Innovative P-wave detection for discrimination between ventricular and supraventricular tachycardia in single-chamber ICDs: is the P-wave invisible during tachycardia?

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Aims
Differentiation between supraventricular tachycardia (SVT) and ventricular tachycardia (VT) remains a substantial clinical challenge in patients with single-chamber implantable cardioverter-defibrillators (ICDs) due to absence of visible P waves. Innovative optimization of intrathoracic electrogram (EGM) configuration will facilitate P-wave detection and rhythm differentiation during tachycardia.

Methods and results
Innovative optimization of EGM configuration was originally performed to improve patient care. In this retrospective cohort study, we examined our database for records of 140 consecutive patients undergoing single-chamber ICD implantation. During the follow-ups of 61 included patients with optimized EGM configuration, 27 patients were identified to have VT and/or SVT. EGMs in the Can (generator) to superior vena cava (Can–SVC) configuration were compared with those conventionally from the Can to right ventricular coil (Can–RV coil) source in the same patients. In Can–SVC EGMs, the ratio of P/QRS amplitude was 14-fold higher (0.57 ± 0.08 vs. 0.04 ± 0.00, P < 0.001) compared with those in Can–RV coil EGMs during sinus rhythm. With Can–SVC configuration, the odds of atrioventricular dissociation detection in patients with VT was increased 15-fold (61.9% vs. 9.5% with Can–RV coil; odds ratio, 15.4; 95% confidence interval, 2.8 to 84.7; P = 0.0009). In patients with SVT, P-waves or retrograde P-waves were markedly more identifiable in Can–SVC configuration compared with Can–RV coil (odds ratio, 40; 95% confidence interval, 3.6 to 447.1; P = 0.0010).

Conclusion
P-wave recognition by optimizing EGM configuration provides a novel diagnostic tool for differentiation between VT and SVT in single-chamber ICDs. A potential discrimination algorithm would provide a cost-effective approach to improving the qualitative outcomes.

Keywords
Optimized programming • ICDs • P-wave detection • Arrhythmia discrimination

Introduction
The implantable cardioverter-defibrillator (ICD) is an essential component of preventing cardiac sudden death.1,2 Furthermore, the device is an important diagnostic tool of cardiac arrhythmia. However, discrimination of supraventricular tachycardia (SVT) from ventricular tachycardia (VT) remains a major clinical challenge.3,4 Inappropriate shocks lead to psychological stress, poor quality of life, increased medical cost, reduced generator longevity, proarrhythmia, and increased mortality.5–11

The intrathoracic far-field electrogram (EGM) derived from the active Can (generator) to superior vena cava (SVC) coil has
What’s new?

- In patients with conventional single-chamber ICDs, differentiation between supraventricular tachycardia (SVT) and ventricular tachycardia (VT) remains a substantial clinical challenge due to the absence of visible P waves.
- Innovative optimization of stored intrathoracic electrogram (EGM) configuration will facilitate P-wave detection and rhythm differentiation during tachycardia.
- With Can-SVC configuration, the odds of atrioventricular dissociation detection in patients with VT was increased to 15-fold. In patients with SVT, P-waves or retrograde P-waves were markedly more identifiable in Can-SVC configuration compared with Can-RV coil (odds ratio of 40). In addition, atrial flutter waves or atrial fibrillation waves could also be recorded.
- P-wave recognition by optimizing EGM configuration provides a novel diagnostic tool for differentiation between VT and SVT in single-chamber ICDs. A potential discrimination algorithm would provide a cost-effective approach to improving the qualitative outcomes.

morphological similarity compared with the surface electrocardiogram (ECG). The intrathoracic EGM derived from the Can to SVC coil (Can−SVC) could be used as a surrogate for surface ECG in clinic (e.g. leadless ECG) during an ICD follow-up session. Furthermore, the Can−SVC configuration was shown to provide additional information on atrial activation, even during stimulated VT. However, it has never been recommended or studied as an approach to differentiate between spontaneous or clinical VT and SVT in patients with single-chamber ICDs.

In this study, we compared the intrathoracic EGMs derived from between the Can−SVC and Can to right ventricular (Can−RV) coil in patients with single-chamber ICDs. Spontaneous VT and SVT were analysed during ICD follow-ups. Recognition of P waves in the intrathoracic EGMs is clearly feasible by optimization of EGM recording configuration. With Can−SVC configuration, the P waves were favourably revealed during SVT and VT. Our results suggest that automated P-wave detection in Can−SVC EGMs could be incorporated into the discrimination algorithm for SVT and VT in single-chamber ICDs.

Methods

Although it is a retrospective cohort study, innovative optimization of EGM configuration was originally performed to improve patient care prior to this study by enhanced recognition of sinus P waves during VT. The study was approved by the Institutional Review Board of the University of Arkansas for Medical Sciences (to W.W.X.). We reviewed our database for records of 140 consecutive patients who underwent single-chamber Medtronic ICD (Medtronic Inc., Minneapolis, MN, USA) implantation or generator changes between July 2009 and May 2010 at our institution. All the patients had indications for ICD according to the American College of Cardiology/American Heart Association guidelines and gave written informed consents for procedures. The review included inpatient and outpatient charts, operative reports, and all other available records in paper or electronic form.

Specifically, the Can−SVC was chosen as one of two EGM sources for data collection for all the patients with an SVC coil. Only model 6944, 6947, and 6949 leads from Medtronic have SVC coils. These 140 patients were further subjected to the exclusion criteria of our study that included: age younger than 18 years, RV lead without an SVC coil, geographically inaccessible, and prisoner. After exclusion, there were 61 patients with optimized EGM configuration (age 56.3 ± 19.9 years; male 49, female 12; left ventricular ejection fraction 29% ± 1%). During the follow-up for 1 year, we identified 27 patients with one or more episodes of VT, SVT, or both. The EGMs were reviewed in a blinded manner by two board-certified cardiac electrophysiologists and classified as VT, SVT, or neither. When the EGM reading was uncertain, a third cardiac electrophysiologist was asked to read the EGM and a consensus reading was determined.

In this study, we made comparison of EGMs generated from two different sources. The first EGM was derived from the active Can electrode and SVC coil, the second EGM was from the active Can and right ventricular coil (high-voltage port B, HVB), the latter of which

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Measure</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>57.2 ± 2.7</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>21 (77.8%)</td>
</tr>
<tr>
<td>Female</td>
<td>6 (22.2%)</td>
</tr>
<tr>
<td>LVEF at implantation</td>
<td>27 ± 2%</td>
</tr>
<tr>
<td>Cardiac disease</td>
<td></td>
</tr>
<tr>
<td>Ischaemic cardiomyopathy</td>
<td>15 (55.6%)</td>
</tr>
<tr>
<td>Nonischaemic cardiomyopathy</td>
<td>12 (44.4%)</td>
</tr>
<tr>
<td>ICD indication</td>
<td></td>
</tr>
<tr>
<td>Arrest</td>
<td>2 (7.4%)</td>
</tr>
<tr>
<td>VT</td>
<td>4 (14.8%)</td>
</tr>
<tr>
<td>MADIT (inducible VT at EP testing, prior myocardial infarction, low EF)</td>
<td>1 (3.7%)</td>
</tr>
<tr>
<td>MADIT II (EF&lt;30% and prior myocardial infarction)</td>
<td>11 (40.7%)</td>
</tr>
<tr>
<td>Other</td>
<td>9 (33.3%)</td>
</tr>
<tr>
<td>Cardiac arrhythmia</td>
<td></td>
</tr>
<tr>
<td>VT (in total)</td>
<td>21 (77.8%)</td>
</tr>
<tr>
<td>VT and SVT</td>
<td>7 (25.9%)</td>
</tr>
<tr>
<td>SVT (in total)</td>
<td>13 (48.1%)</td>
</tr>
<tr>
<td>ICD</td>
<td></td>
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<tr>
<td>Secura VR D224VRC</td>
<td>13 (48.1%)</td>
</tr>
<tr>
<td>Virtuoso VR D154VVWC</td>
<td>9 (33.3%)</td>
</tr>
<tr>
<td>EnTrust D154VRC</td>
<td>5 (18.5%)</td>
</tr>
<tr>
<td>Defibrillator lead</td>
<td></td>
</tr>
<tr>
<td>Sprint Quattro Secure 6947</td>
<td>19 (70.4%)</td>
</tr>
<tr>
<td>Sprint Fidelis lead 6949</td>
<td>6 (22.2%)</td>
</tr>
<tr>
<td>Sprint Quattro 6944</td>
<td>1 (3.7%)</td>
</tr>
<tr>
<td>St Jude Durata 7121</td>
<td>1 (3.7%)</td>
</tr>
</tbody>
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LVEF, left ventricular ejection fraction.
had been routinely used. In both configurations, the amplifier range ($\pm 1$--$32$ mV) was optimized by maximizing the size of sinus P waves without saturation of P waves or QRS complexes for data storage. The filter setting for both the Can–SVC coil and Can–RV coil EGM vectors was non-programmable (2.5–100 Hz). The ICDs were implanted in the left prepectoral fascia. The left-laterally positioned ICD along with the defibrillator coils located in SVC and right ventricle served as the far-field electrodes for intrathoracic EGMs.

The EGM derived from the active Can electrode and SVC coil reveals an approximation of a surface ECG signal and is available when an SVC coil is present. For data collection, this configuration must be programmed for episode record storage in Medtronic single-chamber ICDs. Supplementary Figure S1 illustrates that the active Can of ICD, SVC coil, and right ventricular coil were configured in the manner described by Einthoven. Intrathoracic EGMs were generated between the Can and SVC coil (similar to Einthoven lead I) and between the Can and right ventricular coil (similar to Einthoven lead III). The EGMs from the Can to SVC source were compared with those from the Can to RV coil in the study.

To quantify the amplitude of P waves and QRS-complex, it was measured from the peak to nadir in each patient either in real-time EGMs or stored EGMs. The stored EGMs were reflective of daily activities of patients. Mean values and standard error were calculated and compared with Origin software (Microcal Origin 6.0, Northampton, MA, USA) using a two-tailed paired t-test. Categorical data were calculated using the two-tailed Fisher’s exact test. A P value of $<0.05$ was considered statistically significant.

### Results

Patient characteristics were listed in Table 1. Twenty-seven patients (age range 22–87 years, mean 57.2 ± 2.7) were found to have SVT and/or VT via ICD interrogations during 1-year follow-up. Among those, 77.8% of the patients had VT, 48.1% of the patients had SVT, and 25.9% of the patients had both (Table 1).

Figure 1 demonstrates examples of discernible P waves of different sizes in the Can–SVC channel in comparison with other EGMs including the Can–RV coil (HVB) in four patients in the study. The amplitude of P waves in the Can–SVC coil channel was significantly higher than that in the Can–RV coil channel during sinus rhythm. The mean amplitude of P waves in these 27 patients was $0.61 \pm 0.07$ mV with Can–SVC configuration, but only $0.28 \pm 0.02$ mV in the Can–RV coil (HVB) channel ($P < 0.0001$) (Figure 2A). The amplitude of QRS complex was smaller in the Can–SVC channel (Figure 2B, $n = 27$). The ratio of P/QRS amplitude was 14-fold greater in the Can–SVC channel ($0.57 \pm 0.08$, $P < 0.0001$) compared with that in the Can–RV coil channel ($0.04 \pm 0.00$) (Figure 2C).

**Figure 1** Examples of sinus P wave in real-time electrograms from different patients. (A–D): In contrast to the Can to right ventricular coil coil (high-voltage port B) or other configurations, sinus P waves, albeit different in size and morphology, are readily visible with the Can to superior vena cava configuration. Red arrows illustrate the peak and nadir of P waves for quantification; green arrows are for QRS complex. Quantifications were only made when P waves or QRS-complex were fully displayed.
In summary, the P waves are visible in the optimized Can–SVC recording readily demonstrated P waves, whereas sinus P waves were only barely visible in the Can–RV coil recording (EGM2) in the first example (Figure 3A). Similarly, in the example in Figure 3B, the Can–SVC recording readily demonstrated P waves, whereas sinus P waves were only barely visible in the Can–RV coil recording (EGM2) in the second example (Figure 3B). In our patients with VT, 61.9% (13 of 21) of patients had identifiable AV dissociation in the Can–SVC channel, compared with 9.5% (2 of 21) of patients in the Can–RV channel (odds ratio, 15.4; 95% confidence interval, 2.8–84.7; P = 0.0009) (Figure 4). Similarly, 55.7% (59 of 106) of VT episodes had AV dissociation in the Can–SVC configuration, in comparison with 7.5% (8 of 106) of VT episodes in the Can–RV coil channel (odds ratio, 15.4; 95% confidence interval, 6.8–34.8; P < 0.0001). In addition, in patients with VT, 28.6% (6 of 21) of patients had 1:1 retrograde P waves with Can–SVC configuration compared with none of the patients in the Can–RV coil channel, although the retrograde 1:1 VA conduction is not diagnostic for differentiation.

Although the P waves in Can–SVC EGMs were generally perceptible, independent verification will certainly add value to the validity. In a patient with VT (Supplementary Figure S2), simultaneous recordings of real-time EGMs (Supplementary Figure S3A) and standard 12-lead surface ECG (Supplementary Figure S3B) were demonstrated to verify the P waves and QRS complexes at the bedside (Supplementary Figure S4).

Figure 5A shows a flow chart of an SVT episode. A sudden onset and termination pattern of tachycardia were consistent with the paroxysmal characteristics of SVT. Figure 5B illustrates the EGM example of this episode (as in Figure 5A) of atrial tachycardia. In the Can–SVC channel, sinus P waves after termination of tachycardia were discernible and there were P' waves (morphologically different from sinus P wave) during atrial tachycardia. Again, the diagnosis of SVT is clear when the Can–SVC recording is examined but P waves remain uncertain from the Can–RV coil recording.

Supraventricular tachycardia with clearly visible retrograde P waves in the Can–SVC channel was shown in Figure 6. The retrograde P wave was not expected to be inverted because the Can–SVC configuration approximates Einthoven lead I rather than inferior ECG leads. Thirteen patients were found to have SVT. In 92.3% (12 of 13) of patients with SVT, P waves or retrograde P waves were identifiable in the Can–SVC channel, compared with 23.1% (3 of 13) in the Can–RV coil configuration (odds ratio, 40; 95% confidence interval, 3.6–447.1; P = 0.0010) (Figure 7). There were 88.8% (79 of 89) of SVT episodes with identifiable P waves in the Can–SVC channel vs. 19.1% (17 of 89) of SVT episodes in the Can–RV coil channel (odds ratio, 33.5; 95% confidence interval, 14.4–77.8; P < 0.0001).

Although the focus of the present investigation was the amplitude of P waves and visibility of P waves during VT in patients with single-chamber ICDs, it would be of interest to know whether F waves in atrial flutter or f waves in atrial fibrillation could be discernible in the Can–SVC configuration. Our additional data showed strikingly evident F waves and f waves in the Can–SVC channel (Supplementary Figures S5–S6).

In summary, the P waves are visible in the optimized Can–SVC channel due to its favourable P/QRS ratio in patients with single-chamber dual-coil ICDs. Innovative device optimization is a
valuable tool for the management of patients with these single-chamber ICDs.

**Discussion**

Implantable cardioverter-defibrillators (ICDs) play a central role in prevention of cardiac sudden death. However, inappropriate ICD shocks continue to be a clinical challenge, resulting in pain, psychological distress, proarrhythmia, increased health care cost, and increased mortality. 5–11 By far, the leading cause of inappropriate ICD shocks is the misclassification of an SVT as VT. The P wave is generally indiscernible from single-chamber ICDs due to a single lead in the right ventricle, which presents an additional obstacle to differentiation. Determining whether ICD discharges are appropriate, and improving ICD discrimination between SVT and VT are causes of considerable consternation for the internists, general cardiologists, and electrophysiologists. It is a priority to reduce the occurrence of inappropriate shocks. 11

Compared with dual-chamber ICDs, single-chamber ICDs remain the mainstay of therapy due to lack of significant proof of morbidity/mortality benefit as well as procedural complexity and economic concerns. At least in the United States, the

![Figure 3](https://academic.oup.com/europace/article-abstract/15/6/827/485467/831)

**Figure 3** Examples of intrathoracic electrograms depicting readily discernible sinus P waves during ventricular tachycardia with Can to superior vena cava configuration. (A) Sinus P waves were clearly visible throughout the electrogram in the Can to superior vena cava channel, but absent in the Can to right ventricular coil channel. (B) The ventricular tachycardia was terminated by antitachycardia pacing. Sinus P waves were clearly present in the Can to superior vena cava electrogram both before and after termination. Sinus P waves were buried in the T waves during tachycardia with Can to right ventricular coil configuration.

![Figure 4](https://academic.oup.com/europace/article-abstract/15/6/827/485467/831)

**Figure 4** Atrioventricular dissociation is shown more frequently with Can to superior vena cava configuration during ventricular tachycardia. In 61.9% (13 of 21) of patients with ventricular tachycardia, atrioventricular dissociation was present in the Can to superior vena cava channel (vs. 9.5% or 2 of 21 patients with Can high-voltage port B configuration; odds ratio, 15.4; 95% confidence interval, 2.8–84.7; \( P = 0.0009 \)). The shaded area represents the percentage of patients with discernible atrioventricular dissociation during tachycardia in the intrathoracic electrograms.
Center for Medicare and Medicaid Services reached a decision that 'providers must justify the medical necessity of devices other than those with a single lead.' Unless atrial pacing is required, single-chamber ICDs are generally implanted. This occurs particularly in patients with severe congestive heart failure, in which a shorter procedure time and a decreased perioperative risk could be important. Historically, discrimination algorithms in single-chamber ICDs have included ventricular rate and interval stability, onset and offset characteristics, the outdated EGM width criterion, and the subsequent Wavelet EGM morphology criterion. Even with Wavelet criterion in Medtronic single-chamber ICDs or combined morphology, interval stability, and sudden-onset criteria in St Jude Medical single-chamber ICDs in the Detect SVT trial, the inappropriate SVT detection rate remains as high as 39.5–39.7%. Atrioventricular dissociation is a hallmark of VT with almost 100% specificity. Detection of sinus P waves during wide QRS-complex tachycardia is of great clinical value.

It is well-established that atrial rhythm analysis and AV timing relationships can provide critical guidance in differentiation of SVT and VT. These relationships were routinely examined in the surface ECG but the analysis has not been implemented to date in single-chamber ICDs. Although there was debate about early nonrandomized studies and small randomized studies regarding the utility of dual-chamber vs. single-chamber ICDs in reducing rates of inappropriate device therapy, the failure of improved discrimination in dual-chamber ICDs in early studies was attributed to atrial sensing issues. It has been suggested that the early-generation device was employed with a fixed and relatively long post-ventricular atrial blanking period. A subsequent larger randomized trial, however, suggests that dual-chamber ICDs can decrease overall inappropriate ICD discharges due to SVTs by nearly 50% compared with single-chamber detection. Therefore, the additional rhythm discrimination provided by adding an atrial lead provides benefits for differentiation between SVT and VT. Nevertheless, it is unknown whether these benefits remain applicable if the single-chamber ICDs would have enhanced P wave detection by optimizing EGM recording configuration as suggested by this study. It is particularly true if this automated P-wave detection in Can–SVC EGMs could be incorporated into the discrimination algorithm for SVT and VT. Furthermore, a recent study has shown that dual-chamber ICD implantation was associated with increased complications and in-hospital mortality compared with single-chamber ICDs. Therefore, enhanced P-wave detection in single-chamber ICDs may play a unique role in both retaining the benefits of dual-chamber ICDs and avoiding adverse sequelae of adding the additional atrial lead.

Although the Can–RV coil configuration has been frequently used as the EGM source, the P wave on this EGM channel (similar to Einthoven lead III) is barely discernible. The P axis in
the frontal plane varies from 0 to $+75^{\circ}$.21 The mean P vector is almost perpendicular to lead III. Thus, the P wave is always upright in leads I and II, whereas it may be upright, biphasic, or inverted in lead III.21 Among six intrathoracic leads (similar to leads I, II, III, aVR, aVL, and aVF), Einthoven leads I and III have the highest and lowest ratio of P/QRS amplitude, respectively. Those intrathoracic leads similar to leads II, III, and aVF have the highest magnitude of QRS complex.13 The low ratio of P/QRS complex amplitude, namely 4%, in the routinely used Can–RV coil channel in this study is consistent with a previous study.13

Myopotentials might interfere with far-field EGMs, thereby leading to misclassification of SVT. However, the incidence is low with a 0.5% rate of episodes in the large prospective study by Klein et al.17 Moreover, the myopotential noise potentially caused by pectoral muscle was not an issue in the REMEDIO study when the active Can was employed as an electrode for the far-field EGMs.22 Myopotentials were not observed in this study.

Study limitations

This is a retrospective cohort study. There may be less bias and confounding factors if it was originally designed as a prospective cohort study. The employment of a self-controlled approach, however, was helpful in reducing confounding factors. Second, only Medtronic ICDs were tested in this study. It does not exclude the possibility of potential application to single-chamber ICDs by other manufacturers. Third, we only investigated the frontal plane varies from 0 to $+75^{\circ}$.21 The mean P vector is almost perpendicular to lead III. Thus, the P wave is always upright in leads I and II, whereas it may be upright, biphasic, or inverted in lead III.21 Among six intrathoracic leads (similar to leads I, II, III, aVR, aVL, and aVF), Einthoven leads I and III have the highest and lowest ratio of P/QRS amplitude, respectively. Those intrathoracic leads similar to leads II, III, and aVF have the highest magnitude of QRS complex.13 The low ratio of P/QRS complex amplitude, namely 4%, in the routinely used Can–RV coil channel in this study is consistent with a previous study.13

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left-laterally positioned ICDs. It remains unclear whether the results could be extrapolated to ICDs located on the right chest. Fourth, although dual-coil leads may have a higher risk from the standpoint of potential lead extraction in a minority of patients, this study itself does not necessarily advocate dual-coil over single-coil leads in every patient solely for the purpose of improved P-wave detection. Rather, it clearly offers a better approach for the management of patients with single-chamber dual-coil ICDs. Finally, this study identifies the potential advantages of development of VT discrimination algorithms based on the Can–SVC EGM but does not establish or test the algorithm.

Conclusions

Innovative P-wave detection enhanced by optimizing EGM recording configuration without adding an atrial lead is highly feasible and provides a valuable diagnostic tool for discrimination between SVT and VT. Atroventricular dissociation is a hallmark of VT. Recognition of atrial signals during SVT is of great significance in prevention of inappropriate device shocks. Furthermore, identification of P waves in tachycardia during single-chamber ICD follow-up sessions also expedites arrhythmia diagnosis. We propose that automated P-wave detection in Can–SVC EGMs should be incorporated into the discrimination algorithm for SVT and VT. This potentially provides a cost-effective approach to improving the qualitative outcome of single-chamber ICDs even without adverse sequelae of adding the atrial lead.

Supplementary material

Supplementary material is available at Europace online.

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Conflict of interest: none declared.

References