Oversensing of atrial fibrillatory waves in a subcutaneous implantable cardioverter-defibrillator

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Introduction

Implantable cardioverter-defibrillators (ICDs) have been shown to improve survival in patients with ischemic or nonischemic cardiomyopathy when used for primary and secondary prevention settings.[1–3] The limitations of transvenous ICDs include postimplant adverse events,[4,5] defibrillator lead failure,[6] and inappropriate shocks for atrial tachyarrhythmias due to fast ventricular response rate that are associated with an increase in all-cause mortality.[7,8] Given these shortcomings, subcutaneous ICDs (S-ICDs) may offer several potential advantages. Prior S-ICD studies have shown a complication rate and shock efficacy comparable to transvenous systems[9] and significantly better supraventricular tachycardia (SVT) discrimination compared to transvenous ICDs.[10] Inappropriate shocks in S-ICDs are almost exclusively due to double counting secondary to T-wave oversensing.[9] We report a patient with an S-ICD and hypertrophic cardiomyopathy (HCM) who received an inappropriate shock for atrial fibrillation due to oversensing of atrial fibrillatory waves. This has not been reported previously.

Case report

A 38-year-old man with HCM underwent secondary prevention transvenous ICD implantation in 2006 after resuscitation from an out-of-hospital ventricular fibrillation arrest. His device was explanted in 2007 because of endocarditis from intravenous drug use and later reimplanted. He had recurrent endocarditis in 2011, requiring extraction of the second ICD system. He also had long-standing persistent atrial fibrillation and antiphospholipid syndrome with multiple deep venous thromboses and pulmonary embolisms. He presented to our institution with diastolic heart failure. His presenting electrocardiogram (ECG) showed coarse atrial fibrillation (Figure 1A), and his transthoracic echocardiogram showed a left ventricular ejection fraction of 70% with a septal thickness of 21 mm and a left atrial size of 56 mm.

After prolonged abstinence from intravenous drug use, an ICD system was deemed to be appropriately indicated and an S-ICD system was chosen. The S-ICD patient screening tool confirmed candidacy in both supine and upright positions. He underwent implantation of an A209 EMBLEM S-ICD (Boston Scientific Corporation, Natick, MA) without incident; a primary sensing configuration (proximal electrode ring to pulse generator) was chosen. The defibrillation testing threshold was 65 J with appropriate sensing.

The device was programmed with a conditional zone using morphology discrimination for rates between 200 and 230 beats/min and an unconditional shock zone for rates greater than 230 beats/min. Two-view chest radiographs showed appropriate electrode and generator placement (Online Supplemental Figures 1A and 1B). The ECG postprocedure showed sinus rhythm with biatrial hypertrophy (Figure 1B).

He was admitted 2 months later with rapid atrial fibrillation and diastolic heart failure and had received an ICD shock. Device interrogation of the event (Figure 2) showed atrial fibrillation with oversensing of atrial fibrillatory waves resulting in device discharge. Four consecutive oversensed atrial fibrillatory waves (second row, decision phase) resulted in classification in the shock zone; after 18 of 24 events were binned, a shock was delivered. There was no evidence of T-wave oversensing or bundle branch aberrancy during tachycardia. The chest radiograph showed unchanged electrode and generator position. The sensing configuration was changed to alternate and SMART Pass filter software upgrade was applied. He had recurrent rapid atrial fibrillation 1 month later without further shocks.

Discussion

Inappropriate shocks may occur in up to 13% of patients with transvenous ICD systems.[7,8] Series on S-ICD systems have

KEYWORDS Atrial oversensing; Hypertrophic cardiomyopathy; Subcutaneous ICD; Atrial fibrillation; Inappropriate shock
(Heart Rhythm Case Reports 2017;3:e1–e6)

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http://dx.doi.org/10.1016/j.hrcr.2016.12.004

KEY TEACHING POINTS

- Inappropriate shocks in subcutaneous implantable cardioverter-defibrillators are known to occur from oversensing of ventricular events (T-wave oversensing and rapid ventricular rates falling into the shock zone) or noise.
- We report a patient with hypertrophic cardiomyopathy who had inappropriate shock for atrial fibrillation due to atrial oversensing of fibrillatory waves, which has not been described before.
- Patients with hypertrophic cardiomyopathy may be uniquely susceptible to atrial oversensing due to atrial hypertrophy and high R-wave slew rate; careful screening is warranted before subcutaneous implantable cardioverter-defibrillator implantation.

demonstrated a lower risk thus far. The EFFORTLESS S-ICD study showed a 7% rate of inappropriate shocks for S-ICDs at 360 days due to atrial fibrillation, atrial flutter, and SVT with fast ventricular response rate. A total of 73 inappropriate shocks were recorded in 32 patients. Eighty-five percent were due to oversensing, and of those, 94% were due to oversensing of cardiac signals (31% T waves; 53% low-amplitude signals). In the remaining patients, inappropriate therapy was due to noise/electromagnetic interference, SVT that crossed into the shock-only zone, and discriminator error due to signal clipping. Notably, dual-zone programming had a 6.4% inappropriate shock rate whereas single-zone programming had a 12% rate.[9] Direct oversensing of atrial fibrillatory waves has not been reported.

Arrhythmia detection in S-ICDs relies on differential sensing from a selectable pair of the S-ICD system's 3 subcutaneous ring-shaped sensing electrodes situated at the subcutaneous lead tip (A) and on the lead proximal to the parasternal shocking coil (B). A third sensing electrode consists entirely of the pulse generator housing (CAN). Among these electrodes, 3 programmable sensing vectors are available for S-ICD sensing (A to CAN; B to CAN; A to B). Optimal vector selection occurs at the time of implantation according to an automatic programmer–based setup algorithm that selects the best vector on the basis of multiple criteria including signal quality, R-wave amplitude, and R-wave/T-wave amplitude ratio. During continuous operation, T-wave oversensing and low-amplitude signal detection are avoided using a proprietary nonprogrammable detection algorithm consisting of variable blanking periods, fixed sensitivity periods, and exponentially auto-adjusting sensing periods that adapt according to the average of the 2 most recent R-wave amplitudes but adjust on a beat-to-beat basis, much like transvenous ICDs. Effective sensitivity is steadily increased as heart rate progresses through low to mid to high rates and when the ventricular rate (based on a 4 beat average) exceeds the programmed tachycardia detection threshold at which time the sensing floor drops to 0.08 mV (Online Supplemental Figure 2). Within the first level "detection phase," inappropriate therapy is avoided by processing cardiac signals through 3 double-detection algorithms that strive to eliminate inappropriate therapy that may result from R-wave double counting and T-wave oversensing.

Certified events are subsequently examined (Online Supplemental Figure 3) and rate classified using a continuous 4 R-R interval moving average. Singular events falling within the programmable "conditional shock zone" undergo morphology and width analysis, whereby sensed events are compared to a 40-sample digital template of a normally conducted (eg, sinus) R wave in order to determine whether the event should count toward tachyarrhythmia detection. R-waves having $>50\%$ correlation with the sinus template and with narrow QRS are classified as supraventricular in origin and are not counted. Tachyarrhythmia detection and charge initiation require 18 of 24 tachyarrhythmia classified events. Finally, a confirmation algorithm is used throughout to further avoid inappropriate therapy.[10]

The inappropriate shock in our patient with HCM resulted from atrial oversensing, not T-wave oversensing as has been previously described. In our case, the elevated average ventricular rate during atrial fibrillation resulted in adaptation of the S-ICD effective sensitivity to a more sensitive level. Consequently, rapidly occurring atrial fibrillatory waves having relatively large amplitude in the setting of HCM were detected in the tachyarrhythmia detection zone, which further increased the S-ICD's sensitivity. Ultimately, this leads to a cascade of oversensing within the unconditional shock zone, which persisted during charging, and ultimately inappropriate therapy. Since the atrial fibrillatory waves were determined as being within the shock zone (despite ventricular rate being much slower), morphology discriminators were not applied. The surface ECG as well as the echocardiogram showed severe left atrial hypertrophy, which contributed to atrial oversensing.

A key requirement of atrial oversensing in our case was a "baseline shift" that occurred by 6 seconds into tachycardia (Figure 3) after which oversensing starts. The baseline shift occurred because the R wave had a high amplitude and rapid upstroke (ie, slew rate), which exceeded the dynamic processing ability of the analog-to-digital converter (ADC) circuit. The biphasic nature of the R wave does not play a role. The SMART Pass (band-pass) filter, which is a software upgrade for the S-ICD, uses a different range (9–40 Hz vs 3–40 Hz) that removes any DC bias from the ADC as the filtering occurs in the digital domain after ADC occurs.

Figure 3 shows simulation of the effect of the SMART Pass filter on fibrillatory wave and T-wave amplitudes both before (Figure 3A) and after (Figure 3B) the baseline shift in our patient is shown. Superimposed are the sensitivity decay curves. Downward arrows indicate atrial oversensing. The T waves and F waves are much smaller after the application of

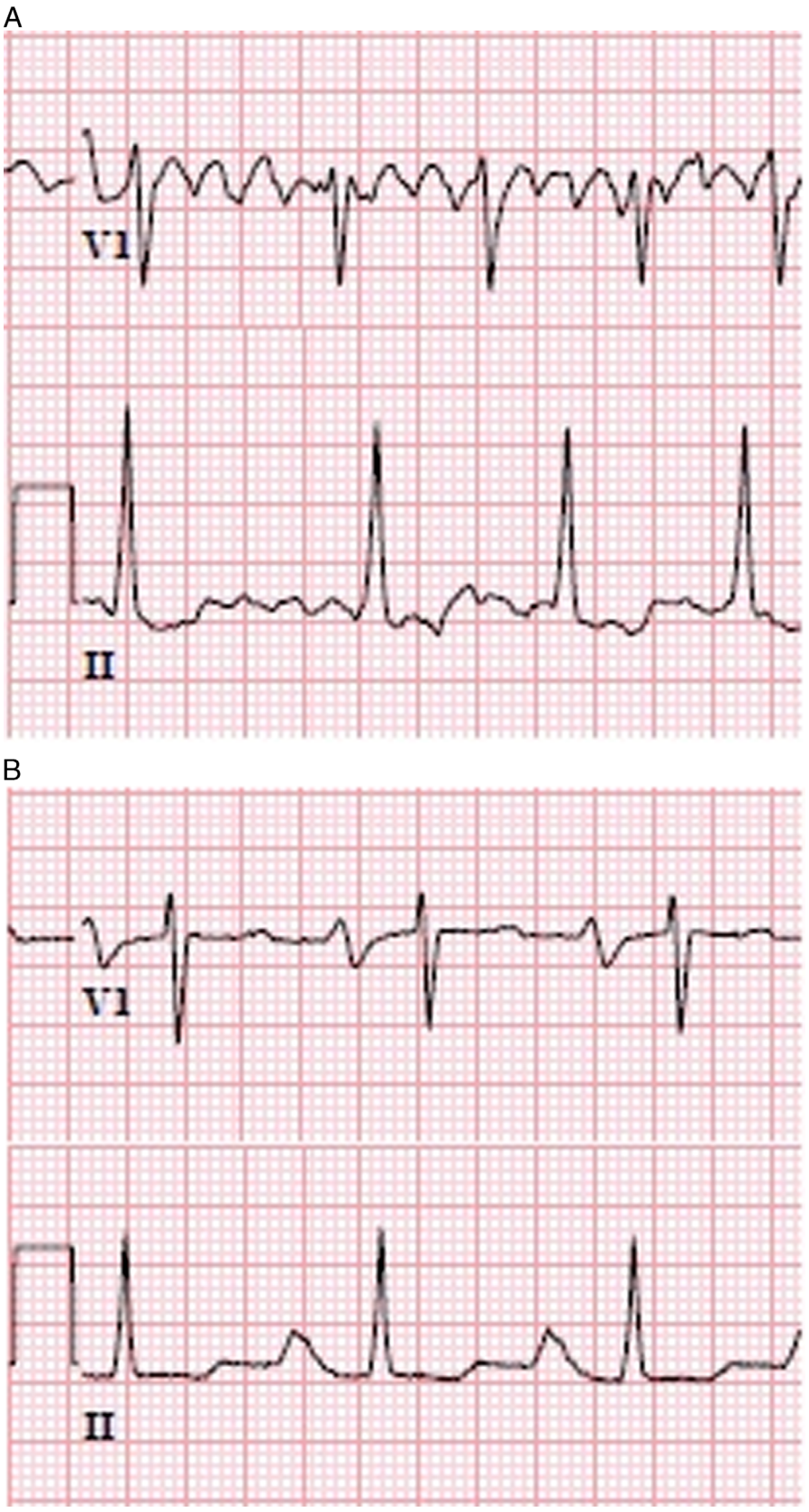

Figure 1 **A:** Baseline electrocardiogram showing coarse atrial fibrillation. **B:** Electrocardiogram postprocedure showing sinus rhythm with biatrial hypertrophy.

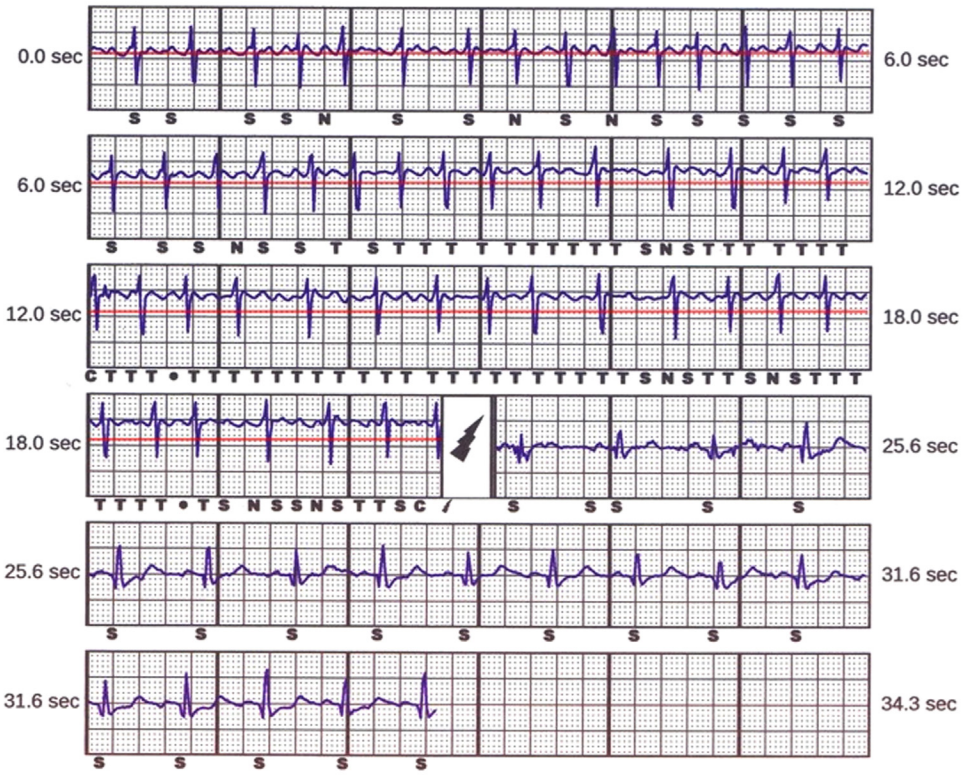

Figure 2 Device interrogation showing oversensing of atrial fibrillatory waves. Four consecutive oversensed atrial fibrillatory waves (second row, decision phase) result in rate detection classification in the shock zone; after 18 of 24 events are binned, a shock is delivered. The baseline (red line) begins to shift around 6 seconds, which corresponds to initiation of oversensing. ● = discard; C = charge start; N = noise; S = sense; T = tachyarrhythmia detection.

the filter, which would be less likely to be oversensed. As with T-wave oversensing, high-amplitude fibrillatory waves would predispose to oversensing when a baseline shift occurs. The baseline shift resulting in inappropriate therapy has been reported in 0.06% patients; there have been more than 19,000 S-ICD implants to date (D Casavant, MS, written communication, September 29 2016).

Since HCM is a common cause of death in young adults,[11] S-ICDs are often chosen as an appropriate choice for prevention of sudden death in this population. A meta-analysis of 27 studies on 16 cohorts showed annualized appropriate and inappropriate ICD intervention rates of 3.3% and 4.8%, respectively, in patients with HCM.[12] Pooled data from the EFFORTLESS and IDE cohorts showed inappropriate shocks occurred in 12.5% of patients with HCM and 10.3% of patients without HCM.[13] The vast majority of inappropriate shocks in prior reports of patients with HCM are from oversensing of ventricular events.[13]

There is only 1 other report of atrial oversensing in an S-ICD leading to inappropriate therapy, which was interestingly in a patient with HCM who developed atrial flutter.[14] Because of repeated shocks, he had explantation of the S-ICD and replacement with a conventional transvenous system. His echocardiogram showed severe biatrial enlargement. We postulate that severely hypertrophied atria and R waves with high slew rates as seen in HCM may predispose to direct oversensing of atrial signals. The SMART Pass filter can reduce this risk, but undersensing of fine ventricular fibrillation is a theoretical downside. Enhanced methods for screening (consideration for atrial size and QRS slew rate) may be appropriate in this population. Caution may be warranted in the patient with HCM with high-voltage P waves or atrial fibrillatory waves.

Conclusion

Patients with HCM have a higher incidence of inappropriate ICD shocks due to atrial arrhythmias; most of those with S-ICDs receive them because of T-wave oversensing. We present a patient who received inappropriate S-ICD therapy because of atrial oversensing for atrial fibrillation, which is a new observation. Patients with HCM who often have high-amplitude R waves with high slew rates may be particularly susceptible to this phenomenon, and improved screening approaches may be needed.

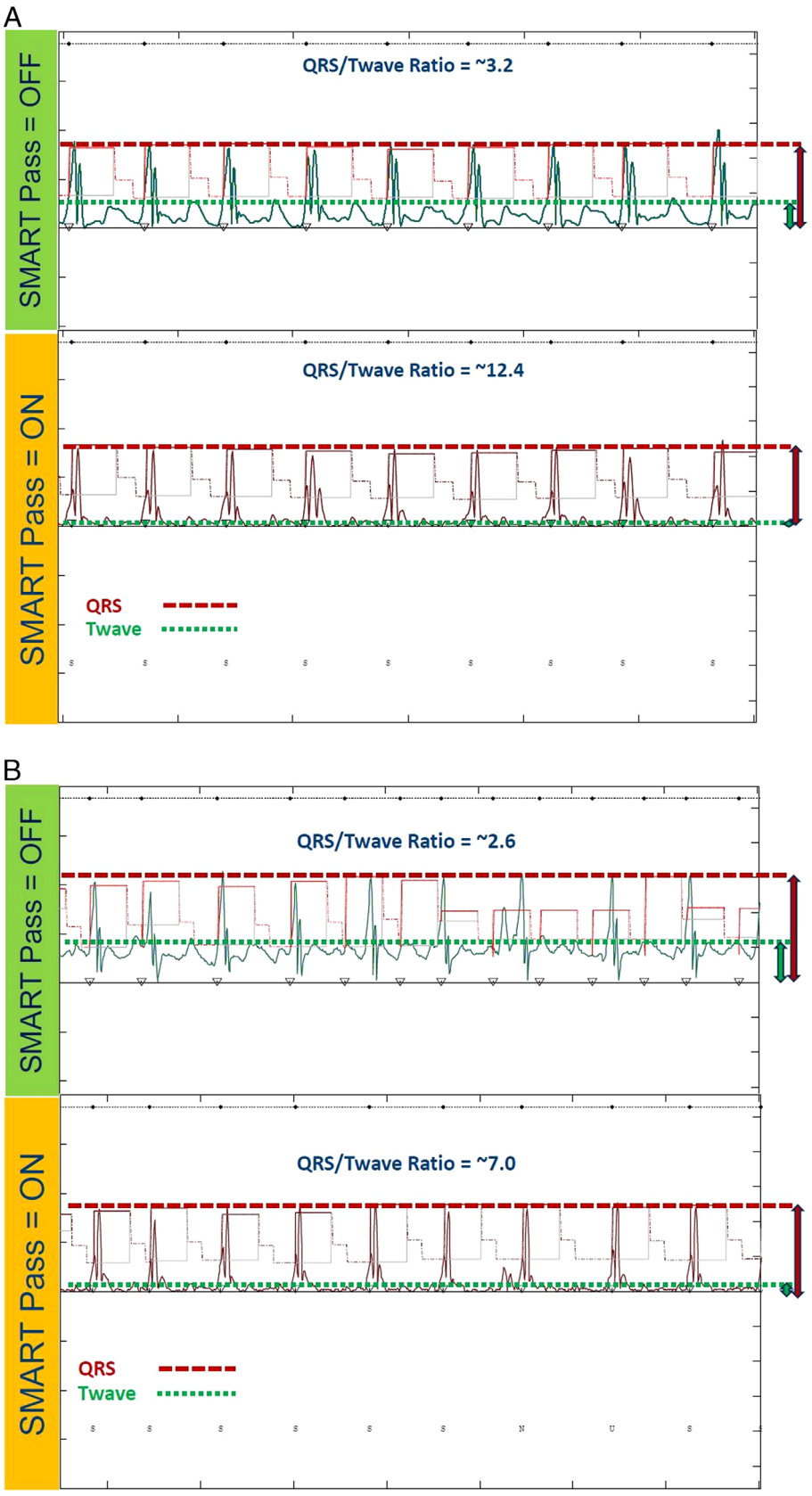

Figure 3 **A:** Tachycardia before the baseline shift, with SMART Pass both OFF (top) and ON (bottom). Superimposed are the sensitivity decay curves. The QRS/T-wave ratio is much higher after SMART Pass filter application, indicating less susceptibility to oversensing. Some oversensing (downward arrows) is seen without the SMART Pass filter. **B:** Tachycardia event after the baseline shift, with SMART Pass both OFF (top) and ON (bottom). Superimposed are the sensitivity decay curves. Atrial oversensing (downward arrows) is eliminated with the SMART Pass filter.

Acknowledgments

We thank David Casavant, MS, and Steven Donnelley, MSS (Clinical Engineers, Boston Scientific), for technical insights.

Appendix

Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.hrcr.2016.12.004.

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