

Electrogram morphology discriminators in implantable cardioverter defibrillators: A comparative evaluation

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Abstract

Background: Morphology algorithms are currently recommended as a standalone discriminator in single-chamber implantable cardioverter defibrillators (ICDs). However, these proprietary algorithms differ in both design and nominal programming.

Objective: To compare three different algorithms with nominal versus advanced programming in their ability to discriminate between ventricular (VT) and supra-ventricular tachycardia (SVT).

Methods: In nine European centers, VT and SVTs were collected from Abbott, Boston Scientific, and Medtronic dual- and triple-chamber ICDs via their respective remote monitoring portals. Percentage morphology matches were recorded for selected episodes which were classified as VT or SVT by means of atrioventricular comparison. The sensitivity and related specificity of each manufacturer discriminator was determined at various values of template match percentage from receiving operating characteristics (ROC) curve analysis.

Results: A total of 534 episodes were retained for the analysis. In ROC analyses, Abbott Far Field MD (area under the curve [AUC]: 0.91; $P < .001$) and Boston Scientific RhythmID (AUC: 0.95; $P < .001$) show higher AUC than Medtronic Wavelet (AUC: 0.81; $P < .001$) when tested for their ability to discriminate VT from SVT. At nominal % match threshold all devices provided high sensitivity in VT identification, (91%, 100%, and 90%, respectively, for Abbott, Boston Scientific, and Medtronic) but contrasted specificities in SVT discrimination (85%, 41%, and 62%, respectively). Abbott and Medtronic's nominal thresholds were similar to the optimal thresholds. Optimization of the % match threshold improved the Boston Scientific specificity to 79% without compromising the sensitivity.

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Conclusion: Proprietary morphology discriminators show important differences in their ability to discriminate SVT. How much this impact the overall discrimination process remains to be investigated.

KEYWORDS

algorithm, arrhythmia, discrimination, implantable cardioverter defibrillator, morphology

1 | INTRODUCTION

Inappropriate shocks represent the most common adverse event in implantable cardioverter-defibrillator (ICD) recipients and remain a major concern in view of their incidence and consequences.¹ They reduce the quality of life and are even associated with increased mortality. The 2015 HRS/EHRA/APHRS/SOLAECE consensus statement on optimal ICD programming provides recommendations stressing the importance of using long detection intervals, high rate therapy, and arrhythmia discrimination.² These strategies aim to reduce inappropriate device interventions for supraventricular tachycardia (SVT) while maintaining a high level of ventricular tachycardia (VT) detection. Suggested programming settings for each manufacturer are proposed in an addendum of the consensus statement. This innovative and practical document offers rate detection thresholds and duration suggestions for each ICD model. Arrhythmia discrimination is encouraged and is essentially based on a comparison of morphology, as a standalone discriminator in single-chamber devices, and as part of the dual-chamber discrimination algorithm. Such generic recommendations are based on the premise that proprietary morphology algorithms performed equally well in their nominal settings. In this multicenter study, we hypothesized that technical specificities and changes in the programming would impact discrimination accuracy. We assessed and compared the morphology discriminators of three manufacturers and proposed optimized settings whenever possible.

2 | METHODS

2.1 | Principles of discrimination based on morphology

Morphology discrimination is designed to withhold inappropriate detection during episodes of conducted SVT. The algorithm compares the patient's current ventricular electrogram (EGM) with a stored template acquired during intrinsic ventricular conduction. VT detection is withheld if the current morphology sufficiently matches the template. A match is assumed when predefined a level of similarity is reached between the morphology during tachycardia and the stored template. The percentage threshold can be programmed, the higher the value the higher chance for a rhythm to be classified as VT. If a minimum of X (number of matches) over Y (detection window) complexes sufficiently match the stored template, the device withholds detection. Technical details are summarized in Table 1. In the

present study, we assessed and compared the Abbott Far Field MD, the Boston Scientific RhythmID, and the Medtronic Wavelet morphology discriminators.

2.2 | Data collection

We have retrospectively collected arrhythmia episodes through remote monitoring in seven French, one Dutch, and one Italian center. All patients gave written, informed consent for analysis of the data provided from remote monitoring. Inclusion criteria were tachycardia episodes from nondependent patients implanted with a dual-chamber (<20% ventricular pacing) or cardiac resynchronization therapy (CRT) defibrillator (ventricular dependency excluded from medical records) with a functional atrial lead. Single-chamber defibrillators were excluded since we used the atrial EGM for identification of the rhythm. The morphology algorithm could be programmed either "On" or "Monitor." The EGM morphology source was to be programmed Coil to Can. All devices had template autoupdate function except Medtronic CRT defibrillators for which the template was acquired manually. For Abbott and Boston Scientific CRT defibrillators, the "hysteresis" and "active method" were to be programmed to favor intrinsic activity.

All stored episodes of tachycardia less than 250 bpm (treated or not) were analyzed regardless of the final device diagnosis (VT or SVT). An episode was included when a manual diagnosis of either monomorphic VT or SVT could be made with near certainty as follows:

- **VT definition.** Ventricular intervals are shorter than atrial intervals. For each patient, up to 10 VT episodes were included which had to differ either in rate (>10 bpm) or in time of occurrence (>24 hours).
- **1:1 SVT definition.** Similar atrial and ventricular rates with PR association. The ventricular rhythm is driven by the atrial activity evidenced by either (a) beginning with an atrial premature event, or (b) anticipated atrial events induce anticipated ventricular events, or (c) premature ventricular complexes do not influence the atrial rhythm. Up to five episodes were included which had to differ either in rate (>10 bpm) or in time of occurrence (>24 hours).
- **Atrial fibrillation definition.** Atrial activity is compatible with atrial fibrillation and obvious irregular ventricular rhythm. Up to five episodes were included which had to differ either in rate (>10 bpm) or in time of occurrence (>24 hours).

Each episode was reviewed by three trained electrophysiologists which all had to agree on the diagnosis for the episode to be included.

TABLE 1 Technical data and settings of the three morphology discriminators

	Vector	% Threshold	Nb Matches	Windows size	Auto Update	Hysteresis	Manual
Abbott Far Field MD	RV Coil/Can RV Tip/Can	90 [30-95]	3 [3-20]	10 [6-20]	3h-30d.	Yes	Yes
Boston Sc. RhythmID	RV Coil/Can	94 [70-96]	3	10	2h.	Yes	Yes
Medtronic Wavelet	Can/RV coil Can /RV ring RVtip/ RV coil RVtip/RVring Can/ SVC RV coil/SVC	70 [40-97]	3	8	If Quality Check fails	No	Yes

The last three columns refer to the morphology reference template. Abbott Far Field MD and Boston Scientific RhythmID periodically update the reference template. Medtronic Wavelet acquires a new template when less than 70 of the last 100 tested ventricular EGMs match the reference. This quality check analyses one EGM every 17 min. Hysteresis referred to the ability to temporarily adjust the atrioventricular delay or the basic rate to favors intrinsic ventricular EGMs. In gray: nominal settings.

Every questionable episode was discarded. SVT tracings from Medtronic displaying EGM truncation were rejected.³ The same number of episodes was required for each manufacturer, with a sample size estimated from Bujang and Adnan tables, assuming than the VT prevalence was 60% and the expected sensitivity was 80% with a power of at least 80% and a *P* value of at least .05.⁴⁻⁶ For each episode, the percentages match before the final ICD diagnosis of the arrhythmia was collected (last 8 for Medtronic, last 10 for Boston Scientific, and up to 20 for Abbott devices).

2.3 | Statistical analysis

Continuous variables were expressed as mean $\pm$ standard deviation and compared using either the one-way analysis of variance or the Kruskal-Wallis test, as appropriate. Categorical variables were expressed as absolute numbers (%) and compared using Pearson's χ^2 test or Fisher's exact test. Sensitivity was defined as the number of VT episodes correctly classified by the morphology discriminator divided by the total number of VT episodes labeled by the physicians. Specificity was defined as the number of SVTs classified by the morphology discriminator divided by the total number of SVTs labeled by the physicians. Because the patients contributed to an unequal number of episodes, a generalized linear mixed model (GLMM) was constructed and fitted to the repeated measurements as described by Liu and Wu.⁷ From this model were computed the area under a receiving operating characteristics (ROC) curve for repeated measures. Sensitivity and related specificity of each manufacturer discriminator was determined at various values of percentage match thresholds (ie, the programmable threshold above which an EGM wanalysis. A summary of the ROC construction is presented in Figure 1. A sensitivity analysis was conducted by introducing the ratio of

dual-chamber/CRT defibrillator as a covariate into the GLMM. ROC curves of Figure 1 were constructed using a fixed nominal matches/detection window ratio. Statistical significance was assumed at *P* value less than .05. Statistical analyses were performed using SPSS software, version 18.0 (SPSS Inc, Chicago, IL) and the Stata software (version 15, StataCorp, College Station, TX).

2.4 | Algorithms performances

Sensitivity and specificity were extracted from the ROC curves at nominal percentage match thresholds for the different algorithms. These values were compared to three alternative match thresholds defined as (a) the threshold associated with 90% sensitivity, (b) the threshold associated with 90% specificity, (c) the optimal threshold corresponding to the highest number of correctly classified cases. A lower bound of 75% sensitivity (allowing 25% VTs being missed) and 75% specificity (25% of inappropriate therapies, ie, applied VT therapies on SVT episodes) were considered as minimal acceptable cut-offs and were required for each configuration. A specific analysis was conducted for Abbott, looking at the effect of changing the number of required matches over a variable detection window. The effect of the template amplitude was investigated in the Medtronic group.

3 | RESULTS

3.1 | Arrhythmia dataset and characteristics

A total of 185 ICDs (123 dual-chamber ICDs and 62 CRT defibrillators) provided 534 episodes divided in 330 VT and 204 SVT

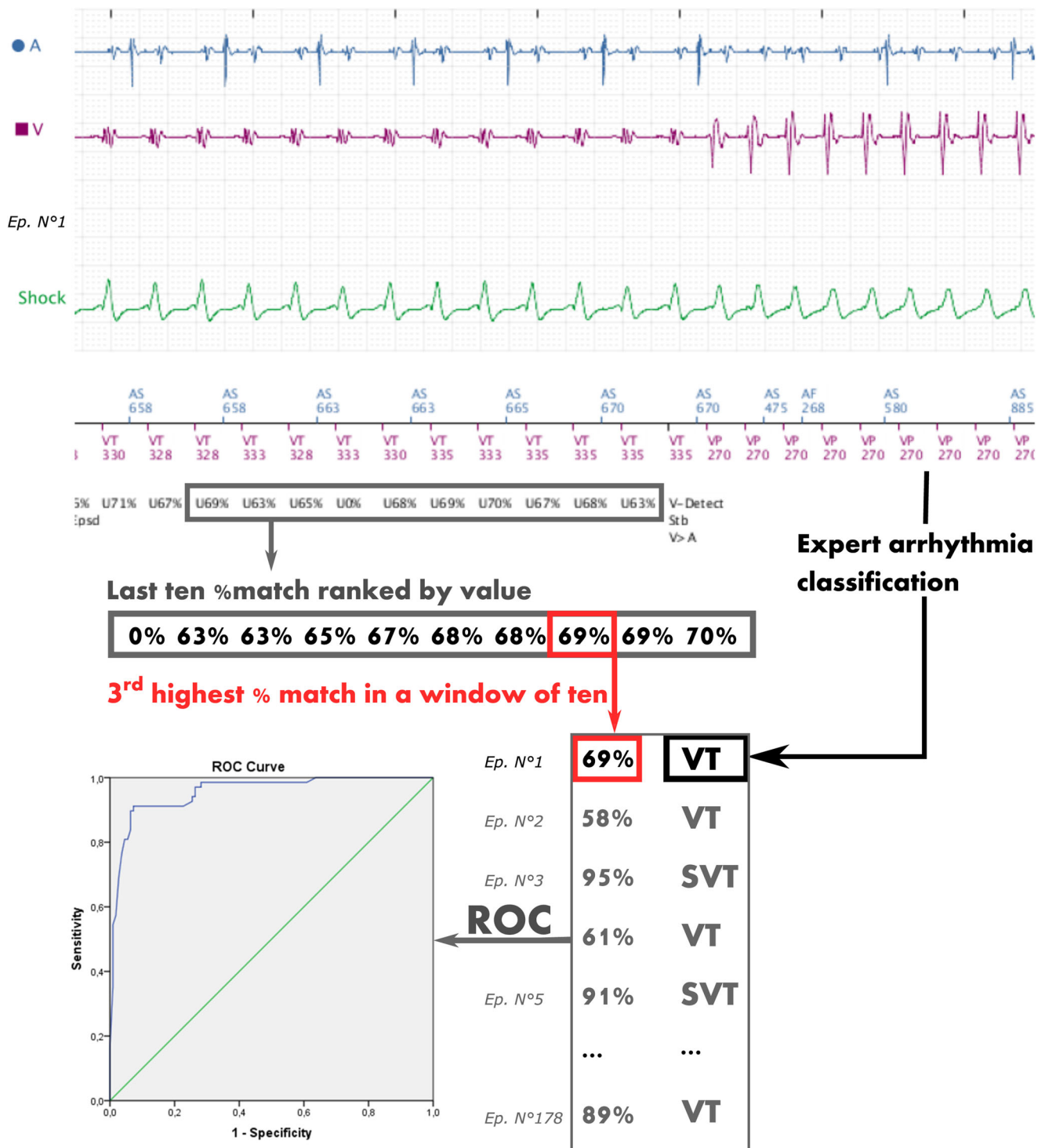


FIGURE 1 Schematic representation of how the ROC curve was acquired for the Boston Scientific RhythmID algorithm. Shown episode (*Ep N°1*) is classified as VT by the expert committee since there are more ventricular than atrial events. For each of the 178 episodes, the third-highest in the last 10% match score is kept for the analysis in accordance with the 3 of 10 nominal ratios (number of matches/morphology window size). The third highest match score gives the lowest threshold under which the episode would have been classified SVT, or above which it would have been classified VT. The ROC curve is constructed with 178 match scores coded as either VT or SVT, from the whole Boston Scientific population. ROC, receiving operating characteristics; SVT, supraventricular tachycardia; VT, ventricular tachycardia

equally distributed among the three manufacturers (110 VT/68 SVT). The VT and SVT cycle lengths were similar among the three groups. Among the SVT, the Abbott and Boston Scientific groups showed a near equal distribution between 1:1 tachycardia and atrial fibrillation.

whereas atrial fibrillation was less common in the Medtronic group (30%, $P < .001$). While for Abbott most ICDs were CRT devices (66%), for Boston Scientific and Medtronic, most ICDs were dual chamber (87% and 75%, respectively, see Table 2). This imbalance translates

TABLE 2 Arrhythmia dataset

	Abbott Far Field MD	Boston Scientific RhythmID	Medtronic Wavelet
Patients/devices			
Total	54	60	71
DR (%) [*]	18 (33)	52 (87)	53 (75)
CRT-D (%) [*]	36 (66)	8 (13)	18 (25)
Episodes			
Total	178	178	178
VT	110	110	110
SVT	68	68	68
Episode rates			
VT, bpm	176 ± 21	180 ± 25	183 ± 26
SVT, bpm	163 ± 18	169 ± 21	164 ± 36
AF episodes (%) [*]	35 (51)	32 (47)	22 (30)

Abbreviations: AF, atrial fibrillation; CRT-D, number of cardiac resynchronization therapy defibrillator; DR, number of dual-chamber ICD; SVT, supraventricular tachycardia; VT, ventricular tachycardia.

^{*} $P < .001$ between groups.

into different QRS duration and left ventricular ejection fractions among the three groups. The QRS duration was significantly shorter for the Boston Scientific group (109 ± 29 ms) than for the Abbott (129 ± 33 ms, $P < .01$) and Medtronic (130 ± 34 ms, $P < .01$) groups. The mean ejection fraction was significantly lower for the Abbott ($34\% \pm 12\%$) group than for the Boston Scientific ($42\% \pm 15\%$, $P < .05$) and Medtronic ($42\% \pm 16\%$, $P < .05$) groups. The three groups did not differ in terms of mean age (61 ± 14 years), sex (78% of male), and the proportion of ischemic cardiomyopathy (46%).

3.2 | Ability to discriminate VT and SVT

In ROC analyses, Abbott Far Field MD (area under the curve [AUC]: 0.91; 95% confidence interval [CI]: [0.81-1]; $P < .001$), Boston Scientific RhythmID (AUC: 0.94; 95% CI: [0.88-1]; $P < .001$), and Medtronic Wavelet (AUC: 0.78; 95% CI: [0.67-0.9]; $P < .001$) show a significant AUC when tested for their ability to discriminate VT from SVT. The results were similar when the ratio dual-chamber/CRT ICD was inserted into the model, the AUC for Abbott Far Field MD (AUC: 0.91; 95% CI: [0.87-0.96]; $P < .001$) and Boston Scientific RhythmID (AUC:

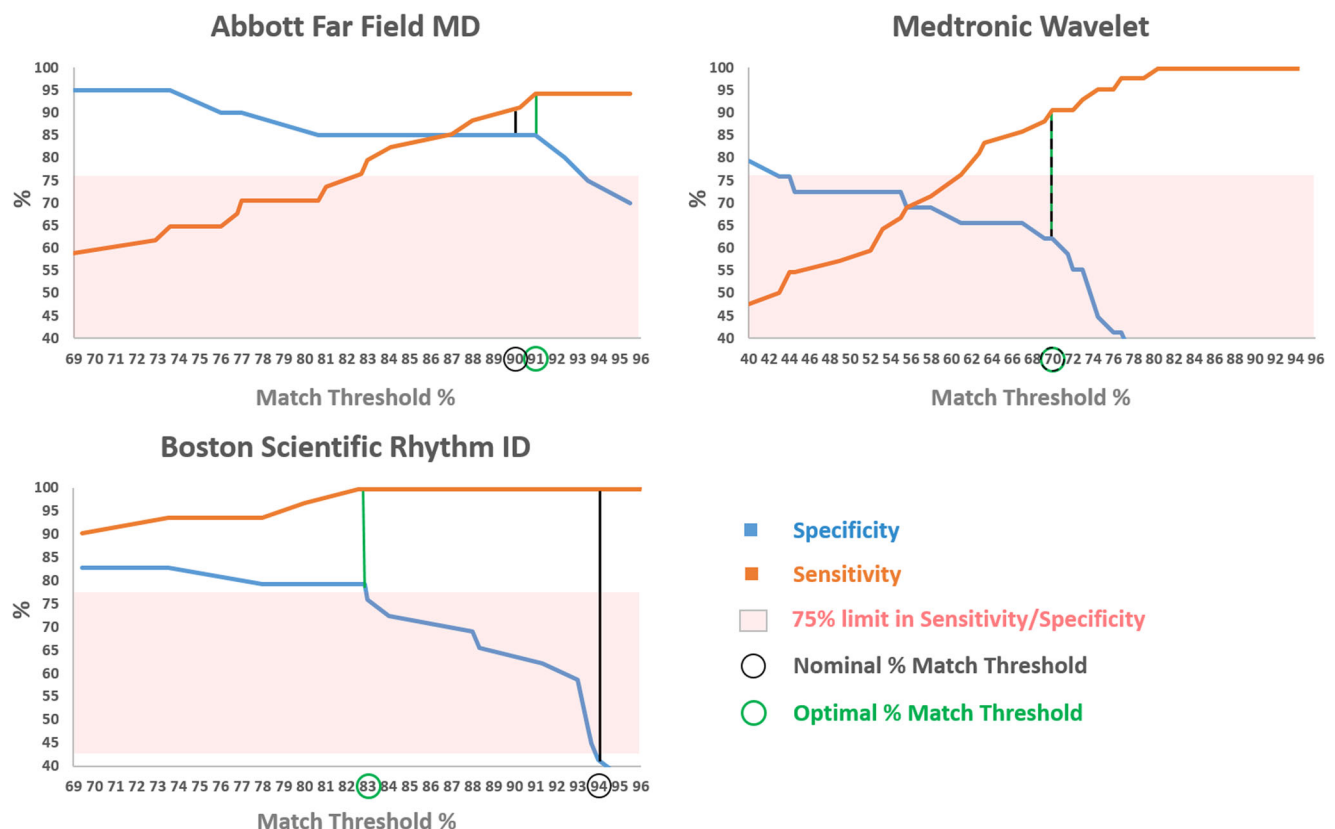


FIGURE 2 Discriminators' performance as a function of the match threshold. The match threshold percent is shown on the x-axis and on the y-axis are in orange the sensitivity (percent of true VT episodes identified as VT) and in blue the specificity (true SVT episodes rejected as SVT). Black circles and bars indicate nominal match thresholds. Green circles and bars indicate optimal match thresholds. All analysis was performed using the nominal matches/detection window ratio (3/10 for Abbott and Boston Scientific and 3/8 for Medtronic). SVT, supraventricular tachycardia; VT, ventricular tachycardia

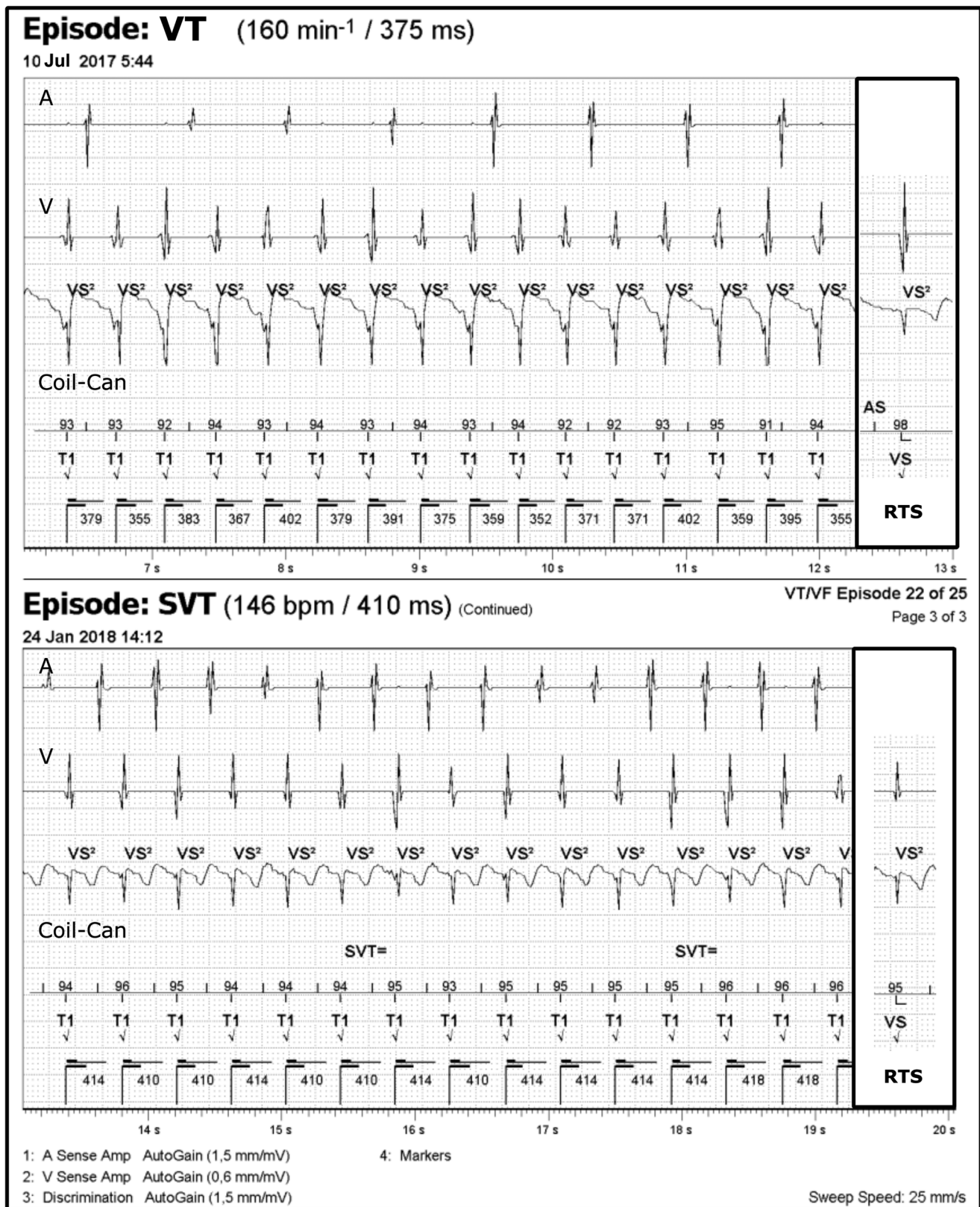


FIGURE 3 Continued.

0.95; 95% CI: [0.92-0.98]; $P < .001$) were statistically higher than for Medtronic Wavelet (AUC: 0.81; 95% CI: [0.72-0.87]; $P < .001$).

3.3 | Sensitivity and specificity

The graphs shown in Figure 2 indicate that the sensitivity/specificity pattern vary distinctly between manufacturers. On average, percent match scores were higher for Abbott Far Field MD than Boston Scientific RhythmID or Medtronic Wavelet. Therefore, the specificity of Abbott's algorithm exceeds the sensitivity until a very high value of the percentage match (87%). In comparison, the sensitivity/specificity patterns of Boston Scientific and Medtronic are inverted: they favor sensitivity until a low value of the percentage match (66% and 55%, respectively).

3.4 | Nominal settings vs alternative thresholds

At a nominal threshold, Abbott Far Field MD provides both high sensitivity (91%, for VT detection) and specificity (85% for SVT detection). Interestingly, this nominal threshold corresponds to both the 90% sensitivity threshold and is very close to the optimal threshold. A specificity of 90% is only reachable at the expense of low sensitivity (71%). In Figure 3, VT and SVT tracings from the same patient are presented, exhibiting both high % match scores.

The 94% nominal threshold of the Boston Scientific RhythmID is associated with a suboptimal sensitivity/specificity ratio resulting in an unacceptable 41% specificity. Lowering this threshold to 83% results in an improved specificity of 79% for a similar 100% estimated sensitivity. Figure 4 shows a misclassified atrial fibrillation episode, requiring the lowering of the % match threshold.

The nominal Medtronic Wavelet threshold is equal to both the 90% sensitivity and the optimal threshold. All these configurations are associated with very low specificity (below the predefined 75% boundary). There is no possibility to reach a specificity above 79% which would be associated with an unacceptable 48% of sensitivity (at 40% threshold). Table 3 summarizes the comparisons. Figure 5 shows an example of SVT with an inconsistent match of the ventricular complexes with the template.

3.5 | Number of matches/detection window

Abbott Far Field MD is the sole manufacturer that allows you to alter the number of required matches (ranging from 3 to 20) and the

detection window (6-20 cycles). The nominal ratio is 3 matches per detection window of 10 cycles. Figure 6 shows the AUCs for ROC curves at different ratios of matches per detection window. This table indicates that the accuracy of the discrimination improves with a lower number of matches and a longer detection window. It also shows that the importance of the window length diminished gradually as the number of matches required decreases. According to this data a single match would give optimal results, but it is not programmable. Within the programmable options, no combination significantly outperforms the nominal 3 matches in a window of 10.

3.6 | Effect of template amplitude

The Medtronic arrhythmia report allows measurement of the template amplitude in mV. Figure 7 shows the SVT recognition capacity (mean % match) of the Wavelet algorithm as a function of the template amplitude. This graph shows that a template amplitude ≤ 3 mV precludes a proper SVT recognition. When the 13 patients (18%) with a template amplitude of less than 3 mV were excluded from the analysis, the AUC for the ROC analysis rises to 0.94; 95% CI: [0.90-0.98]; $P < .001$.

4 | DISCUSSION

We report the first study investigating the accuracy of morphology discrimination using a real-life multicenter multivendor approach. Although the systematic use of the morphology discriminator is recommended with shipment settings, we report major differences between manufacturers and suboptimal nominal thresholds.

4.1 | Limitation of the morphology as a standalone discriminator

This study demonstrates that morphology algorithms have limitations and their use as a standalone discriminator at nominal settings is accompanied by significant missed VT and inappropriate VT classifications. Low specificity at nominal settings (Boston Scientific RhythmID and Medtronic Wavelet) is particularly problematic since morphology only applies at initial detection (one failure of the algorithm, if used as single discriminator, may result in the full treatment delivery). Our results differ from previously published studies that report higher accuracy of the tested algorithms. These discrepancies

FIGURE 3 Abbott VT and SVT tracings from the same patient showing high % match scores. Rectangles on the far right show the ventricular EGM after return to sinus (RTS) for each of the episodes. Top panel: Example of a VT episode with a high % match despite marked visual disparities between the tachycardia EGM and the sinus rhythm EGM. Bottom panel: Atrial tachycardia episode with high % match scores. Using the 90% nominal match threshold and morphology as a standalone discriminator, both of these episodes would have been labeled SVT. Raising the % match threshold to its maximum (95%) and/or changing the detection vector may improve future discrimination. EGM, electrogram; SVT, supraventricular tachycardia; VT, ventricular tachycardia

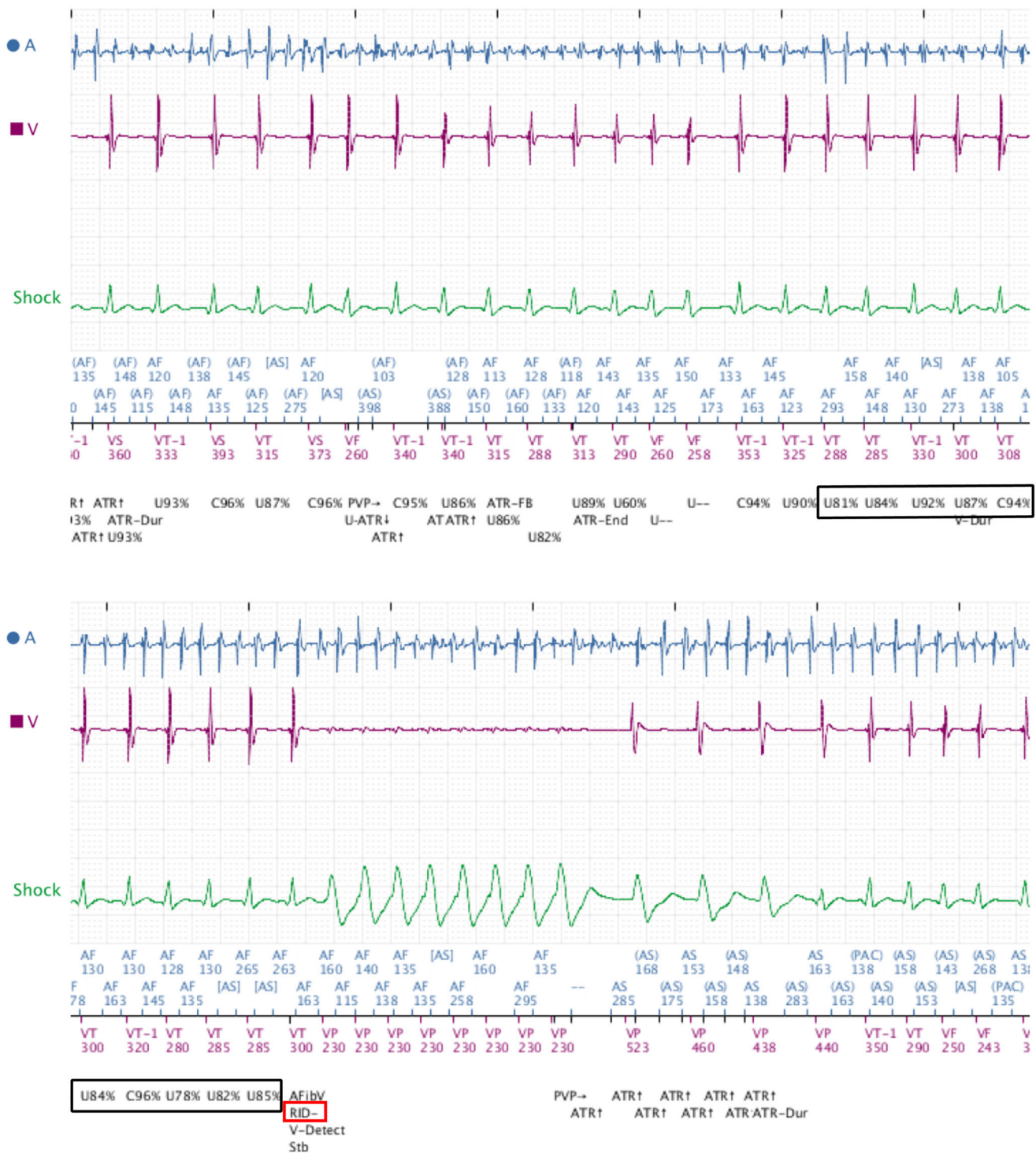


FIGURE 4 Atrial fibrillation misinterpreted as VT by the RhythmID algorithm. Among the 10 match scores before detection (85%, 82%, 78%, 96%, 84%, 94%, 87%, 92%, 84%, 81%—black squares) only two are $\geq 94\%$ (nominal threshold). RhythmID misdiagnoses the episode as VT (RID—red square). This patient would benefit from a lower % match threshold (eg, using an 83% threshold would have resulted in a diagnosis of SVT with 7/10 matches). SVT, supraventricular tachycardia; VT, ventricular tachycardia

could be explained by differences in study design. We analyzed episodes extracted from dual-chamber and CRT devices which allow firm diagnosis instead of single-chamber devices in which the arrhythmia diagnosis mostly rely on visual morphology assessment.^{4,5,8} In their morphology discrimination evaluation Theuns et al⁵ found

improved results for the single-lead ICDs as compared with the dual-lead ICDs. We collected real-life cases in contrast to studies where the template and the arrhythmias were externally introduced into the ICD.⁹ The START study was conducted to compare different discrimination algorithms fed with artificial signals constructed on

the basis of pacing-induced arrhythmias. The arrhythmia signals were recorded from multiple atrial and ventricular channels. The signals were digitized and cleaned from pacing and therapy delivery artifacts. They were looped once (to extend duration) and finally the resulting recordings were converted into analog form and delivered to the different tested devices. It is likely that these modifications have affected the original signals. In addition, the signals used for morphology analysis were acquired between the RV Tip and the Can (instead of the Coil to Can vector used in our study). With this latter configuration, the signal complexity decreases, and the advantage of peak alignment from two different EGM sources is lost (see below).

Finally, we have restricted our analysis to the morphology algorithm performance which is distinct from the final device decision. The prospective RIGHT trial compared the rate of inappropriate therapy between Boston Scientific and Medtronic devices.¹⁰ The true performance of the respective discrimination process could not be evaluated in this study which only looked at treated episodes. Nevertheless, there were almost twice as many inappropriate therapies in the Boston Scientific VR defibrillators as in the Medtronic VR defibrillators. This result is in accordance with our finding that at the nominal 94% match threshold (the threshold used in the RIGHT trial), the RhythmID algorithm has a very poor specificity associated with a high rate of inappropriate therapies. The lower rate of inappropriate therapy in the Medtronic arm is likely related to the use of the consecutive VT counter which offers a high level of protection against atrial fibrillation detection (it acts as an additional stability discriminator since each slow interval resets the VT counter). In contrast, the probabilistic Boston Scientific VT counter (8/10 then 6/10) is vulnerable to atrial fibrillation as it tolerates long cycles. The rate of inappropriate therapy delivered for fast conducted atrial fibrillation was, therefore, more than four times higher in the Boston group than in the Medtronic one.

4.2 | Differences in discrimination accuracy

Although the three algorithms share a common principle and all rely on far-field (FF) vector channels for the morphology analysis, we observed significant differences in the algorithms performances. In particular, the Medtronic Wavelet algorithm suffers from a lack of specificity. Several technical specificities may account for these results. There are differences in the FF signal measurement accuracy which depends on the amplifier range and power. Medtronic uses an 8 bits amplifier which confers at the nominal ± 8 mV range a signal resolution of 0.06 mV. Abbott uses autoscaling during the in-clinic template acquisition ($\sim \pm 7$ to ± 14 mV), which offers a slightly higher resolution of ~ 0.05 to 0.1 mV. Boston uses a fixed and broader range of ± 32 mV in association with a 12 bits amplifier which confers the highest resolution of ~ 0.016 mV. Second, there are major differences in signal processing. Two main approaches can be distinguished (a) a time domain analysis (temporal analysis of EGM morphology by Abbott Far Field MD and Boston Scientific RhythmID) and (B) a Haar wavelet domain analysis (implemented by Medtronic). Figure 8 summarizes the principal features of each algorithm. Abbott and Boston Scientific systems construct a quantitative representation of each ventricular EGM based on the coordinates of eight points including a fiducial point aligned with the peak amplitude time of the near field (NF) EGM. Importantly these two algorithms differ in the way the points are distributed along with the QRS complex: eight points evenly spaced around (and including) the fiducial point for Abbott whereas Boston Scientific uses a more specific distribution including the fiducial point, turning points, intermediate and baseline values (exact formula is protected).⁹ These differences could explain that Abbott Far Field MD maintains a high specificity until high values of the % match threshold (easier match) and Boston Scientific maintains consistently an higher level of sensitivity (more demanding) along

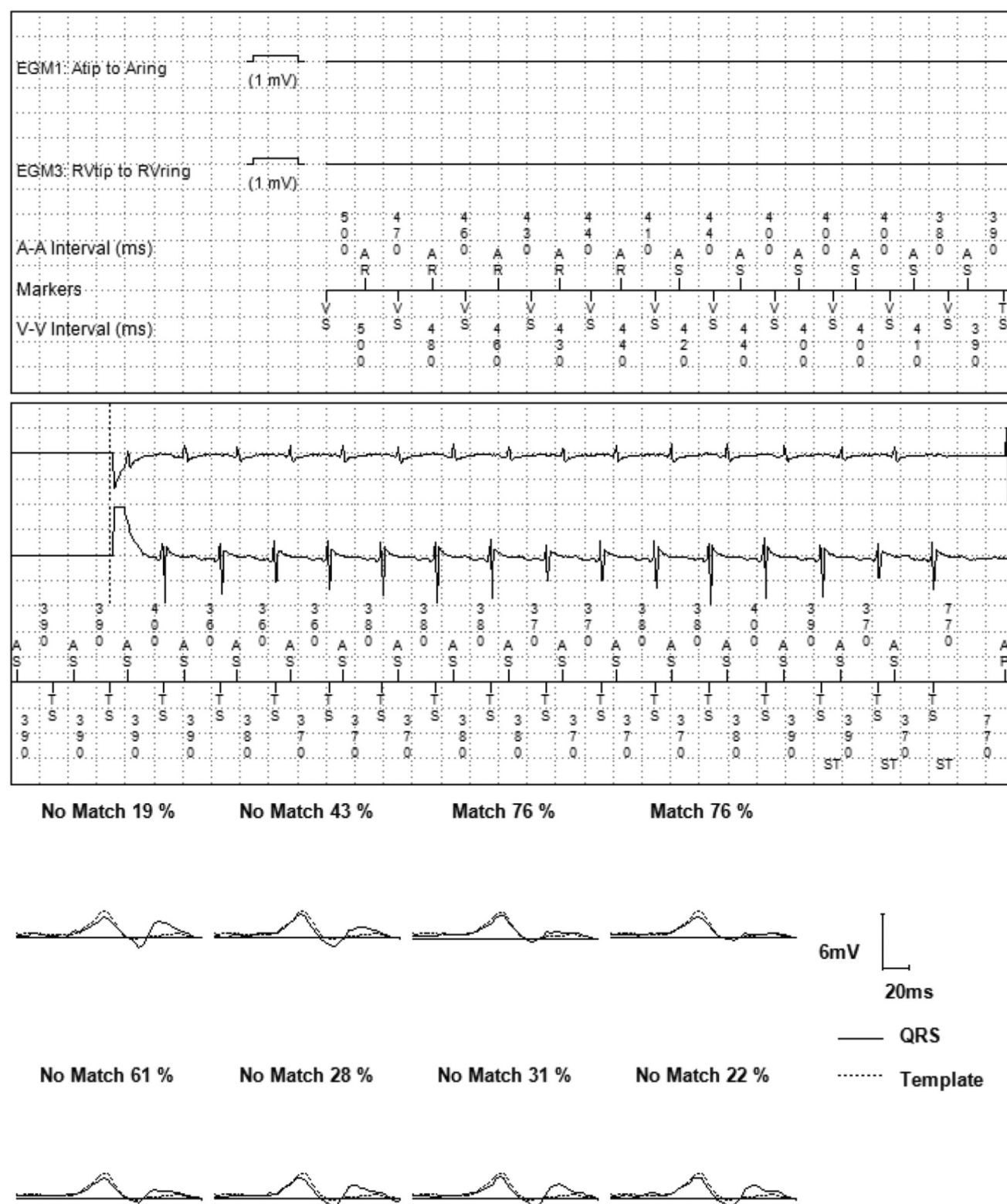
TABLE 3 Nominal and optimized match thresholds performances

	Nominal Settings			90% Sensitivity Th			90% Specificity Th			Optimal Th		
	% Th	SS	SP	% Th	SS	SP	% Th	SS	SP	% Th	SS	SP
Abbott Far Field MD	90	91	85	90	91*	85	77	71	90	91	94	85
Boston Sc RhythmID	94	100	41	69	90	83	63	77	90	83	100	79
Medtronic Wavelet	70	90	62	70	90	62	NR	NR	NR	70	90	62

Note: SP max < 90%. In red, numbers < 75%.

Abbreviations: NR, not reachable; SP, specificity; SS, sensitivity; Th, threshold; %Th, percentage match threshold (in gray).

*Closest value to 90%. NB: SS and SP are estimated from the model, actual value may differ.



Wavelet measurements

FIGURE 5 Continued.

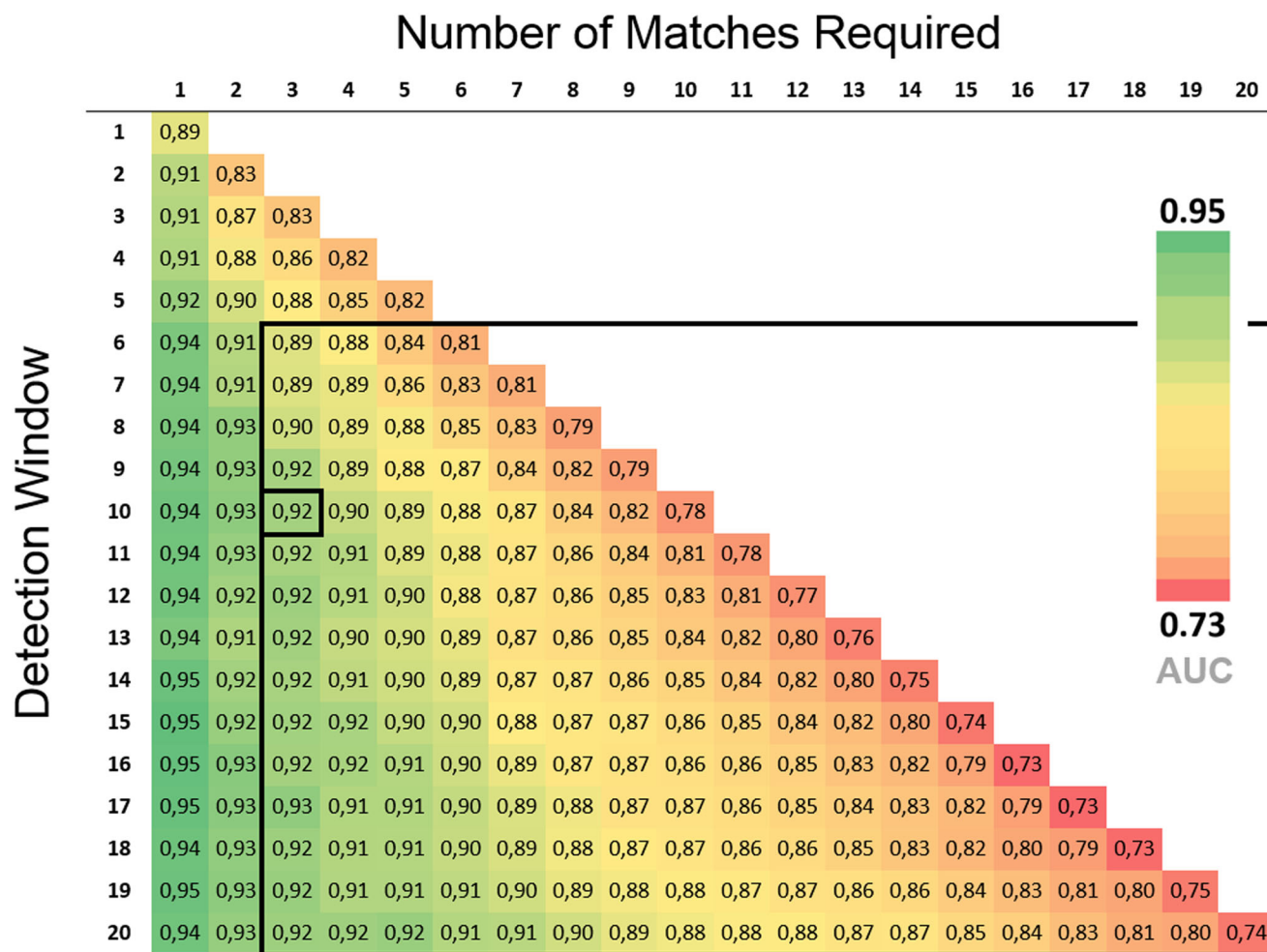


FIGURE 6 AUC for ROC curves constructed at a different number of matches/detection window ratios for the Abbott MD Far Field. Large black rectangle: AUC for the available combinations at programming. Small rectangle: AUC at nominal ratio 3/10. AUC, area under the curve; ROC, receiving operating characteristics

with the programmable range of % match threshold, and this at similar AUC for arrhythmia discrimination. Medtronic uses a completely different approach in the signal processing, applying a wavelet transform (derived from Haar wavelet) to the FF EGM. The wavelet transform yields a set of 48 wavelet transform coefficients of which a representative subset (8-20) is used to represent the ventricular EGM. This type of signal analysis intends to accurately represent the original signal while providing a high degree of information compression. Surprisingly this algorithm shows difficulties to recognize similar ventricular complexes. Accordingly, the match threshold is nominally set lower

than the two competitors (70%) and the automatic template quality check, which is used to determine if the template has become obsolete, tolerates up to 29 nonmatch complexes of 100 complexes. A hypothetical explanation would be that the wavelet transforms based analysis provides a paradoxically too detailed picture of the ventricular EGM which renders the algorithm intolerant to physiological beat-to-beat signal variations. Another potential limitation may be found in the signals alignment which is based on the greatest absolute value of each FF EGM. This alignment may be less accurate than alignment based on the NF signal: during a ventricular arrhythmia, the location of

FIGURE 5 SVT with variable Wavelet match scores. An episode of atrial tachycardia recorded by a Medtronic Evera XT DR with detection withheld by PR Logic after 16 consecutive TS markers. The Wavelet discriminator is not applied but the match scores are shown for the 8 last beats before PR Logic decision. If Wavelet had been used as a sole discriminator, it would have concluded to VT (only 2 match scores >70%). The Wavelet measurements (bottom) show that subtle changes between the tachycardia EGM (solid lines) and the template EGM (dotted lines) lead to important differences in the match score. EGM1, atrial bipolar channel. EGM3, ventricular bipolar channel. The shock channel is not shown on the tracing. EGM, electrogram; SVT, supraventricular tachycardia; VT, ventricular tachycardia

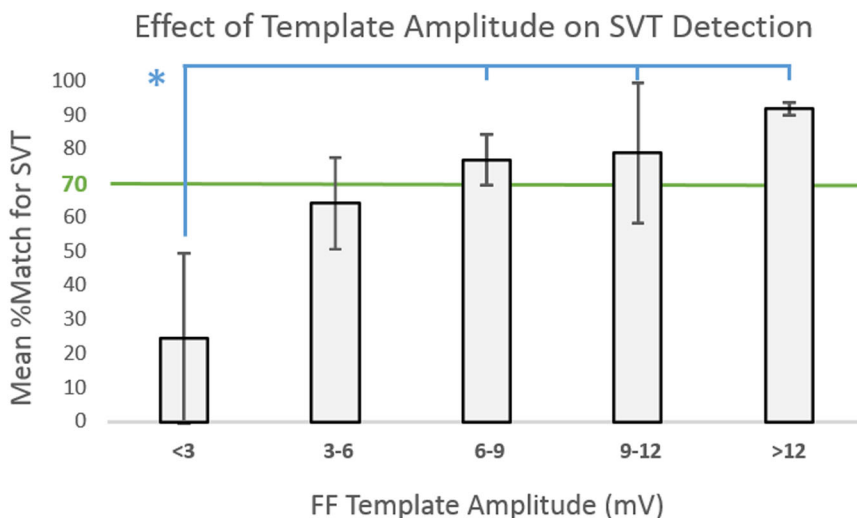


FIGURE 7 Mean percentage match scores for SVT according to the amplitude of the template. The nominal threshold appears in green. * $P < .01$ for comparison between groups. The theoretical match score for an SVT is 100%. The mean % match score for patients with a template amplitude <3 mV is significantly lower than those of the patients with a template of 6 mV and above. SVT, supraventricular tachycardia; VT, ventricular tachycardia

the alignment point may shift in the NF channel with respect to the shock channel due to differing conduction vectors. This timing difference can accentuate differences already present in the shock channel EGM and facilitate diagnosis of ventricular arrhythmias.

4.3 | Consequences for programming

Our results indicate that none of the tested morphology algorithm could be considered as a panacea for arrhythmia discrimination. This is expected considering the inherent limitations of such algorithms, among which myopotential interference (arm exercises), low amplitude EGM, EGM truncation, alignment error (double peaks), conduction aberrancy, and possible others. Considering the limitations of the discrimination process overall it is recommended to limit the therapy zone above 185 to 200 bpm in primary prevention. The question is could we optimize the programming to improve the algorithm accuracy? Our results indicate that the Wavelet algorithm performs poorly then the FF EGM amplitude is below 3 mV. This is not surprising considering that at this level of amplitude, the signal/noise ratio is lower. In such an instance, Medtronic advises selecting another EGM source. This option has to be balanced against the prerequisite to deactivate the RV lead noise discrimination algorithm which uses the same EGM source and requires at least one Coil electrode. This means than with a single coil ICD lead, any change in the Wavelet EGM vector will disable the RV lead noise discrimination algorithm. Alternatively, one may consider reducing the range of the Wavelet EGM source to improve the signal resolution. Above all, this raises the question of the need to test systematically the FF detection at implant, as suggested by others to improve the accuracy of noise detection algorithms that rely on this EGM source.¹¹ Regarding the question of optimizing the % match threshold, our results indicate that the Abbott and Medtronic nominal thresholds are similar or close to the optimal calculated

thresholds. In contrast, the Boston Scientific nominal threshold appeared to be too conservative compared with the optimal threshold which allows a 38% gain in specificity. In fact, the ratio sensitivity/specificity (ie, the % match threshold) may be determined according to the expected ratio of SVT/VT. For instance, at a lower detection rate, SVTs are more likely to occur, and VTs are more likely to be hemodynamically tolerated. In the “1+1” trial, the percentage of SVTs decreased with the tachycardia rate: 68% of SVTs above 140 bpm, 49% of SVTs above 162 bpm, and 9% of SVTs above 176 bpm.¹² Practically the match threshold could be lowered in accordance to the lowest VT zone limit. Whether the morphology algorithm is used as a standalone discriminator or in combination with other criteria represents a second technical challenge. It seems logical to use different thresholds in single-chamber (when morphology is a standalone discriminator) vs dual-chamber or CRT device (when morphology is part of the discrimination tree). The latter devices benefit from the atrial/ventricular rate comparison. In the branches of $A = V$ and $A > V$, more than 80% of the tachycardia are SVT which argues in favor of aiming for high specificity by lowering match threshold.¹³ Of note, our results do not support modifying the nominal number of 3 matches in a detection window of 10 in Abbott devices.

4.4 | Limitations

Our results acquired with dual and CRT ICDs may slightly differ in a single-chamber device population where the cardiomyopathy and the indications may be different. These results do not reflect the proper discrimination accuracy of each device since detection capabilities and counters' rules have not been taken into account. The VT counter length and eventually the presence of additional discriminators have influenced the timing of the morphology algorithm intervention, which is, therefore, different from one patient to the other.

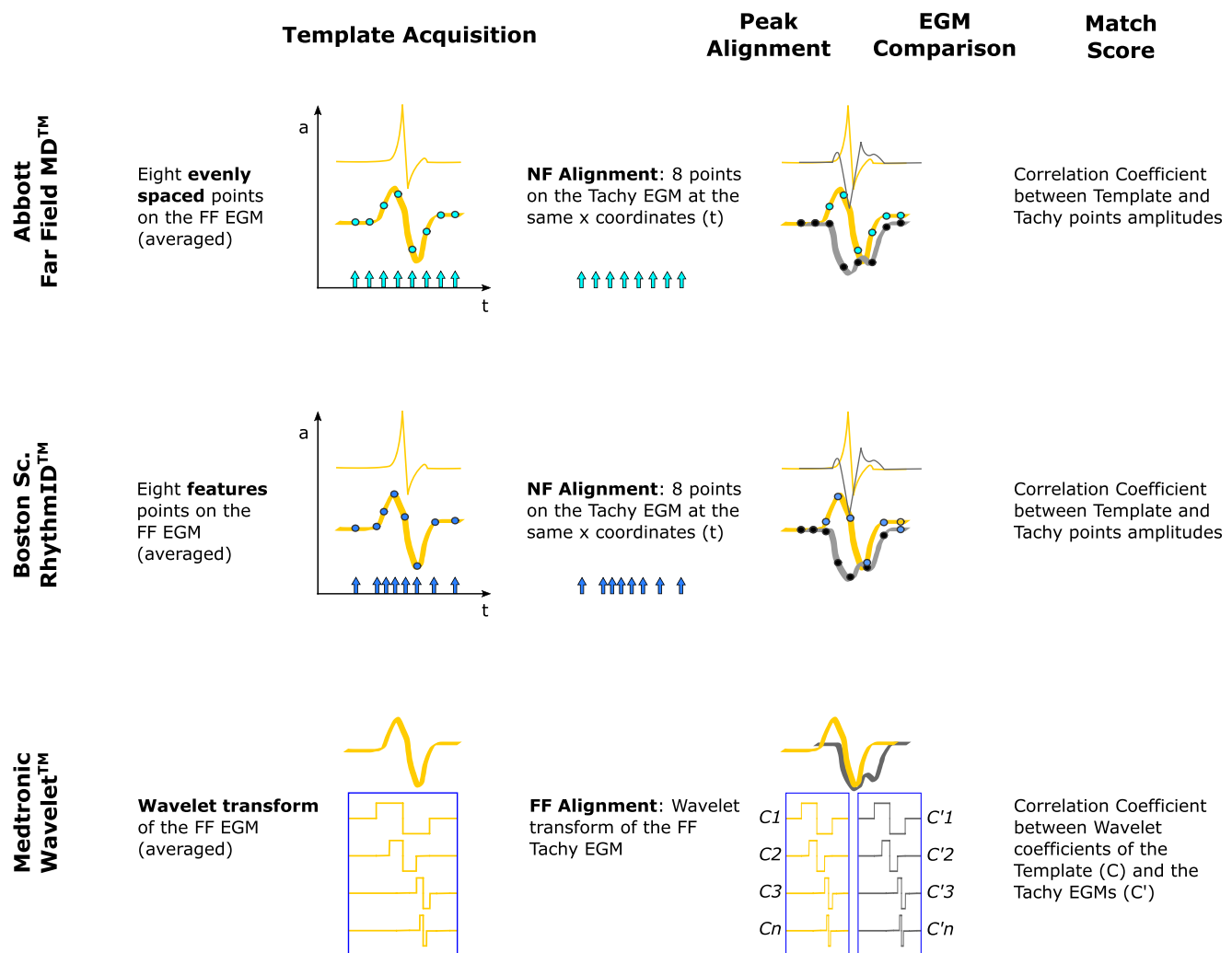


FIGURE 8 Discriminators specificities in signal processing. For Abbott Far Field MD and Boston Scientific RhythmID, a comparison between arrhythmia and template EGMs is made by computing the product-moment correlation coefficient between two sets of eight points. The way these eight points are chosen over the ventricular EGM differs between the manufacturers: evenly spaced with Abbott Far Field MD (light blue dots) and feature points (dark blue dots which include turning points, intermediates, and baseline values) for Boston Scientific RhythmID. Medtronic applies a wavelet transformation to both the template and the tachycardia EGMs and compares the respective wavelet coefficients (C and C'). a, amplitude; EGM, electrogram; t, time

5 | CONCLUSION

Proprietary morphology discriminator specificities and nominal settings translate into major differences in arrhythmia discrimination accuracy. A combination of discriminators and the modification of the nominal percentage match threshold may be considered under certain circumstances.

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