-related γ and control γ . Because only six patients contributed nonzero values, the patient-level evidence remains inconclusive and requires evaluation in a larger cohort.

An additional contribution of this study is the empirical derivation of thresholds for changes in intrathoracic impedance, as no established thresholds currently exist. Previous work has explored cutoffs of 5% and 10% for decreases in impedance [14]. In the present study, the thresholds were derived empirically from population-level distributions rather than selected based on the strength of their association with tachyarrhythmias. They may therefore serve as candidate reference values for future studies defining short-term impedance decrease and increase events. However, since event detection depends on the selected threshold, alternative threshold definitions may change both the number and timing of identified impedance events.

Previous studies have used windows of 1–7 days for intrathoracic impedance decreases [14] and up to 30 days for fluid index analyses [5, 6]. In the present study, T was set to 3 days to focus on short-term temporal associations. The window-length analysis in Figure 3 further showed that impedance-based relational strength stabilized at approximately 3 days.

Relational strength depends on both the number of impedance events and the underlying tachyarrhythmia episode pattern. A previous simulation study showed that greater AF burden can itself increase γ , as events were more likely to coincide with intervals containing AF episodes [9]. Event-related γ should therefore always be interpreted relative to patient-specific control γ . A larger positive difference between event-related and control γ indicates a stronger temporal association; however, its magnitude does not have a straightforward clinical interpretation. This is primarily because γ relies on tachyarrhythmia burden, whose clinical relevance depends on the outcome of interest and patient characteristics, and no universal threshold has been established [16]. We therefore do not assign clinical significance to any particular difference between event-related and control γ . Clinically meaningful thresholds remain to be established in prospective studies by relating such differences to clinical outcomes.

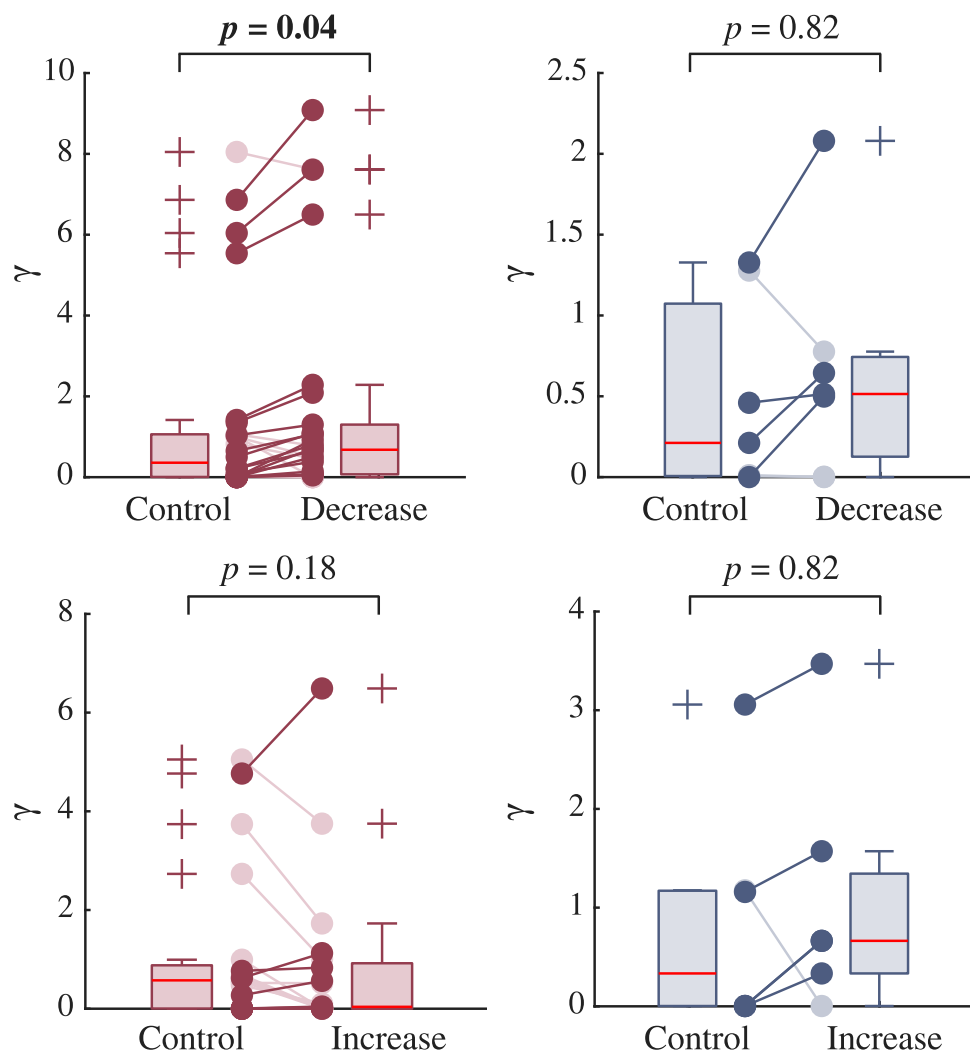


FIGURE 4 | Patient-specific comparisons of event-related and control γ for AF (left panels) and VT (right panels). Each pair of connected dots represents one patient. An upward line indicates that event-related γ is higher than control γ . Boxes represent the interquartile range, red horizontal lines indicate the median, and whiskers extend to the most extreme values within 1.5 times the interquartile range. Values outside this range are marked with a +. p values are Holm-adjusted.

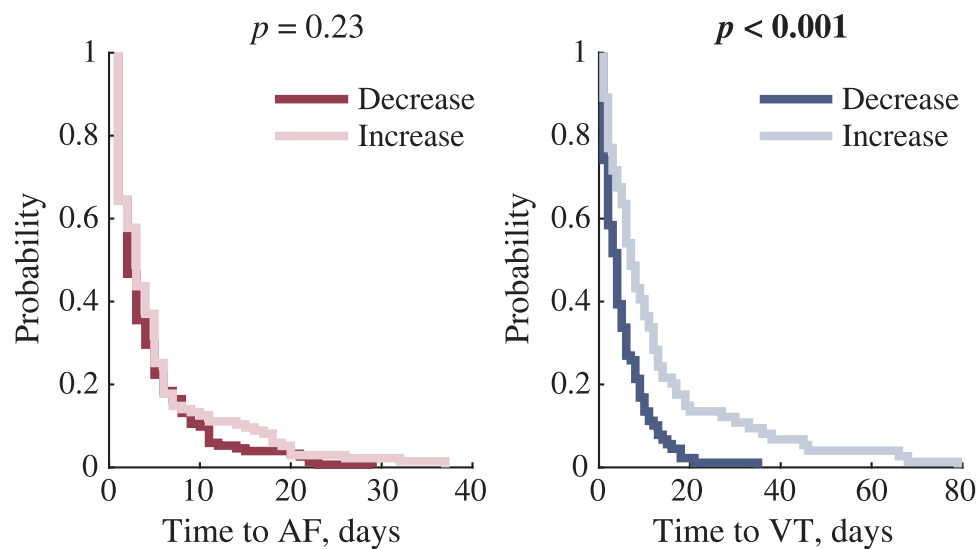


FIGURE 5 | Time between impedance events and the occurrence of AF (left) and VT (right). Curves show empirical survivor functions, representing the probability that the time to tachyarrhythmia occurrence exceeds a given number of days after an impedance event.

Previous studies of impedance-based remote monitoring have focused mainly on detecting worsening heart failure rather than assessing its association with tachyarrhythmias. The fluid index algorithm showed low sensitivity and positive predictive value for heart failure hospitalization [17], while automated fluid status alerts did not reduce all-cause death or cardiovascular hospitalization [18]. Subsequent studies suggest that device alerts may be more useful when they prompt timely review of device data, patient contact, assessment of signs and symptoms of fluid retention, and treatment based on the clinical findings [19, 20]. The relational strength measure could support a similar monitoring strategy by identifying patients in whom recurrent impedance decreases are followed by increased tachyarrhythmia burden. Patients for whom event-related γ consistently exceeds their control γ could be prioritized for review of recorded arrhythmias, ventricular rate, and signs and symptoms of fluid retention. Future studies could investigate whether longitudinal changes in the difference between event-related and control γ reflect changes in clinical status or management. At present, however, the approach should be considered a novel research tool rather than a clinically validated alert.

AF and VT have distinct pathophysiological mechanisms and should therefore be considered separately. AF and thoracic fluid accumulation may be bidirectionally related [5, 6, 13]. Increased filling pressures and atrial stretch can facilitate AF in a susceptible atrial substrate, whereas AF, particularly with a rapid ventricular response, can reduce hemodynamic efficiency and promote fluid accumulation. In heart failure, VT commonly arises from scarred or remodeled ventricular myocardium, particularly in patients with reduced left ventricular ejection fraction. Worsening heart failure may increase VT risk through ventricular stretch, sympathetic activation, ischemia, hypoxemia, inflammation, and electrolyte or metabolic disturbances related to renal dysfunction or diuretic treatment [2]. Therefore, the decrease in impedance observed around the time of VT may reflect a period of clinical instability rather than a cause of the tachyarrhythmia.

4.1 | Limitations

This study has several limitations. Intrathoracic impedance is an indirect marker of thoracic fluid accumulation and correlates inversely with filling pressure and fluid balance [3]. However, pulmonary conditions (e.g., pneumonia, pleural effusion, pneumothorax), device-related factors (e.g., lead dislodgement), and underlying tissue edema may also alter intrathoracic impedance [1, 6, 12]. Impedance data were available only as daily averages; the number and timing of individual AF episodes within a day were unavailable; and VT data were provided as the daily number of detected episodes. These device-related restrictions precluded assessment of impedance changes immediately before tachyarrhythmia occurrence.

The data set included 773 adjudicated VT episodes, but these episodes were recorded in a small number of patients, and only a subset contributed to the relational strength analysis, thereby reducing statistical power. Accordingly, the nonsignificant patient-level VT result for γ should be interpreted cautiously.

Event-related and control γ were computed within each patient, thereby reducing confounding by stable patient characteristics.

However, the sample size did not permit reliable stratified analyses or adjustment for potential effect modifiers, including age, cardiomyopathy etiology, left ventricular ejection fraction, device type, heart failure severity, history of AF, and medical therapy. These factors may influence intrathoracic impedance, susceptibility to tachyarrhythmias, or both, and thereby modify the observed associations [2, 6, 7, 15]. Moreover, time-varying changes in heart failure status, volume management, medication, and arrhythmia treatment may have influenced both intrathoracic impedance and tachyarrhythmia occurrence. The findings should therefore be interpreted as unadjusted temporal associations. Larger studies with stratified analyses are needed to determine whether these associations differ across clinically relevant patient groups.

5 | Conclusion

A decrease in intrathoracic impedance is temporally associated with subsequent AF occurrence and, at the episode level, with a shorter time to VT. These findings suggest that daily intrathoracic impedance may provide information on short-term changes preceding tachyarrhythmia occurrence, beyond what is captured by cumulative fluid indices.

Acknowledgments

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Ethics Statement

The present study was approved by the Swedish Ethical Review Authority (2020-05843, 2021-05826-01).

Conflicts of Interest

Pyotr G. Platonov reports receiving speaker fees from Medtronic. The other authors declare no conflicts of interest.

Data Availability Statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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