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DEVICES

Real-world performance of the atrial fibrillation monitor in patients with a subcutaneous ICD

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Abstract

Introduction: The third-generation subcutaneous implantable cardioverter-defibrillator (S-ICD) (EMBLEM™ A219, Boston Scientific) contains a new diagnostic tool to detect atrial fibrillation (AF) in S-ICD patients, without the use of an intracardiac lead. This is the first study to evaluate the performance of the S-ICD AF monitor (AFM).

Methods: The AFM algorithm analyzes a subcutaneous signal for the presence of AF, similar to the signals collected by implantable and wearable diagnostic devices. The AFM algorithm combines heart rate (HR) scatter analysis with an HR histogram. The algorithm was tested against publicly available electrocardiogram databases (simulated performance). Real-world performance of the algorithm was evaluated by using the S-ICD LATITUDE remote monitoring (RM) database.

Results: The simulated performance of the AFM algorithm resulted in a sensitivity of 95.0%, specificity of 100.0%, and positive predictive value (PPV) of 100.0%. To evaluate the real-world performance of the AFM, 7744 S-ICD devices were followed for up to 30 months by RM, whereof 99.5% had the AFM enabled. A total of 387 AF episodes were randomly chosen for adjudication, resulting in a PPV of 67.7%. The main cause of misclassification was atrial and ventricular ectopy.

Conclusion: The AFM exhibited a very high sensitivity and specificity in a simulated setting, designed to maximize PPV in order to minimize the clinical burden of reviewing falsely detected AF events. The real-world performance of the AFM, enabled in 99.5% of S-ICD patients, is a PPV of 67.7%.

KEYWORDS
algorithm, atrial fibrillation, remote monitoring, S-ICD, subclinical atrial fibrillation, subcutaneous implantable cardioverter-defibrillator

1 | INTRODUCTION

Atrial fibrillation (AF) or subclinical AF (SCAF) is a common comorbidity in patients with an implantable cardioverter-defibrillator (ICD) indication and may occur in up to 40% of patients with an ICD.[1] In ICD

Abbreviations: AF, atrial fibrillation; AFM, AF monitor; ECG, electrocardiogram; PPV, positive predictive value; RM, remote monitoring; SCAF, subclinical atrial fibrillation; S-ECG, subcutaneous electrocardiogram; S-ICD, subcutaneous implantable cardioverter-defibrillator; SR, sinus rhythm

patients without previously diagnosed AF, the incidence of new onset AF may be as high as 20% per year.[2] It is important to identify patients who experience AF as early detection of AF in ICD patients may impact AF treatment, quality of life, stroke prevention, and prevent of inappropriate ICD therapy.[3-5]

During the last 8 years, the subcutaneous ICD (S-ICD) has been proven to be an effective treatment option for the primary and secondary prevention of sudden cardiac death and serves as a class I recommended alternative for the transvenous ICD (TV-ICD) in patients without the need for pacing.[6-8] Until recently, the S-ICD and single-chamber TV-ICD devices did not have the potential to detect AF, as, unlike dual- or triple-chamber devices, there is no lead in the right atrium to detect atrial signals. To facilitate AF detection in a patient population with a single-chamber ICD, new solutions have been created, such as adding R-R interval based AF detection algorithms or proximal dipole rings in single-lead TV-ICDs.[9,10] While simulated performance of AF detection in an ICD without a dedicated atrial lead has been published, real-world performance data are lacking.[10-12] Likewise, in the most recent generation S-ICD (EMBLEM™ A219, Boston Scientific), a new diagnostic algorithm has been added to detect AF without requiring the information from an intracardiac lead, using signals similar to those collected by implantable and wearable patch diagnostic-recording devices. Therefore, the aim of this study was to evaluate the simulated and the real-world performance of the atrial fibrillation monitor (AFM) in the latest generation S-ICD devices.

2 | METHODS

In this study, we describe AFM development and performance testing in simulated setting. Further, we tested the real-world performance of the AFM using S-ICD episodes derived from the US LATITUDE database.

2.1 | AFM algorithm description

The S-ICD's signal is subcutaneous, similar to that sensed by implantable loop recorders and wearable patched-based technology. The proprietary algorithm uses R-R intervals as input as P-wave detection is not available in the S-ICD*. Metrics of R-R interval regularity and the relative width of the R-R interval histogram are derived. The S-ICD AFM algorithm classifies the rhythm as AF when R-R interval regularity is unstable, and the relative width of the R-R interval is wide. The AFM algorithm evaluates whether AF is present for each window of 192 certified R-R intervals and is under continuous operation when the heart rate (HR) is less than 185 beats per minute.[13,14] Forty-four seconds of the first AF episode detected within the last 24 hours will be stored if the cumulative duration of AF exceeds 6 minutes, and if another episode (e.g. VT/VF) of any type is not present. A daily trend of AF burden is recorded and available, providing up to 100 days of history. A programmable AF burden alert can be sent to the physician if the burden exceeds the programmed threshold. The AFM algorithm was designed to not interact with VT/VF detection or discrimination.

* Hereafter, all R-R intervals are assumed to be certified intervals.

2.2 | AFM algorithm development and performance testing

2.2.1 | AFM algorithm development

The thresholds for R-R interval regularity and instantaneous HR (R-R interval histogram) were determined using training datasets. The robustness of the chosen thresholds was evaluated in algorithm performance testing. The process of algorithm development and performance testing is illustrated in Figure 1, and the datasets used are listed in Table 1. Inputs for algorithm development were electrocardiograms (ECGs) used for previous algorithm development and validation (Table 1). The ECG waveforms were derived from either the Cameron Health ECG Signal Library or from spontaneously occurring S-ICD episodes, both of which have been described in detail previously.[14] R-R intervals were obtained by feeding ECG waveforms into a computer model that simulates the sensing of the S-ICD system. The R-R intervals subsequently served as input for the AF algorithm. AF detection algorithm thresholds were chosen to maximize the positive predictive value (PPV) for AF detection using receiver operating characteristics analysis.

2.2.2 | AFM algorithm simulated performance

The datasets used for the algorithm's simulated performance testing consisted of adjudicated rhythms and R-R intervals derived from publicly available ECG databases from PhysioNet and were not used during algorithm development (Figure 1, Table 1).[15] ECG recordings of 10-24 hours in duration were separated into segments, where each segment was adjudicated as AF or non-AF as part of the PhysioNet databases. A segment is a subset of the full data recording, with at least 192 R-R intervals, where the rhythm is consistently AF or non-AF. Aggregate data from a given human subject comprised all true and all false AF segments. These segments were fed into the AF algorithm. Metrics of sensitivity, specificity, and PPV were used to evaluate the algorithm's performance. The algorithm's performance was assessed at the patient level and biased toward detection—if the algorithm detected true AF in at least one of the patient's segments, the patient was defined as a true positive patient. Conversely, the patient was considered a false positive patient if the algorithm falsely detected AF in a segment where no AF was present.

2.3 | AFM algorithm real-world performance

S-ICD AFM algorithm real-world performance was evaluated with the use of the US LATITUDE™ database of 7744 EMBLEM™ A219 S-ICD devices and episodes (Figure 1, Table 1). In August 2018, 39 170

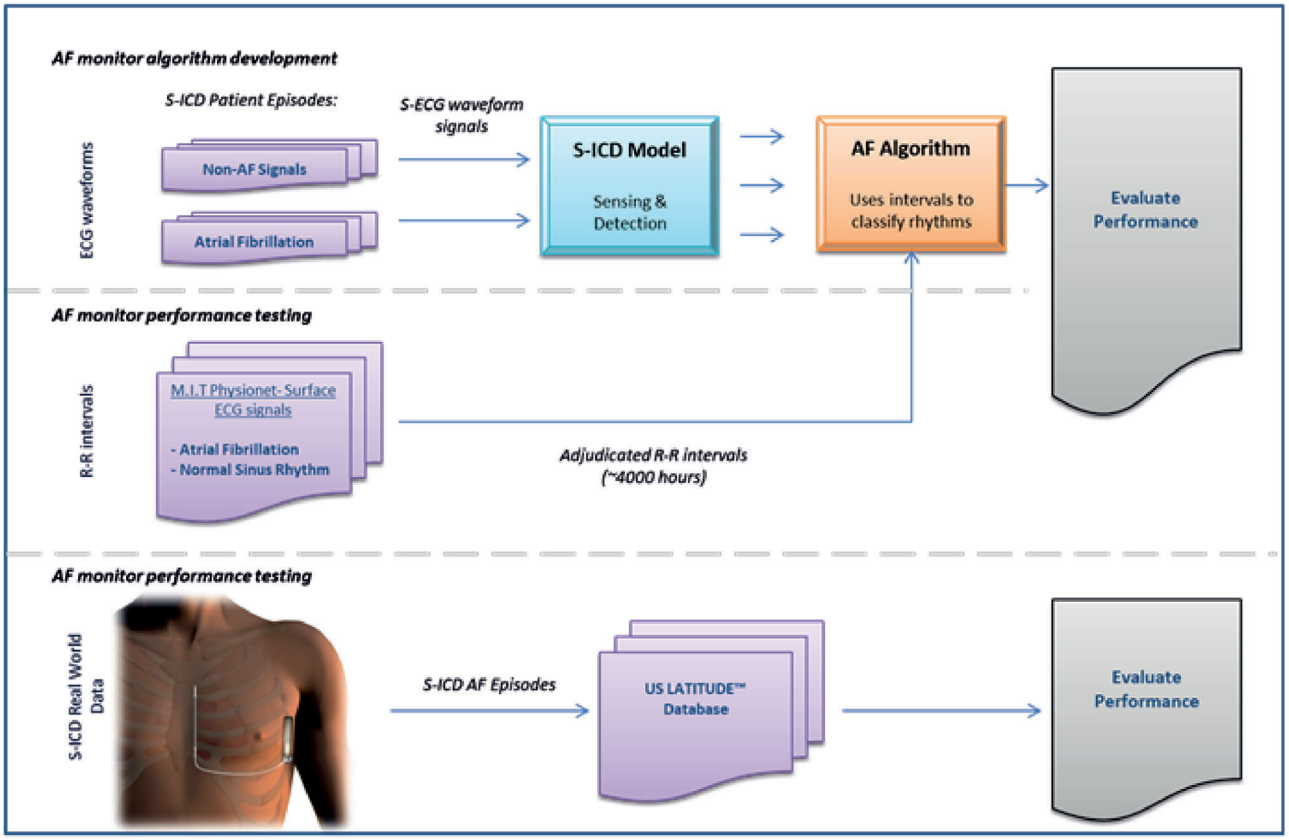

FIGURE 1 Datasets, processing, and metrics used for algorithm development (ECG waveforms), simulated performance testing (R-R intervals), and real-world performance evaluation. ECG waveform data were used for algorithm development and processed by the S-ICD model, both described previously.[14] The resulting intervals were inputs into the AF algorithm. Performance testing data were adjudicated intervals from several databases available from Physionet.[15] AF episodes recorded from implanted S-ICDs are stored in the US LATITUDE™ database. These data were used for evaluating the AFM algorithm real-world performance. Each dataset is described in Table 1. Abbreviations: AF, atrial fibrillation; S-ECG, subcutaneous electrocardiogram; S-ICD, subcutaneous implantable cardioverter-defibrillator [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Overview of the AFM algorithm development, simulated performance, and real-world performance testing datasets

Development or performance testing	Data type	Dataset	No. of patients with AF episodes (%)	No. of patients with non-AF episodes (%)	Total number of patients
Development	Surface ECG, S-ICD vectors	Signals collected by Cameron Health using surface electrodes and device	68 (22%)	235 (78%)	303
Simulation performance	Interval data	Physionet databases*	99 (56%)	79 (44%)	178
Real-world performance	S-ICD episode data	US LATITUDE™ database	NA	NA	387

Abbreviations: AF, atrial fibrillation; NA, not available; S-ICD, subcutaneous implantable cardioverter-defibrillator.
*Four separate Physionet datasets were used: (a) n = 78 from long-term AF (24 -hour recordings)[19]; (b) n = 21 from MIT-BIH AF (10-hour recordings)[15]; (c) n = 54 from Physionet NSR (24-hour recordings),[15]; (d) n = 18 from MIT-NSR (24-hour recordings).[15]

episodes that were classified by the device as AF were available in the database. One episode per patient was downloaded for all patients who had the AFM enabled. A total of 387 episodes were randomly chosen for human adjudication of presence or absence of AF. With this sample size, we could establish the PPV with a 95% confidence interval of 5 and that this confidence interval would suffice. Baseline subcutaneous-electrocardiograms (S-ECGs) obtained during LATITUDE™ connection sessions were also downloaded and referenced when needed during the adjudication process. Episodes were evaluated by five adjudicators not associated with development of the algorithm, trained

TABLE 2 Atrial fibrillation monitor algorithm development and simulated performance testing results

	Development dataset	Simulated performance dataset (pooled analysis)
True AF, n	68	99
Non-AF, n	235	79
Sensitivity, % (95% CI)	79.4 (67.9-88.3)	95.0 (88.6-98.3)
Specificity, % (95% CI)	98.3 (95.7-99.5)	100.0 (95.4-100.0)
Positive predictive value, % (95% CI)	93.1 (83.5-97.3)	100.0*
Negative predictive value, % (95% CI)	94.3 (91.2-96.3)	94.1 (87.1-97.4)
AF prevalence, %	22.4	55.6

Abbreviations: AF, atrial fibrillation; CI, confidence interval.
*95% CI cannot be calculated.

in S-ECG morphology recognition and with a median of 33 years of experience in cardiac electrophysiology (range: 18-45 years). Each episode was reviewed by one adjudicator on an internal viewer created in MATLAB (The MathWorks, Inc., Natick, MA). The adjudicator could adjust the amplitude and temporal resolution of the stored episode if deemed required.

The S-ICD AFM performance was evaluated by its PPV. Episode sensitivity, specificity, and negative predictive value could not be calculated from this dataset as the dataset does not allow quantification of undetected true AF episodes nor true negative episodes. PPV was calculated from reported true positives, false positives, and prior probability/prevalence.[16,17]

3 | RESULTS

3.1 | AFM algorithm development and performance testing

3.1.1 | AFM algorithm development

A total of 303 ECGs (68 AF, 235 non-AF) with recording durations of 2-10 minutes were used for the development of the S-ICD AFM algorithm (Table 2). The 235 non-AF ECGs contained sinus rhythm at rest or during exercise, including 133 episodes adjudicated internally as inappropriate due to cardiac oversensing. Table 2 shows the overall development and the testing results of the AFM. Fifty-four of the 68 true AF episodes were detected as AF by the AFM with a sensitivity of 79.4% and specificity of 98.3%. The PPV indicating the proportion of ECGs with true AF that were detected as AF by the AFM was 93.1%.

3.1.2 | AFM algorithm simulated performance

To test the simulated performance of the AFM algorithm, we used four different independent datasets of 10-24 hours recordings available on Physionet (Table 1).[15,18,19] In total, the simulated performance testing set consisted of 178 ECGs, including 99 AF ECGs and 79 non-AF ECGs, resulting in an AF prevalence in this dataset of 55.6%. The algorithm correctly excluded AF in all 79 non-AF patients (PPV 100%, specificity 100.0%; Table 2). Conversely, the AF algorithm correctly identified 94 of the 99 AF patients (sensitivity 95.0%). AF was not detected when AF episodes were short (<8 minutes; n = 3) or when the ventricular response was stable (n = 2).

3.2 | AF algorithm real-world performance

The real-world performance of the AFM was determined by evaluating the data from 7744 EMBLEM™ A219 devices that were followed up for a duration up to 30 months with the use of the US LATITUDE™ database. The AFM was enabled in 7707 (99.5%) of the 7744 patients with an S-ICD EMBLEM™ A219 device (Figure 2). Of the 7707 patients with the AFM switched on, 2004 patients (26%) had ≥1 stored episodes of possible AF, of whom 462 (6%) of patients had one stored episode and 1542 (20%) had >1 stored possible AF episodes (Figure 2). Figure 3 shows the distribution of stored AF episodes by the AFM per patient. In August 2018, 39 170 possible AF episodes were available in the US LATITUDE™ database, from which 387 randomly chosen episodes from 387 patients were adjudicated by the human reviewers as AF or non-AF. The overall performance of the AFM in this real-world dataset resulted in a PPV of 67.7%, indicating the proportion of detected AF episodes that were concordant with the adjudicated AF (n = 262). A total of 125 (32.3%) stored AF episodes were misclassified as AF by the AFM. Table 3 shows the PPV and AF incidence relation of the S-ICD AFM as well as the causes of misclassifications. Atrial and ventricular ectopy were the greatest source of false positive AF at almost 70% of misclassified cases. Noise and bad signals resulted in almost 18% of misclassifications. Oversensing, including T-wave oversensing, was the source of misclassification in only 6.4% of cases.

4 | DISCUSSION

4.1 | Main findings

This study is the first to report both the simulated and real-life performance of a novel monitoring algorithm to detect AF integrated

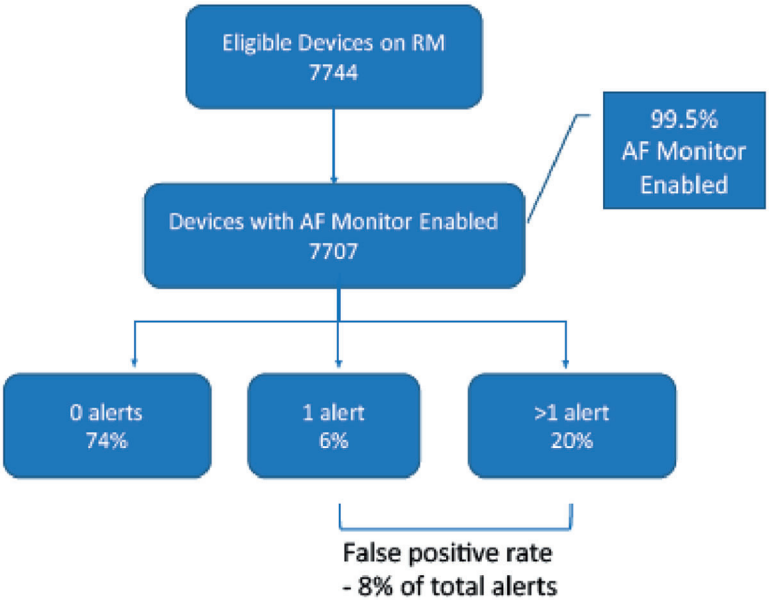

FIGURE 2 Alert rate of monitored AF episodes by the AFM observed in the US LATITUDE remote monitor database. Twenty-six percent of the 7707 patients had one or more stored AF alert. The PPV of 67.7% results in an estimated false positive rate of AF alerts of 8%, assuming that the 74% of patients with no stored AF alert are true negatives. Abbreviations: AF, atrial fibrillation; RM, remote monitoring [Color figure can be viewed at wileyonlinelibrary.com]

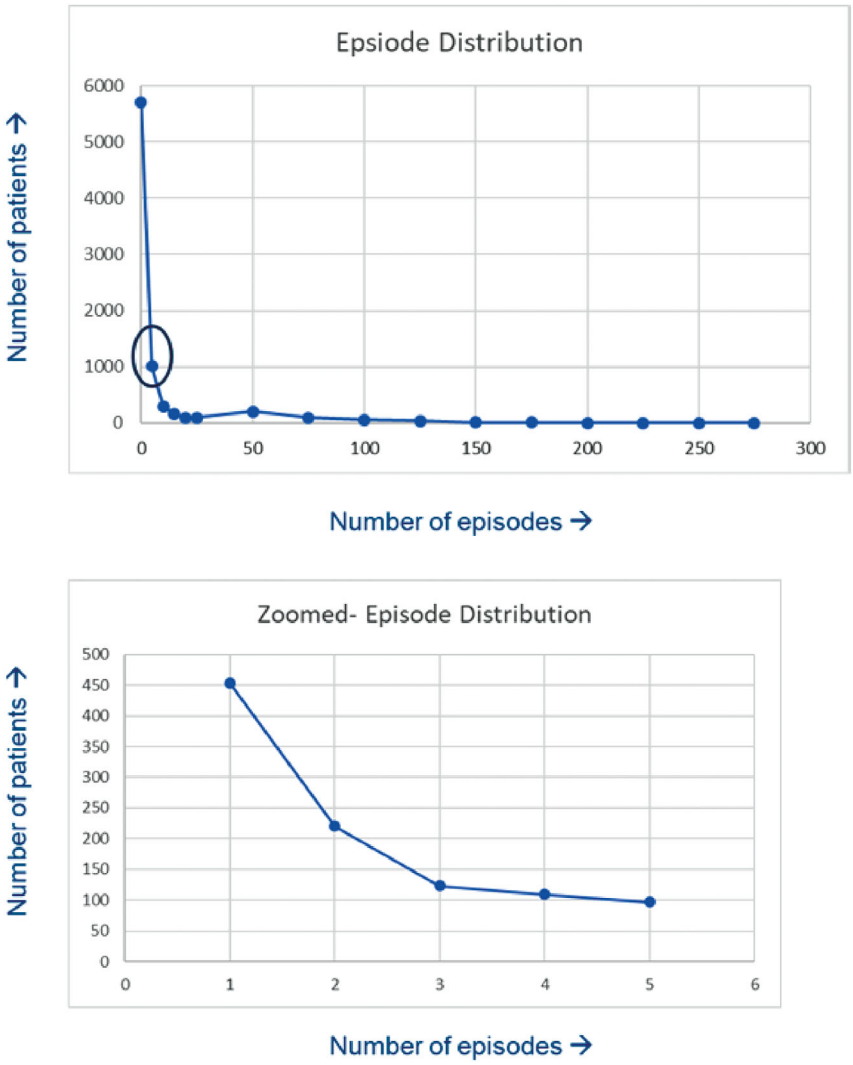

FIGURE 3 AF episode distribution across patients with 1 or more AF episodes monitored by the AFM. Top: total episode distribution. Bottom: zoomed episode distribution. Abbreviations: AF, atrial fibrillation; AFM, atrial fibrillation monitor [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 S-ICD AFM real-world performance of random selected events of the US LATITUDE database and cause of misclassification

AFM real-world performance	
Stored AF episodes, n	387
AF incidence, %*	15-17
PPV, % (95% CI)	67.7 (62.8-72.3)
Cause of misclassification	
Ectopy, %	69.6
Oversensing + TWOS, %	6.4
Noise + bad signals, %	17.6
Undersensing, %	2.4
Other arrhythmias, %	1.6

*Estimated by previous publications reporting the incidence of AF in S-ICD cohorts.[7,29]

Abbreviations: AF, atrial fibrillation; AFM, atrial fibrillation monitor; CI, confidence interval; PPV, positive predictive value; TWOS, T-wave oversensing.

in the third generation of the S-ICD (EMBLEM™, A219). The purpose of the AFM is to early detect symptomatic AF or SCAF in S-ICD patients to potentially prevent AF-related complications, timely initiate anticoagulation therapy guided by the CHA_2DS_2VASc score in patients with new onset AF, and to manage AF in patients with a history of AF.

The main findings of this study are that the development and simulated performance of the AFM demonstrated that the AFM has a promising high sensitivity, specificity, and PPV. The real-world PPV of the AFM algorithm is 67.7%, and the algorithm remained enabled in almost all of the S-ICD patients in the United States with remote monitoring.

4.2 | AF monitor simulation and real-world performance

The high PPV of 100.0% for the AFM during simulated performance testing shows that all the episodes adjudicated by the AFM as AF were concordant with physician adjudicated AF. The AFM correctly excluded AF in 79 of the 79 patients without AF (specificity 100%) and correctly identified 94 of the 99 AF patients (sensitivity 95.0%), in a cohort with a true AF prevalence of 56%. Real-world performance testing of the AFM, using remote monitor S-ECGs of patients implanted with an EMBLEM™ A219 S-ICD, showed a PPV of 67.7%. The fact that the S-ICD currently does not detect P-waves in real time in subcutaneous signals, which could help to discriminate AF from other rhythms, may impede real-world performance relative to ICDs with atrial leads.[20] Future algorithms using deep learning models may overcome the disadvantage of lacking this information and improve the real-world performance of S-ICD AFM and other subcutaneous insertable cardiac monitors (ICMs) by reducing the false positive rate caused by other irregular rhythms, such as frequent atrial or ventricular ectopy.[21]

4.3 | Comparison of AF detection by the AFM with single-chamber TV-ICDs

In line with the S-ICD AFM, other TV-ICD algorithms have been developed with the aim to enable physicians to monitor AF in patients with a single-chamber ICD indication. The VISIA AF™, Medtronic is a CE-marked and FDA-approved transvenous single-chamber ICD with integrated AF monitor, consisting of a dedicated AF detection algorithm previously developed for use in the Medtronic Reveal XT ICM.[10,22] Simulated performance of the VISIA AF™ shows promising results with a similar high sensitivity and specificity comparable to the simulated performance of the S-ICD AFM.[10] Real-world data and thereby real-world performance of the VISIA AF are lacking so far. The Medtronic LINQ™ ICM includes the same R-R interval based algorithm as the VISIA AF™ and also uses subcutaneous signals for the detection of AF similar to the S-ICD AFM.[23] The Medtronic Reveal LINQ™ has a reported comparable real-world performance as the S-ICD AFM, with a PPV of 25.7% in the cryptogenic stroke population with an AF prevalence of 8% and a PPV of 72.5% in a patient population with an AF prevalence of 47.1%.[23] The sources of misclassification with AF detection in the Reveal LINQ™ appear similar to that for the S-ICD AFM, with the possible exceptions of the S-ICD reporting false AF due to noise and bad signals more frequently than the Reveal LINQ™ (17.6% vs 10%), and the Reveal LINQ™ having a higher proportion of false AF due to cardiac oversensing (22% vs 6.4%).[24]

The Biotronik DX™ single-chamber ICD contains an atrial sensing dipole on the ventricular lead, which provides continuous atrial monitoring and thereby the option to detect AF or other atrial arrhythmias.[9] With the exception of a small sized study, large real-world performance data are not yet available.[12] The observational MATRIX registry (NCT01174357) and ongoing randomized Dx-AF study should provide reliable data on the real-world performance of this integrated system to diagnose AF in single-chamber TV-ICD patients.[11,25] To the best of our knowledge, this is the first study presenting large real-world performance data of an AF detection monitor integrated in an ICD without the use of an atrial lead.

The existing S-ICD AFM algorithm is based solely on R-R intervals. Previous analyses based on Holter and ECG have shown that an ICM-based algorithm employing signal morphology and rhythm identification in addition to R-R interval analysis shows improved PPV and false positive rates with minimal impact to sensitivity.[26,27] It is anticipated that these algorithmic improvements can be adapted for the S-ICD for future generation devices, analogous to the S-ICD algorithmic advances that have been observed for mitigating T-wave oversensing.[14,28]

4.4 | Clinical implications

The AFM has been designed to detect AF or SCAF in the S-ICD patient population. Our results show that the AFM is enabled in almost 100% of patients with an EMBLEM A219 device monitored by US LATITUDE

and thereby likely used by physicians to assist in monitoring of (SC)AF. With an incidence of ≥1 episodes of AF of 17.6% (corrected for the estimated false positive rate of 8% of total AF episodes based on the PPV of 67.7% of the AFM and the 26% alert rate), our results are in line with previous published data reporting an AF incidence of 15-17% in the S-ICD population.[7,29]

4.4.1 | Device detected subclinical atrial fibrillation

By enabling the AFM, (SC)AF detection in S-ICD patients may be improved as already established or new-onset (SC)AF may be more appropriately managed to avoid AF-related complications. Episodes of SCAF are defined as newly detected, asymptomatic, episodes of AF detected by ICMs like loop recorders, pacemakers, or ICDs.[30] A recently published comparison study reported a higher incidence of (SC)AF detection in patients receiving a single-chamber ICD capable of detecting AF/AT than in patients with a conventional ICD.[31] In this study, the diagnosis of these arrhythmias resulted in clinical interventions as prescription of OAC therapy in most cases.[31] However, the implication of SCAF detected by this novel device remains incompletely understood. Similarly, whether or not all patients with detected SCAF require OAC therapy remains controversial. A recent meta-analysis showed that patients with SCAF have a 2.4-fold higher stroke risk compared to patients without SCAF.[32] A subanalysis of the ASSERT study reports a correlation that stroke mainly occurs in patients with SCAF lasting longer than 24 hours.[33] Whether patients with SCAF are at the same stroke risk as patients with clinical AF, and whether the same anticoagulation indications apply, is the subject of two large ongoing clinical trials.[34,35] With the reported real-world S-ICD AFM data, in routine clinical practice, physicians are advised to accurately determine AFM outcome per patients and/or consider additional monitoring in case of detected (SC)AF by the S-ICD AFM, before prescribing OAC in patients at high risk for stroke.

4.4.2 | Value of false positives

False AFM episodes were found to be due to oversensing, undersensing, ectopy, or other arrhythmias (see Table 3). These episodes could be leveraged as alerts: ectopy and slow VTs may be leveraged as clinically relevant alerts to the physician to intervene with changes in device or medication therapy, undersensing could alert the physician to corrective action to prevent arrhythmia undersensing, and cardiac or noncardiac oversensing observed in a false AFM episode could result in corrective actions to prevent inappropriate shock due to oversensing.

4.4.3 | Inappropriate shocks

Identifying patients with (SC)AF may indirectly reduce the number of IAS, as physicians can initiate and manage appropriate AF therapy. Currently, the AFM is not designed to interact with other S-ICD integrated algorithms and filters while almost 25% of AFM false positive episodes are due to S-ICD cardiac and noncardiac oversensing. Future cooperation between the AFM and the S-ICD algorithms may directly reduce the number of IAS.

4.5 | Study limitations

This analysis has several limitations. (a) For simulated performance dataset, we used ECG and Holter recordings only. Holter monitors and ECG machines use prespecified AF detection algorithms that may have selected only the most evident AF episodes, leading to more unmistakable AF episodes and thus a higher performance of the AFM. (b) S-ICD signal morphology was not externally validated by surface ECG and we could not calculate the sensitivity of the real-world performance of the AFM and could only estimate the false positive rate, as the number of AF episodes and patients with no record of AF in the real-world performance cohort were not available as no real-time Holter monitors were used for data collection. (c) The AFM is not optimized for the detection of the burden of (SC)AF, which may be relevant for clinical decision making, as stroke risk appears to correlate with the duration of AF. In addition, duration of AF may increase the incremental likelihood of catching AF. (d) The AFM only detects episodes of AF and not episodes of atrial flutter or atrial tachycardia. (e) Real-world adjudication was performed with each episode evaluated by one reviewer. (f) We did not have programming information (e.g., SMART PASS) along with the AF episodes detected by the AFM. Therefore, we do not know if misclassification of AF by T-wave oversensing occurred with SMART PASS enabled or disabled. (g) The lack of direct detection of atrial signals may have increased the false positive episodes and may have missed other atrial arrhythmias that may require further monitoring and OAC therapy.

5 | CONCLUSION

The S-ICD AFM detection algorithm exhibited a high sensitivity and specificity during development and simulated performance testing. Real-world performance of the S-ICD AFM was less accurate than in the development and simulation cohort, but similar to the real-world performance of other comparable devices.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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REFERENCES

1. Kramer DB, Kennedy KF, Noseworthy PA, et al. Characteristics and outcomes of patients receiving new and replacement implantable cardioverter-defibrillators: results from the NCDR. *Circ Cardiovasc Qual Outcomes*. 2013;6:488-497.
2. Zweibel S, Cronin EM, Schloss EJ, et al. Estimating the incidence of atrial fibrillation in single-chamber implantable cardioverter defibrillator patients. *Pacing Clin Electrophysiol*. 2019;42:132-138.
3. Camm AJ, Corbucci G, Padeletti L. Usefulness of continuous electrocardiographic monitoring for atrial fibrillation. *Am J Cardiol*. 2012;110:270-276.
4. Daubert JP, Zareba W, Cannom DS, et al. Inappropriate implantable cardioverter-defibrillator shocks in MADIT II: frequency, mechanisms, predictors, and survival impact. *J Am Coll Cardiol*. 2008;51:1357-1365.
5. Olde Nordkamp LRA, Brouwer TF, Barr C, et al. Inappropriate shocks in the subcutaneous ICD: incidence, predictors and management. *Int J Cardiol*. 2015;195:126-133.
6. Brouwer TF, Knops RE, Kutyifa V, et al. Propensity score matched comparison of subcutaneous and transvenous implantable cardioverter-defibrillator therapy in the SIMPLE and EFFORTLESS studies. *Europace*. 2018;20:f240-f248.
7. Weiss R, Knight BP, Gold MR, et al. Safety and efficacy of a totally subcutaneous implantable-cardioverter defibrillator. *Circulation*. 2013;128:944-953.
8. Priori SG, Blomstrom-Lundqvist C, Mazzanti A, et al. ESC guidelines for the management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: the task force for the management of patients with ventricular arrhythmias and the prevention of sudden cardiac death of the European Society of Cardiology (ESC). Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC). *Eur Heart J*. 2015;36:2793-2867.
9. Safak E, Schmitz D, Konorza T, Wende C, De Ros JO, Schirdewan A. Clinical efficacy and safety of an implantable cardioverter-defibrillator lead with a floating atrial sensing dipole. *Pacing Clin Electrophysiol*. 2013;36:952-962.
10. Deshmukh A, Brown ML, Higgins E, et al. Performance of atrial fibrillation detection in a new single-chamber ICD. *Pacing Clin Electrophysiol*. 2016;39:1031-1037.
11. Worden NE, Alqasrawi M, Mazur A. Long-term stability and clinical utility of amplified atrial electrograms in a single-lead ICD system with floating atrial electrodes. *Pacing Clin Electrophysiol*. 2016;39:1327-1334.
12. Iori M, Giacopelli D, Quartieri F, Bottoni N, Manari A. Implantable cardioverter defibrillator system with floating atrial sensing dipole: a single-center experience. *Pacing Clin Electrophysiol*. 2014;37:1265-1273.
13. Sanghera R, Sanders R, Husby M, Bentsen JG. Development of the subcutaneous implantable cardioverter-defibrillator for reducing sudden cardiac death. *Ann N Y Acad Sci*. 2014;1329:1-17.
14. Brisben AJ, Burke MC, Knight BP, et al. A new algorithm to reduce inappropriate therapy in the S-ICD system. *J Cardiovasc Electrophysiol*. 2015;26:417-423.
15. Goldberger AL, Amaral LA, Glass L, et al. PhysioBank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiologic signals. *Circulation*. 2000;101:E215-E220.
16. Sergeant E, Perkins N. *Epidemiology for Field Veterinarians: An Introduction*. Oxfordshire UK: CAB International; 2015.
17. Thrusfield MV. *Veterinary Epidemiology*. Oxford, UK: Blackwell Science; 1995.
18. Moody GB, Mark RG. A new method for detecting atrial fibrillation using R-R intervals. *Comput Cardiol*. 1983;10:227-230.
19. Petrutiu S, Sahakian AV, Swiryn S. Abrupt changes in fibrillatory wave characteristics at the termination of paroxysmal atrial fibrillation in humans. *Europace*. 2007;9:466-470.
20. Kaufman ES, Israel CW, Nair GM, et al. Positive predictive value of device-detected atrial high-rate episodes at different rates and durations: an analysis from ASSERT. *Heart Rhythm*. 2012;9:1241-1246.
21. Richards M, Perschbacher D, Hermann K, Lu C, Mahajan D. Artificial neural network algorithm improves atrial fibrillation detection. *Heart Rhythm*. 2019:S-AB24-03.
22. Sarkar S, Ritscher D, Mehra R. A detector for a chronic implantable atrial tachyarrhythmia monitor. *IEEE Trans Biomed Eng*. 2008;55:1219-1224.
23. Mittal S, Rogers J, Sarkar S, et al. Real-world performance of an enhanced atrial fibrillation detection algorithm in an insertable cardiac monitor. *Heart Rhythm*. 2016;13:1624-1630.
24. Maddox S, Hoskins M, Lloyd M, et al. High false positive rates of atrial fibrillation detection among stroke patients who receive medtronic implantable loop recorders. *Stroke*. 2016;47:A206.
25. KG BSC. Management and detection of atrial tachyarrhythmias in patients implanted with BIOTRONIK DX systems (MATRIX). 2013. https://clinicaltrials.gov/ct2/show/NCT01774357. Accessed January 24, 2013.
26. Richards M, Perschbacher D, Herrmann K, Saha S, Siejko KS. A novel algorithm to improve positive predictive value in atrial fibrillation detection in implantable cardiac monitors. *Heart Rhythm*. 2018;PO01-PO037.
27. Mittal S, Saha S, Perschbacher D, Siejko KS. Improved AF rhythm discriminaton with an implantable cardiac monitor using QRS morphology. *Heart Rhythm*. 2019:PO03-PO079.
28. Theuns DAMJ, Brouwer TF, Jones PW, et al. Prospective blinded evaluation of a novel sensing methodology designed to reduce inappropriate shocks by the subcutaneous implantable cardioverter-defibrillator. *Heart Rhythm*. 2018;15:1515-1522.
29. Lambiase PD, Barr C, Theuns DAMJ, et al. Worldwide experience with a totally subcutaneous implantable defibrillator: early results from the EFFORTLESS S-ICD Registry. *Eur Heart J*. 2014;35:1657-1665
30. Gorenek BC, Bax J, Boriani G, et al. Device-detected subclinical atrial tachyarrhythmias: definition, implications and management-an European Heart Rhythm Association (EHRA) consensus document, endorsed by Heart Rhythm Society (HRS), Asia Pacific Heart Rhythm Society (APHRS) and Sociedad Latinoamericana de Estimulacion Cardiaca y Electrofisiologia (SOLEACE). *Europace*. 2017;19:1556-1578.
31. Biffi M, Iori M, De Maria E, et al. The role of atrial sensing for new-onset atrial arrhythmias diagnosis and management in single-chamber implantable cardioverter-defibrillator recipients: results from the THINGS registry. *J Cardiovasc Electrophysiol*. 2020;31:846-853.

32. Mahajan R, Perera T, Elliott AD, et al. Subclinical device-detected atrial fibrillation and stroke risk: a systematic review and meta-analysis. *Eur Heart J*. 2018;39:1407-1415.
33. Van Gelder IC, Healey JS, Crijns HJGM, et al. Duration of device-detected subclinical atrial fibrillation and occurrence of stroke in ASSERT. *Eur Heart J*. 2017;38:1339-1344.
34. Lopes RD, Alings M, Connolly SJ, et al. Rationale and design of the Apixaban for the Reduction of Thrombo-Embolism in Patients With Device-Detected Sub-Clinical Atrial Fibrillation (ARTESiA) trial. *Am Heart J*. 2017;189:137-145.
35. Kirchhof P, Blank BF, Calvert M, et al. Probing oral anticoagulation in patients with atrial high rate episodes: rationale and design of the Non-vitamin K antagonist Oral anticoagulants in patients with Atrial High rate episodes (NOAH-AFNET 6) trial. *Am Heart J*. 2017;190:12-18.

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