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Bidirectional temporal association of device-detected atrial fibrillation and sleep apnea

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ABSTRACT

BACKGROUND The relationship between atrial fibrillation (AF) and sleep apnea (SA) is well established, but the day-to-day temporal direction of this association remains uncertain.

OBJECTIVE This study aimed to examine the bidirectional day-to-day association between device-detected AF (DDAF) and device-detected SA (DDSA), while distinguishing DDAF episode onset from continuation of ongoing episodes.

METHODS Data were obtained from the prospective ACaSA study in pacemaker patients undergoing continuous remote monitoring. Data collected from September 2020 to August 2025 were analyzed. Severe DDSA was defined as a respiratory disturbance index of ≥20 and a DDAF episode as a daily burden of ≥6 minutes. 3 day-level, time-stratified intraindividual case-crossover analyses were performed: pathway 1 related preceding-day DDAF burden to incident severe DDSA on the subsequent night, pathway 2 related preceding-night severe DDSA to incident DDAF episode onset the next day, and pathway 3 related preceding-night severe DDSA to continuation of an already active DDAF episode. Generalized linear mixed-effects models were used as secondary analyses.

RESULTS A total of 112,242 patient-days from 218 patients were analyzed. Incident severe DDSA was preceded by higher odds of elevated DDAF burden on the previous day in a graded manner, with odds ratios (ORs) of 1.38 (95% confidence interval [CI], 1.10–1.74) for 6 minutes to 1 hour, 1.81 (95% CI, 1.52–2.15) for 1–12 hours, and 2.52 (95% CI, 1.97–3.22) for ≥12 hours (all $P \leq .005$). Both incident DDAF episode onset and the continuation of ongoing DDAF episodes were preceded by higher odds of severe DDSA on the previous night (OR, 1.35; 95% CI, 1.10–1.64; $P = .003$, and OR, 2.39; 95% CI, 1.47–3.88; $P < .001$, respectively).

CONCLUSION Continuous monitoring identified a bidirectional temporal association between DDAF and DDSA. Incident severe DDSA was preceded by higher odds of elevated DDAF burden, whereas both incident DDAF episode onset and continuation of ongoing episodes were preceded by higher odds of severe DDSA.

KEYWORDS Atrial fibrillation; Sleep apnea; Respiratory disturbance index; Remote monitoring; Pacemaker

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Atrial fibrillation (AF) and sleep apnea (SA) frequently coexist, and each condition is independently associated with adverse cardiovascular outcomes.[1,2] Patients with SA have a higher risk of developing AF, and SA is common among patients with AF, where it may complicate management and reduce the success of rhythm control strategies.[3] Contemporary

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cardiac implantable electronic devices can continuously monitor both daily AF burden and a device-derived surrogate of sleep-disordered breathing, the respiratory disturbance index (RDI), providing an opportunity to study their temporal relationship at high resolution.[4,5]

Although the association between AF and SA is well established, its short-term temporal direction remains incompletely defined.[6] Previous work has largely focused on the pathway from SA to AF. In the VARIOSA-AF study, device-based monitoring showed that greater SA severity was associated with subsequent AF.[4] Potential mechanisms include intermittent hypoxemia, intrathoracic pressure swings, autonomic activation, and acute atrial stretch, all of which may promote arrhythmogenesis.[7,8]

The reverse pathway, whereby AF may be associated with subsequent worsening of nocturnal respiratory disturbance, has been less well characterized. AF-related hemodynamic changes, reduced cardiac output, and alterations in volume status could plausibly affect respiratory stability during sleep, although high-resolution longitudinal data addressing this question remain limited.[9–11]

Accordingly, we used continuous remote monitoring data from pacemaker recipients in the ongoing ACaSA study to examine the bidirectional day-to-day association between device-detected AF (DDAF) and severe device-detected SA (DDSA).

Methods

Study cohort

Patients enrolled in the ongoing prospective observational ACaSA study (NCT05127720) who were implanted with a MicroPort BOREA DR or TEO DR dual-chamber pacemaker formed the basis of this analysis. Participants were recruited at the Medical University of Innsbruck after providing a written informed consent. All patients underwent telemonitoring, with device data transmitted weekly to the study center. For the present analysis, data collected from September 2020 to August 2025 were included. Patients with permanent AF, single-chamber devices, or fewer than 90 days of valid follow-up transmissions were excluded. Finally, to rule out any influence of surgery on the results, the first 4 weeks after pacemaker implantation were excluded from analysis.

Abbreviations

AF: atrial fibrillation

CI: confidence interval

CPAP: continuous positive airway pressure

DDAF: device-detected atrial fibrillation

DDSA: device-detected sleep apnea

GLMM: generalized linear mixed-effects model

OR: odds ratio

RDI: respiratory disturbance index

SA: sleep apnea

Data collection

DDSA

The RDI was measured from midnight to 5:00 AM, using thoracic impedance to monitor the patient's respiratory effort. This specific measurement window is a hardcoded, nonadjustable manufacturer default programmed into the device algorithm to capture the core sleep period. The SA algorithm in MicroPort pacemakers counts an apnea event in the absence of a significant respiratory cycle for >10 seconds and a hypopnea event upon a sustained (>10-second) reduction of the respiratory amplitude by at least 50% compared with the mean minute ventilation of preceding validated respiratory cycles. The RDI correlates with the apnea-hypopnea index measured by polysomnography.[5] The MicroPort thoracic impedance algorithm relies on a stable signal. If a patient's pacing percentage fluctuates or intrinsic rhythm variations create excessive signal noise that the sensor cannot reliably interpret, the algorithm's internal quality control automatically flags the measurement as invalid (>400 unstable signals/h) and suppresses the RDI output. Consequently, the valid nights included in this analysis represent only those where signal quality and pacing dynamics were deemed strictly sufficient by the device to calculate an accurate RDI.

DDAF

DDAF was measured using pacemaker-detected "mode switch events." A mode switch happens when the atrial heart rate rises abnormally to more than 120 beats per minute and is at least 25% faster than the previous eight beats. The device confirms this if either at least 28 of 32 beats or 36 of 64 beats are fast. Once triggered, the pacemaker records how long mode switching lasts, from 1 second up to 24 hours per day.

Outcome definitions

For the bidirectional analysis, 3 day-level outcomes were defined. Severe DDSA was defined as an RDI of $\geq$20 events/h during the nightly monitoring period, consistent with previous validation of the device-derived RDI.[5] A DDAF episode day was defined as a daily DDAF burden of $\geq$6 minutes within a 24-hour period. This specific threshold was chosen in accordance with the 2024 European Society of Cardiology guidelines for the definition of clinically relevant atrial high-rate episodes. Episodes of this duration have been robustly associated with increased thromboembolic risk and reliably exclude brief, clinically insignificant atrial oversensing or short bursts of premature atrial contractions.[12]

For pathway 1, the outcome was incident severe DDSA, defined as severe DDSA occurring after a previous nonsevere night (RDI <20 events/h). For pathway 2, incident DDAF episode onset was defined as a DDAF burden of $\geq$6 minutes on the index day after a quiescent previous day (<6 minutes). For pathway 3, analyses were restricted to days after an active DDAF episode. DDAF episode continuation was defined as persistence of DDAF across midnight into the subsequent day, operationalized using prespecified transitions in daily DDAF burden categories (none, partial, or full burden).

Quantitatively, "partial" burden was defined as $\geq$6 to 1400 minutes, and "full" burden as >1400 minutes. The exact algorithmic transitions defining episode continuation

across midnight are visualized in Supplemental Figure 1, with illustrative clinical timeline scenarios presented in Supplemental Figure 2 to demonstrate the algorithm's conservative handling of intraday temporal uncertainty.

Statistical analysis

Categorical variables were summarized as numbers and percentages. Continuous variables were summarized as mean ± standard deviation if normally distributed or as median (interquartile range [IQR]) otherwise.

To evaluate the bidirectional day-to-day temporal associations between DDAF and DDSA, an intraindividual, time-stratified case-crossover design was used. Data were analyzed using conditional logistic regression.

In particular, a time-stratified matching strategy was used. For each patient, a case day was matched to all available control days occurring strictly within the same calendar month of the same year. This time-stratified approach inherently controls long-term time trends and seasonal variations, whereas the intraindividual design balances all static between-subject confounders.

3 pathways were examined (Figure 1): (1) the association between preceding-day DDAF burden and incident severe DDSA on the subsequent night, restricted to days after a nonsevere baseline night (RDI <20 events/h); (2) the association between preceding-night severe DDSA and incident DDAF episode onset the next day, restricted to days after a quiescent baseline day (DDAF burden <6 minutes); and (3) the association between preceding-night severe DDSA and continuation of an ongoing DDAF episode into the subsequent day.

As a secondary analysis to contextualize population-level absolute probabilities and visualize continuous dose-response relationships, generalized linear mixed-effects models (GLMMs) with a logistic link function and a random intercept per participant were used. Multivariable GLMMs were adjusted for core baseline covariates: age, sex, body mass index, heart failure (HF), arterial hypertension, and diabetes mellitus. Absolute marginal probabilities for the respective outcomes were derived from the fitted GLMMs using estimated marginal means, averaged over the distribution of the adjusted covariate. To assess continuous dose-response relationships, natural cubic splines were used for continuous exposure variables. Knots were chosen based on visual inspection and established clinical thresholds to ensure parsimony. In particular, preceding DDAF burden was modeled with internal knots at 1 and 12 hours, whereas continuous RDI was modeled with internal knots at 20 and 40 events/h.

In addition, to assess the robustness of our findings against underlying structural heart disease, subgroup analyses stratified by baseline HF status were performed across all 3 case-crossover pathways. Furthermore, to address potential concurrent measurement overlap, a sensitivity analysis incorporating a strict +1 day temporal lag was performed for the incident DDAF onset pathway (pathway 2). Moreover, to ensure the robustness of the primary findings against alternative outcome definitions, sensitivity analyses using longer duration thresholds for incident DDAF episode onset (≥1 and ≥12 hours) were performed. Finally, to explicitly assess the clinical relevance of the absolute risk increase in a highly vulnerable phenotype, a targeted sensitivity analysis was performed recalculating the absolute marginal probabilities of incident DDAF onset specifically within the subgroup of patients with a documented clinical history of paroxysmal or persistent AF at baseline.

Finally, to assess potential structural time-varying confounding related to behavioral shifts (eg, altered sleep

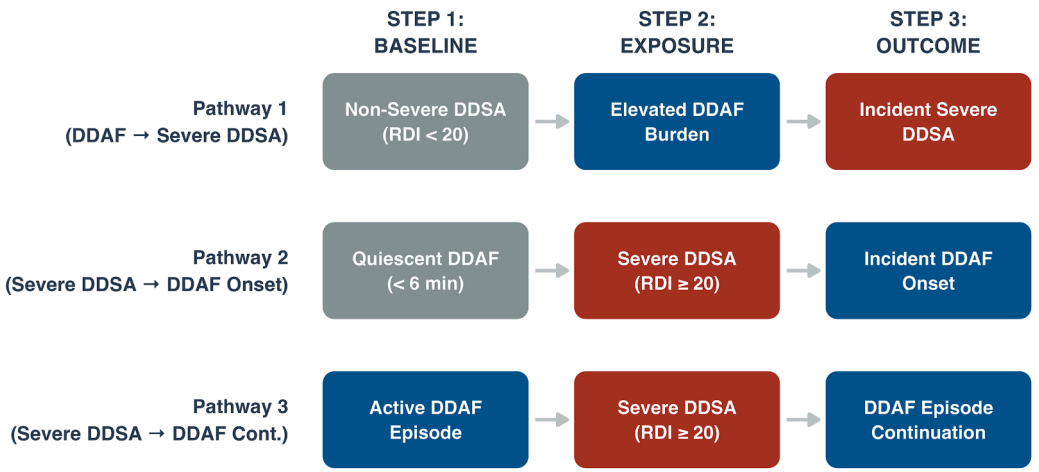


Figure 1
Conceptual framework of the bidirectional case-crossover design. The illustration depicts the 3 temporal pathways examined using the intraindividual, time-stratified case-crossover methodology. To establish a clear chronological sequence, each pathway strictly follows a 3-step design: starting with a defined day/night state (step 1: baseline), assessing the subsequent transient condition (step 2: exposure), and evaluating the temporal association with the event on the next day/night (step 3: outcome). Pathway 1 evaluates whether incident severe DDSA is preceded by higher odds of an elevated DDAF burden. Pathway 2 assesses whether the incident onset of a new DDAF episode out of a quiescent baseline is preceded by higher odds of severe DDSA. Pathway 3 examines whether the continuation (maintenance) of an already active DDAF episode across midnight into the subsequent day is preceded by higher odds of severe DDSA (*blue*, atrial fibrillation; *red*, sleep apnea; *gray*: quiescent/nonsevere baseline). DDAF = device-detected atrial fibrillation; DDSA = device-detected sleep apnea; RDI = respiratory disturbance index.

schedules or alcohol consumption on weekends), a restrictive sensitivity analysis was performed matching case days exclusively to control days occurring on the exact same day of the week within the same calendar month.

All analyses were performed using R software, version 4.5.1 (R Foundation for Statistical Computing, Vienna, Austria). A 2-sided $P < .05$ was considered statistically significant.

Representative patient

To illustrate the temporal sequence of the 3 investigated pathways, representative patient timelines were extracted from the longitudinal dataset using daily DDAF burden and nightly RDI measurements (presented in the Results section).

Results

Cohort characteristics and follow-up

Of 280 enrolled pacemaker patients, 218 met the inclusion criteria after the exclusion of those with permanent AF, ineligible VVI devices (n = 46), and short follow-up (<90 days; n = 16) (Figure 2). Median age was 76 years (IQR 69–81), and 36.7% were female. Baseline characteristics are presented in Table 1. After a strict 28-day postimplantation blanking period, a total of 160,599 follow-up nights were recorded for the included patients. Of these, 47,798 nights (29.8%) were classified as invalid by the pacemaker's internal diagnostic algorithms (eg, caused by sensor noise or movement artifacts) and automatically excluded to ensure high data fidelity. Ultimately, 112,242 valid, fully matched patient-nights were available for the final bidirectional analysis. Median follow-up was 484 days (IQR, 262–738) per patient.

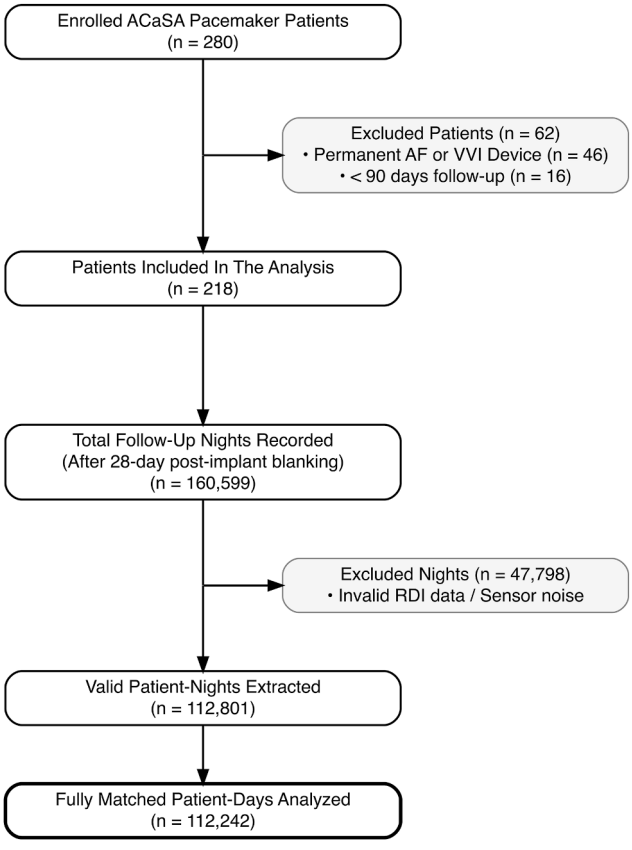


Figure 2
Consolidated Standards of Reporting Trials flow diagram of patient enrollment, exclusions, and final analysis population of the study. AF = atrial fibrillation; RDI = respiratory disturbance index.

Furthermore, an analysis of the raw device data confirmed that sensor invalidation was not systematically driven by DDAF burden. On a day-to-day basis, mean daily DDAF burden was clinically comparable between valid and invalid nights (125.4 vs 117.0 minutes). Similarly, on a patient level, the rate of invalid nights did not significantly differ between patients categorized into high and low overall DDAF burden groups by median split (30.5% vs 30.6%).

An analysis of the raw device data revealed that sensor invalidation was influenced by underlying pacing dynamics. Valid RDI nights were associated with higher mean right atrial pacing (42.0% vs 33.5%) and lower mean right ventricular pacing (39.1% vs 50.2%) than invalid nights.

DDAF

During the follow-up period, DDAF (defined as an episode lasting ≥6 minutes) occurred in 117 patients (53.7%). Across the entire cohort, DDAF was present on 13,186 of the 112,242 analyzed patient-days (11.7%). Notably, 107 patients (49.1%) experienced at least 1 day of both severe DDSA (RDI ≥20) and DDAF during the study period, highlighting the high intraindividual coprevalence of these interrelated conditions within the continuous monitoring cohort.

DDSA

During the follow-up period, at least 1 night of severe DDSA (defined as an RDI of ≥20 events/h) was observed in 190 patients (90.5%). Across the entire cohort, severe DDSA was present on 31,526 (28.1%) of the 112,242 analyzed patient-nights. On nights when severe DDSA occurred, the median RDI was 28.8 events/h (IQR, 23.6–38.2). The longitudinal burden varied considerably among individuals; on average, patients experienced severe DDSA in 33.8% of their monitored nights (IQR, 3.8%–62.3%).

Pathway 1: Preceding-day DDAF burden and subsequent severe DDSA

In the primary time-stratified intraindividual case-crossover analysis, restricted to days after a nonsevere DDSA night, incident severe DDSA was preceded by higher odds of elevated DDAF burden on the previous day (Table 2). Compared with a patient's own quiescent control days (<6 minutes of DDAF) within the same calendar month, DDAF burdens of 6 minutes to 1 hour and 1–12 hours were associated with higher odds of incident severe DDSA (odds ratio [OR], 1.38; 95% confidence interval [CI], 1.10–1.74; $P = .005$, and OR, 1.81; 95% CI, 1.52–2.15; $P < .001$, respectively). A DDAF burden of ≥12 hours was associated with an OR of 2.52 (95% CI, 1.97–3.22; $P < .001$).

Table 1 Baseline characteristics at inclusion into the ACaSA study

Characteristic	Overall (n = 218)
Demographics and anthropometrics	
Age, y	76.0 [69.3–80.8]
Female sex	80 (36.7)
Body mass index, kg/m^2	26.2 [23.1–28.4]
Pacing indication	
SSS	111 (52.1)
AVB II, Wenckebach	7 (3.3)
AVB II, Mobitz	32 (15.0)
AVB III	63 (28.9)
Comorbidities	
Arterial hypertension	145 (66.8)
Diabetes mellitus	39 (18.0)
AF (nonpermanent)	84 (38.5)
Coronary artery disease	82 (37.8)
Previous MI	25 (11.5)
Medications	
Beta blocker	63 (28.9)
CCB	53 (24.3)
ACE inhibitor or ARB	117 (53.7)
Amiodarone	7 (3.2)
Flecainide	4 (1.8)
Digitalis	3 (1.4)
Statin	136 (62.4)
HCT	46 (21.1)
MRA	22 (10.1)
Loop diuretic	32 (14.7)
Aspirin	80 (36.7)
NOAC	69 (31.7)
Cardiac function and laboratory values	
LVEF, %	58.2 [53.5–63.5]
NT-proBNP (ng/L)	325.0 [124.2–681.5]
LDL cholesterol (mg/dL)	83.5 [61.2–119.8]
FEV1/FVC *z* score	0.3 [−0.4 to 0.8]

Results are reported as median [interquartile range] for continuous variables and as n (%) for categorical variables.
ACE = angiotensin-converting enzyme; AF = atrial fibrillation; ARB = angiotensin receptor blocker; AVB = atrioventricular block; CCB = calcium channel blocker; FEV1 = forced expiratory volume in 1 second; FVC = forced vital capacity; HCT = hydrochlorothiazide; HF = heart failure; LDL = low-density lipoprotein; LVEF = left ventricular ejection fraction; MI = myocardial infarction; MRA = mineralocorticoid receptor antagonist; NOAC = non–vitamin K antagonist oral anticoagulant; NT-proBNP = N-terminal pro-B-type natriuretic peptide; SD = standard deviation; SSS = sick sinus syndrome.

In secondary GLMM, the estimated absolute probability of severe DDSA increased from 14.2% after quiescent days to 21.8%, 22.5%, and 29.7% after DDAF burdens of 6 minutes to 1 hour, 1–12 hours, and ≥12 hours, respectively (Supplemental Table 1). Continuous spline modeling showed a nonlinear increase in the odds of severe DDSA with increasing preceding-day DDAF burden (Figure 3A). A representative patient timeline is presented in Figure 4A.

Pathway 2: Severe DDSA and incident DDAF episode onset

In the reciprocal primary analysis, restricted to days after a quiescent baseline (DDAF burden <6 minutes), incident DDAF episode onset was preceded by higher odds of severe DDSA during the previous night (OR, 1.35; 95% CI, 1.10–1.64; P = .003) (Table 2). In secondary population-level modeling, the estimated absolute daily probability of incident DDAF onset increased from 0.20% after nights without severe DDSA to 0.28% after nights with severe DDSA (Supplemental Table 2). To evaluate this absolute risk within a clinically vulnerable phenotype, these probabilities were recalculated exclusively for the subgroup of 82 patients with a known clinical history of paroxysmal or persistent AF at baseline. In this cohort, the estimated absolute daily probability of incident DDAF onset increased from 1.04% after nights without severe DDSA to 1.45% after nights with severe DDSA.

In categorical sensitivity analyses, a graded association was observed between DDSA severity and incident DDAF onset. Compared with nights with an RDI of <20, the adjusted odds of incident DDAF onset were 1.28 (95% CI, 1.04–1.58) for an RDI of 20–29, 1.52 (95% CI, 1.13–2.04) for an RDI of 30–39, and 1.76 (95% CI, 1.24–2.52) for an RDI of ≥40 (all P < .05) (Supplemental Table 3). These findings were consistent with the continuous spline analysis (Figure 3B). A representative patient timeline is presented in Figure 4B.

In sensitivity analyses using longer duration thresholds for incident DDAF onset, the associations remained significant. Incident DDAF episodes lasting ≥1 and ≥12 hours were preceded by 1.33-fold (95% CI, 1.04–1.70; P = .021) and 1.95-fold (95% CI, 1.01–3.79; P = .048) higher odds of severe DDSA on the previous night, respectively (Supplemental Table 4).

Finally, to address potential concurrent overlap between the early-morning measurement windows, a strict +1 day lag sensitivity analysis was performed. When a minimum 19-hour separation buffer was enforced (testing day 1 DDSA against day 2 DDAF onset), the association completely dissipated (OR, 0.98; 95% CI, 0.80–1.20; P = .834) (Supplemental Table 5).

Pathway 3: Severe DDSA and continuation of ongoing DDAF episodes

The continuation of ongoing DDAF episodes into the next day was preceded by higher odds of severe DDSA during the previous night (OR, 2.39; 95% CI, 1.47–3.88; P < .001) (Table 2). In categorical sensitivity analyses, compared with nights with an RDI <20, the odds of episode continuation increased to 2.21 (95% CI, 1.32–3.70) for an RDI of 20–29, 2.36 (95% CI, 1.19–4.68) for an RDI of 30–39, and 4.43 (95% CI, 2.03–9.66) for an RDI of ≥40 (Supplemental Table 6).

In secondary GLMM, the estimated absolute probability of episode continuation increased from 7.3% after nonsevere DDSA nights to 14.1% after severe DDSA nights (Supplemental Table 3). Continuous spline modeling demonstrated a nonlinear increase in the odds of episode continuation with increasing preceding-night RDI (Figure 3C). A representative patient timeline is presented in Figure 4C.

In subgroup analyses stratified by baseline HF status, the bidirectional temporal associations were robustly maintained

Table 2 Bidirectional associations between DDAF and severe DDSA

Pathway and preceding exposure	Outcome	OR (95% CI)	*P* value
Pathway 1	Severe DDSA tonight (RDI ≥20)		
DDAF burden → severe DDSA			
Preceding DDAF: <6 min		Reference	—
Preceding DDAF: 6 min to 1 h		1.38 (1.10–1.74)	.005
Preceding DDAF: 1–12 h		1.81 (1.52–2.15)	<.001
Preceding DDAF: ≥12 h		2.52 (1.97–3.22)	<.001
Pathway 2	DDAF episode onset		
DDSA → DDAF episode onset			
Nonsevere DDSA (RDI <20)		Reference	—
Severe DDSA (RDI ≥20)		1.35 (1.10–1.64)	.003
Pathway 3	DDAF episode continuation		
DDSA → DDAF episode continuation			
Nonsevere DDSA (RDI <20)		Reference	—
Severe DDSA (RDI ≥20)		2.39 (1.47–3.88)	<.001

Analysis using a time-stratified, intraindividual case-crossover design. This model uses each patient as their own control within the same calendar month, inherently adjusting for all static baseline clinical characteristics (eg, age, sex, body mass index, heart failure, and hypertension).
CI = confidence interval; DDAF = device-detected atrial fibrillation; DDSA = device-detected sleep apnea; OR = odds ratio; RDI = respiratory disturbance index.

in the larger non-HF subgroup, demonstrating that these acute interactions are not strictly confined to an HF phenotype. Among patients with HF, statistical power was limited for incident pathways, leading to wider CIs despite point estimates trending in similar directions. Notably, however, the effect of severe DDSA on the continuation of an ongoing DDAF episode was pronounced in patients with HF (OR, 9.90; 95% CI, 2.53–38.79) (Supplemental Table 7).

Sensitivity analysis for day-of-week effects

To ensure the observed temporal associations were not confounded by structural behavioral shifts depending on the day of the week, a strict sensitivity analysis was performed matching cases exclusively to controls on the exact same weekday. Despite the stringent restriction, the primary associations remained robust and significant (eg, OR 1.42 for incident DDAF onset; OR 2.62 for DDAF continuation), confirming that the interactions between DDAF and DDSA are independent of weekday-related lifestyle factors (Supplemental Table 8).

Discussion

In this longitudinal analysis of continuously monitored pacemaker data, we observed a bidirectional temporal

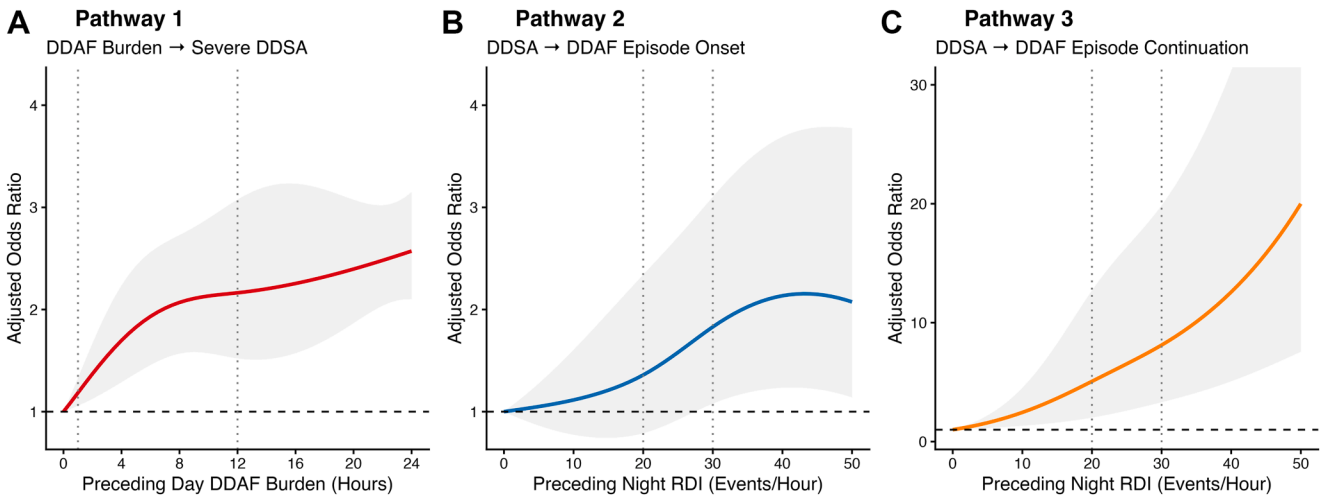


Figure 3
A: Pathway 1: the continuous effect of preceding-day DDAF burden (hours) on the likelihood of experiencing severe DDSA the next night. Modeled using natural cubic splines with internal knots placed at clinical thresholds of 1 and 12 hours (*vertical dotted lines*). **B:** Pathway 2: the nonlinear association between the preceding-night continuous RDI and the odds of DDAF episode onset the next day, modeled using natural cubic splines. **C:** Pathway 3: the nonlinear association between preceding-night continuous RDI and the odds of an ongoing DDAF episode to continue the next day, similarly modeled using natural cubic splines. Note: *Solid colored lines* represent the adjusted odds ratios (aORs) relative to a baseline reference of 0 hours of DDAF (**A**) or an RDI of 0 events/h (**B and C**). *Gray shaded regions* represent 95% confidence intervals. The *horizontal dashed black line* indicates an aOR of 1.0 (null effect). The *vertical dotted lines* in panels B and C indicate the clinical threshold for severe sleep apnea (RDI = 20 events/h). To optimize visual stability and account for data sparsity at extreme values, the x-axes for panels B and C are truncated at an RDI of 40 events/h. All dose-response models are adjusted for age, sex, body mass index, heart failure, hypertension, diabetes mellitus, and a random patient intercept. DDAF = device-detected atrial fibrillation; DDSA = device-detected sleep apnea; RDI = respiratory disturbance index.

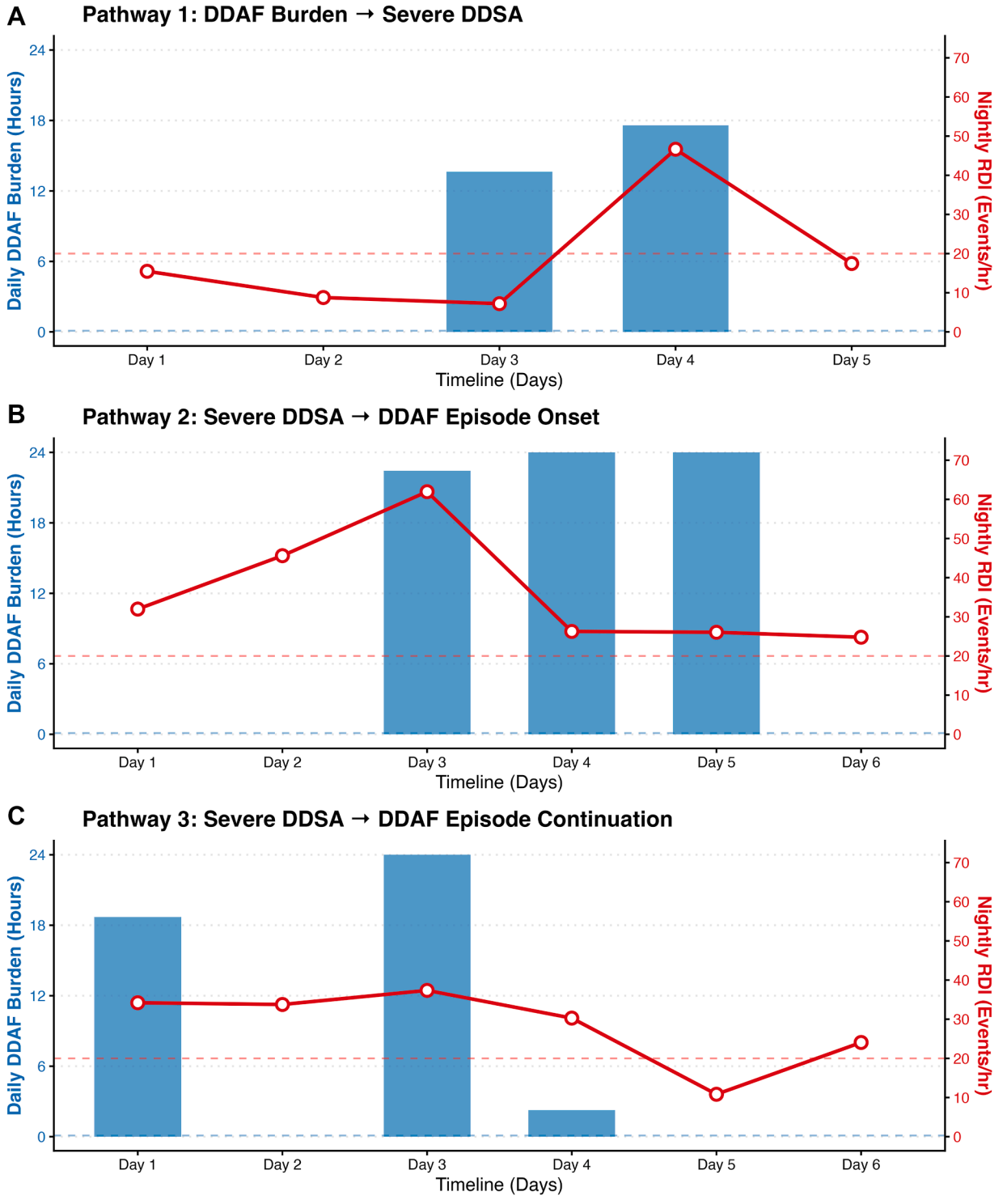


Figure 4
Representative clinical examples of bidirectional day-to-day associations between atrial fibrillation and sleep apnea. Real-world patient timelines extracted from the continuous remote monitoring dataset illustrating the 3 modeled pathways. *Blue bars* indicate daily DDAF burden (hours, left axis). *Red lines* and *open circles* indicate the nightly RDI (events/h, right axis). *Dashed horizontal reference lines* indicate clinical thresholds for a DDAF episode (≥6 minutes) and severe DDSA (RDI ≥20 events/h). DDAF = device-detected atrial fibrillation; DDSA = device-detected sleep apnea; RDI = respiratory disturbance index.

association between DDAF and DDSA. Incident severe DDSA was preceded by higher odds of elevated DDAF burden, whereas both incident DDAF episode onset and continuation of ongoing episodes were preceded by higher odds of severe DDSA.

The observation that incident DDAF is preceded by higher odds of severe DDSA is consistent with previous work linking sleep-disordered breathing to AF.[4,7,8] Intermittent hypoxemia, intrathoracic pressure swings, autonomic activation, and acute atrial stretch may contribute to a

transient electrophysiological milieu favorable to AF. Furthermore, our lag sensitivity analyses demonstrated the association completely dissipated when separated by a full calendar day, closely aligning with the potential transient, short-acting nature of these autonomic and hemodynamic stressors. Our findings extend this literature by separating incident episode onset from continuation of established episodes, suggesting that nocturnal respiratory disturbance may be relevant to both phases of AF expression.

From a clinical perspective, it is important to contextualize the absolute vs relative risk of these events. When modeled across the entire pacemaker cohort, the absolute daily probability of incident DDAF onset seemed mathematically modest (increasing from 0.20% to 0.28%). However, this broad population average is heavily diluted by patients receiving pacemakers for purely bradycardic indications without any intrinsic arrhythmic propensity. When absolute probabilities were restricted to the vulnerable subgroup of 82 patients with a known clinical history of paroxysmal or persistent AF at baseline, the absolute daily probability of a new DDAF episode onset increased from 1.04% after nights without severe DDSA to 1.45% after nights with severe DDSA. Because SA is a chronic, recurring stressor, this daily absolute risk could accumulate substantially over time.

Notably, both incident DDAF episode onset and the continuation of ongoing episodes were preceded by higher odds of severe DDSA. In absolute terms, the estimated daily probability of an active DDAF episode continuing into the next day nearly doubled, increasing from 7.3% after nonsevere DDSA nights to 14.1% after severe DDSA nights. This finding suggests that nocturnal respiratory disturbance may be relevant not only to episode initiation but also to maintenance of AF once an episode is active. Furthermore, in subgroup analyses, this effect on episode continuation seemed particularly pronounced in patients with baseline HF. However, although the odds of DDAF continuation in patients with HF were high, the very wide CI reflects limited statistical power owing to the small subgroup sample size ($n = 26$) and low frequency of specific day-to-day transition events in this cohort. Therefore, the exact magnitude of this effect should be interpreted with caution.

The reverse association, whereby more severe nocturnal respiratory disturbance is preceded by higher DDAF burden, has been less well characterized. On an absolute level, the daily probability of experiencing severe DDSA demonstrated a strong dose-response gradient, increasing from 14.2% after quiescent days to 21.8%, 22.5%, and 29.7% after DDAF burdens of 6 minutes to 1 hour, 1–12 hours, and $\geq$12 hours, respectively. This observation is consistent with the possibility that AF-related hemodynamic changes, loss of atrial contribution to ventricular filling, or changes in volume status may adversely affect respiratory stability during sleep.

However, the present observational analyses cannot establish definitive causality or mechanism. It remains possible that shared physiological mechanisms—such as acute volume overload or abrupt autonomic imbalances—could drive both conditions simultaneously, and temporal ordering alone does not preclude reverse causality. Furthermore, residual time-varying confounding remains possible.

These observational findings highlight the potential value of integrated management approaches addressing both AF and sleep-disordered breathing. For example, given their close temporal interplay, it is clinically plausible that a patient undergoing AF ablation might remain vulnerable to arrhythmic recurrences if concurrent severe SA continues to act as an unaddressed physiological stressor. Conversely, a patient receiving continuous positive airway pressure (CPAP) therapy might continue to experience nocturnal respiratory instability if intermittent AF episodes repeatedly disrupt cardiopulmonary hemodynamics. Although prospective interventional trials are required to confirm whether dual treatment actively improves patient outcomes, our data underscore the rationale for a multidisciplinary approach involving close collaboration between cardiology and sleep medicine.[12–17]

The strengths of this study include the large volume of longitudinal observations, the use of objective daily device-based measures, and the combination of intraindividual, time-stratified case-crossover analyses with secondary mixed-effects modeling. The case-crossover design reduces confounding by stable patient-level characteristics by allowing each participant to serve as their own control.

Several limitations should be acknowledged. First, DDSA was assessed using a device-derived RDI rather than gold-standard polysomnography. Crucially, the device cannot differentiate between obstructive and central SA, introducing potential misclassification bias. This inability to phenotype events limits our mechanistic interpretation, particularly regarding the pathway where DDAF precedes severe DDSA. Because an incident AFib episode can transiently reduce cardiac output and elevate left atrial filling pressures—known triggers for central SA—we cannot definitively determine whether the preceding arrhythmia exacerbates obstructive mechanisms or simply induces central respiratory events. In addition, we lacked concurrent polysomnography to independently validate the RDI within our specific cohort. Second, data regarding daily CPAP adherence were not available. CPAP is a dynamic therapy that strongly influences both respiratory stability and arrhythmia burden; therefore, variable CPAP compliance represents a potentially significant unmeasured time-varying confounder. Third, despite the intraindividual, time-stratified design, residual confounding from other acute daily factors (eg, physical activity, intercurrent illness, acute alcohol consumption, fluctuations in fluid status, or medication noncompliance) cannot be fully excluded. Fourth, our study cohort consists of elderly patients (median age 76 years) with dual-chamber pacemakers from a single center, representing a selected, high-risk population. Consequently, these findings may not be fully generalizable to younger individuals or to patients without implantable cardiac devices. Fifth, given the large number of secondary and sensitivity analyses performed, there is a potential for multiplicity and inflation

of type I error; therefore, these exploratory analyses should be considered hypothesis generating.

Conclusion

Using continuous pacemaker monitoring, we identified a bidirectional temporal association between DDAF and DDSA. Incident severe DDSA was preceded by higher odds of elevated DDAF burden, whereas both incident DDAF episode onset and continuation of ongoing episodes were preceded by higher odds of severe DDSA. These findings support further study of integrated management strategies addressing both AF and sleep-disordered breathing.

Appendix

Supplementary Data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.hrthm.2026.07.026.

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Patient Consent: All participants provided a written informed consent before enrollment.

Ethics Statement: The ACaSA study was conducted in accordance with the Declaration of Helsinki. The protocol was approved by the ethics committee of the Medical University of Innsbruck (EK Nr: 1322/2020, approval date March 11, 2021).

Data Availability: The data underlying this article cannot be shared publicly owing to the privacy of individuals who participated in the study. The data will be shared on reasonable request to the corresponding author.

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References

1. Gami AS, Pressman G, Caples SM, et al. Association of atrial fibrillation and obstructive sleep apnea. Circulation 2004;110:364–367.
2. Mehra R, Benjamin EJ, Shahar E, et al. Association of nocturnal arrhythmias with sleep-disordered breathing: the Sleep Heart Health Study. Am J Respir Crit Care Med 2006;173:910–916.
3. Kanagala R, Murali NS, Friedman PA, et al. Obstructive sleep apnea and the recurrence of atrial fibrillation. Circulation 2003;107:2589–2594.
4. Linz D, Brooks AG, Elliott AD, et al. Variability of sleep apnea severity and risk of atrial fibrillation: the VARIOSA-AF Study. JACC Clin Electrophysiol 2019;5:692–701.
5. Defaye P, de la Cruz I, Martí-Almor J, et al. A pacemaker transthoracic impedance sensor with an advanced algorithm to identify severe sleep apnea: the DREAM European study. Heart Rhythm 2014;11:842–848.
6. Stevenson IH, Teichtahl H, Cunnington D, Ciavarella S, Gordon I, Kalman JM. Prevalence of sleep-disordered breathing in paroxysmal and persistent atrial fibrillation with normal LV function. Eur Heart J 2008;29:1662–1669.
7. Saleeb-Mousa J, Nathanael D, Coney AM, Kalla M, Brain KL, Holmes AP. Mechanisms of atrial fibrillation in obstructive sleep apnoea. Cells 2023;12:1661.
8. Iwasaki Y-K, Nattel S. Mechanism and management of atrial fibrillation in the setting of obstructive sleep apnea. J Arrhythm 2022;38:709–721.
9. Garrigue S, Bordier P, Jaïs P, et al. Benefit of atrial pacing in sleep apnea syndrome. N Engl J Med 2002;346:404–412.
10. Schotland HM, Stein P, Duntley S. Atrial pacing in sleep apnea syndrome. N Engl J Med 2002;347:445–446.
11. Nalliah CJ, Sanders P, Kottkamp H, et al. Impact of CPAP on the atrial fibrillation substrate in obstructive sleep apnea: reversal of atrial remodeling. JACC Clin Electrophysiol 2022;8:1021–1033.
12. Van Gelder IC, Rienstra M, Bunting KV, et al. 2024 ESC Guidelines for the management of atrial fibrillation developed in collaboration with the European Association for Cardio-Thoracic Surgery (EACTS). Eur Heart J 2024;45:3314–3414.
13. Traaen GM, Aakerøy L, Hunt TE, et al. Effect of continuous positive airway pressure on arrhythmia burden in patients with paroxysmal atrial fibrillation and obstructive sleep apnea: a randomized trial. Am J Respir Crit Care Med 2021;204:573–582.
14. Ng CY, Liu T, Shehata M, Stevens S, Chugh SS, Wang X. Meta-analysis of obstructive sleep apnea as predictor of atrial fibrillation recurrence after catheter ablation. Am J Cardiol 2011;108:47–51.
15. Affas Z, Mathew GM, Cherian T. Continuous positive airway pressure reduces the incidence of atrial fibrillation in obstructive sleep apnea: a meta-analysis. Cureus 2022;14:e28158.
16. Gami AS, Hodge DO, Herges RM, et al. Obstructive sleep apnea, obesity, and the risk of incident atrial fibrillation. J Am Coll Cardiol 2007;49:565–571.
17. Joglar JA, Chung MK, Armbruster AL, et al. 2023 ACC/AHA/ACCP/HRS guideline for the diagnosis and management of atrial fibrillation: a Report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation 2024;149:e1–e156.