ICD Sees What You Do Not See: How Does It Beat You?

SERGE Y. STROOBANDT, M.Sc., M.B.A.,* MARCO BRIEDA, M.D.,†
GIUSEPPE ALLOCCA, M.D.,‡ and ROLAND X. STROOBANDT, M.D., Ph.D.*

From the *Ghent University Hospital, Heart Center, Ghent, Belgium; †Cardiology Unit, Azienda Ospedaliera Santa Maria degli Angeli, Pordenone, Italy; and ‡Department of Cardiology, Unit of Electrophysiology, General Hospital of Conegliano, Conegliano, Italy

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Case Presentation

We report about two Italian patients equipped with an implantable cardioverter defibrillator (ICD) who experienced bodily conduction of mains electric current in different countries. These events triggered remote monitoring alerts for atrial episodes. Device interrogation revealed substantial differences between both cases in the recorded noise patterns of the far-field and atrial intracardiac electrograms (Fig. 1). Why are these noise patterns different?

Patient 1 in Italy

A 70-year-old man with ischemic cardiomyopathy, left ventricular ejection fraction (LVEF) 42%, diabetes, and chronic renal failure suffered ventricular fibrillation (VF) during hemodialysis in the absence of electrolyte disturbances. In 2011, a single-chamber ICD was implanted (Lumax 540 DX, Biotronik, Berlin, Germany) with a right ventricular shock lead (Biotronik Linox smart S DX), featuring a floating atrial dipole. The device was programmed for VT-1 zone > 158 beats per minute (bpm) with antitachypacing (ATP) 3 × burst, VT-2 zone > 176 bpm (3 × burst and then 30 J and 7 × 40 J). The VF rate was set at 222 bpm (8 × 40 J). About 1 year later, an atrial episode remote monitoring alert was received. At the time of the recording of Figure 1(A), atrial sensitivity was set at 0.4 mV and ventricular sensitivity was 0.8 mV. Shock impedance measured 52 Ω and pacing lead impedance 496 Ω. Patient interview at follow-up revealed accidental contact with the mains at home (Fig. 1A).

Patient 2 in Venezuela

A 50-year-old man with a nonischemic cardiomyopathy and LVEF 22% received a Biotronik Lumax 540 ICD in primary prevention. The ICD was connected to a Linox smart shock lead (Biotronik) and an atrial lead 4574 (Medtronic Inc., Minneapolis, MN, USA). The device was programmed for >182 bpm with ATP followed by shocks. The VF rate was 200 bpm with ATP (one burst) followed by shocks. On a visit to Venezuela, the Italian patient experienced a tingling sensation when showering. ICD parameters at the time of the recording were: atrial sensitivity set at 0.4 mV and ventricular sensitivity 0.8 mV (Fig. 1B).

Commentary

Analysis of Intracardiac Electrograms

In patient 1 (Fig. 1A), the far-field channel shows an erratic pattern with 10 positive deflections in 200 ms, characteristic of a European 50-Hz mains signal, whereas in patient 2 (Fig. 1B), the far-field channel shows 12 positive deflections in 200 ms, which corresponds to the North and Central American 60-Hz mains frequency. Moreover, wave packages or beats can be observed at a rate of eight per second (8 Hz). Taken two by two, these beats show the characteristic envelope of a double-sideband (DSB) amplitude-modulated carrier.[1] In this case, the carrier is the 60-Hz mains, whereas the modulating signal appears to be a much slower cyclic sinusoidal tone, intertwining the beats. Since two beats correspond to one cycle of the modulating tone, the tone frequency is only half the beat rate; thus, 4 Hz. Intriguingly, a mains signal always tends to be purely sinusoidal without any modulation, rendering the origin of the 4-Hz tone essentially extraneous and perplexing.

Simulation of the ICD Sampling Process

To understand the recordings, the sampling process of the ICD was reproduced by computer

Address for reprints: Roland Stroobandt, M.D., Ph.D., Ghent University Hospital, Heart Center, De Pintelaan 185, 9000, Ghent, Belgium. Fax: +32 59 50 38 08; e-mail: roland@stroobandt.com

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Table I.

Overview of Frequencies Pertaining to Figure 2

Figure	Mains Frequency	Sampling Rate	Nyquist Frequency	Beat Tone
	f_m (Hz)	f_s (Hz)	$\frac{f_s}{2}$ (Hz)	$f_t = \frac{f_s}{2} - f_m$ (Hz)
2A	60	128	64	4
2B	50	128	64	14
2C	60	512	256	196

Table II.

Manufacturer-Specific Sampling Rates for Real-Time Analysis and Electrogram Storage

Manufacturer	Sampling Rate Real-Time Analysis (Hz)	Sampling Rate Stored IEGM (Hz)
Biotronik[4]	512	128
Boston Scientific[5]	400	200
Medtronic[6]	1,000	128
St. Jude Medical[7]	512	128
Sorin[8]	512	128

IEGM = intracardiac electrogram.

simulation. Sampling consists of measuring the amplitude of a signal at set intervals. The interval rate corresponds to the sampling frequency f_s. Sixty-and 50-Hz mains signals sampled at 128-Hz resulted in reconstruction signals (Figs. 2A and B), similar to those stored by the ICD. Hence, the origin of the 4-Hz amplitude modulation on the 60-Hz mains recording must be an inherent artifact of the ICD sampling process.

Beat Tone

Sampling of a signal with a frequency below half the sampling frequency $f_s/2$ induces a beat tone[2,3] of frequency $f_t = (f_s/2) - f_m$. Half the sampling frequency is called the Nyquist frequency or folding frequency. Biotronik Lumax 540 series ICDs have a recording sampling frequency f_s of 128 Hz, resulting in a Nyquist frequency $f_s/2$ of 64 Hz. The 4-Hz beat tone as noticed with patient 2 (Figs. 1B and 2A) results from subtracting the measured 60 Hz mains frequency from the ICD's 64-Hz half sampling frequency during recording (Table I). Similarly, sampling of a 50-Hz mains signal at a sampling rate of 128 Hz results in a beat tone of 14 Hz (Fig. 2B) which is, compared to the 60-Hz case, less apparent and more erroneous because of its higher frequency. A 60-Hz mains signal was also sampled at 512 Hz (Fig. 2C). According to the manufacturer,[4] this higher sampling frequency is used internally by the ICD for signal processing and marker annotation, as opposed to the 128-Hz sampling rate for signal recording. With a sampling rate of 512 Hz, no apparent beat can be discerned. Beating remains present but is not visible due to the high beat tone frequency of 196 Hz. Beating is clearly different from fold-back aliasing; the latter occurs when sampling signals with a frequency above the Nyquist frequency.

Clinical Implications

Accidental contact with the mains may cause oversensing in the atrial and ventricular channel. This may result either in inhibition of pacing for bradycardia, triggering of pacemaker stimuli when programmed in a tracking mode, or inappropriate delivery of ATP and/or shocks. Preferred detection of electromagnetic interference (EMI) in the atrial channel is not uncommon because atrial sensitivity is usually programmed more sensitive than the ventricular channel. As mains electric current flows through the human body, a voltage drop occurs between the current entry and exit points on the body. This voltage drop is proportional to the resistance and therefore the distance traveled inside the body. Hence, mains potentials measured by the far-field channel are far higher than those of the bipolar ventricular channel, because the electrode separation is greater. Furthermore, a proprietary Biotronik digital noise gating algorithm will replace signals with amplitudes below the detection threshold by zeroes, resulting in a smooth flat line. Stored intracardiac electrograms (IEGMs) are retrieved during patient follow-up or through remote monitoring. IEGMs allow the physician to check whether the device rightfully declared an episode based on cardiac events, or whether EMI was involved. However, real-time analysis of intracardiac signals for sensing and detection does occur at a sampling rate of 512 Hz in the above-mentioned ICDs and is therefore not subject to beating at mains

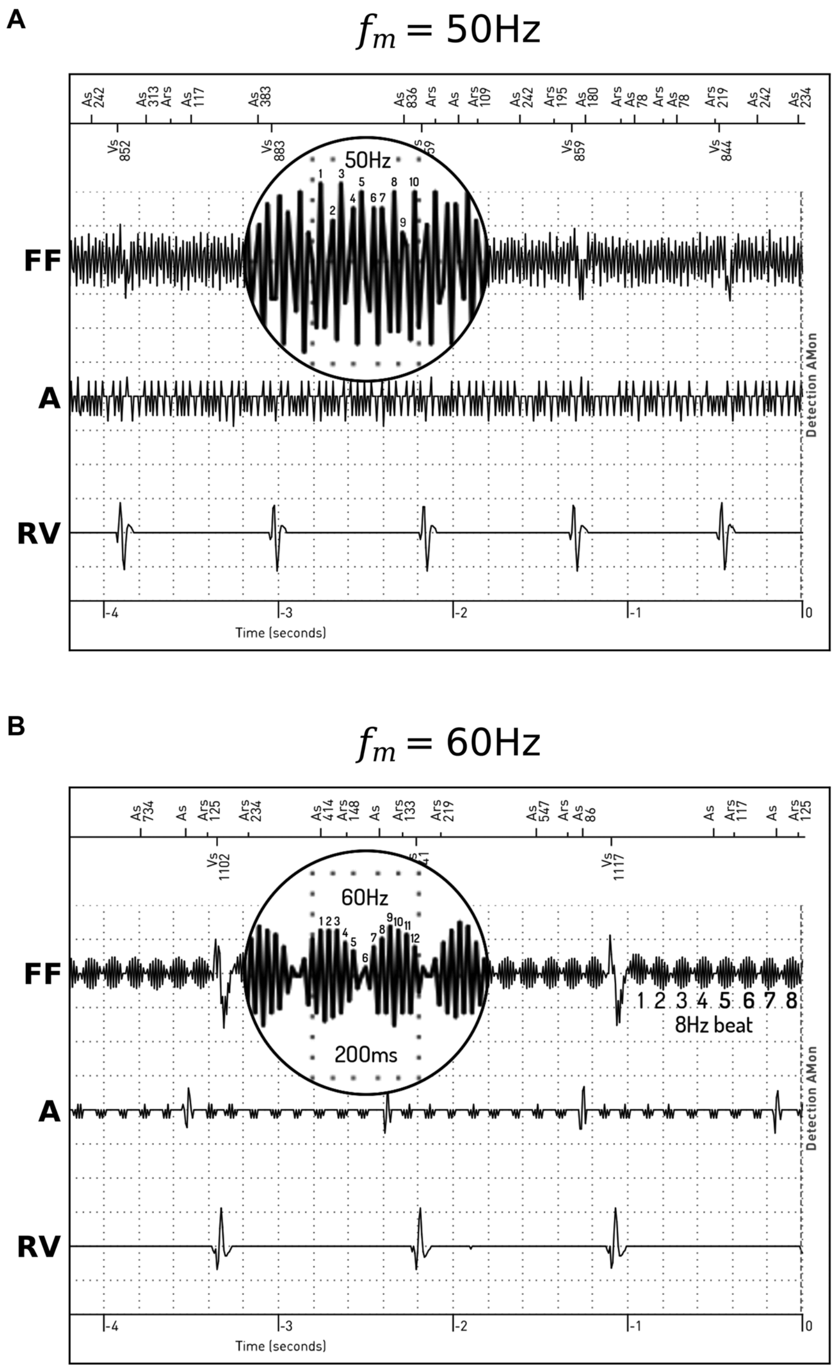

Figure 1. *Intracardiac electrograms (IEGM) of the detection of an atrial episode as recorded by the far-field (FF) and atrial (A) channels of Biotronik Lumax 540 series implantable cardioverter defibrillators in the case of, respectively, (**A**) (Lumax 540 DX) 50-Hz and (**B**) (Lumax 540) 60-Hz mains frequency f_m. Noise signals are only recorded in far-field and atrial electrograms. Noise signals on the atrial IEGM are subject to proprietary Biotronik digital noise gating (see text) as well as a small negative bias potential originating from the electrode-tissue half-cell boundary.*

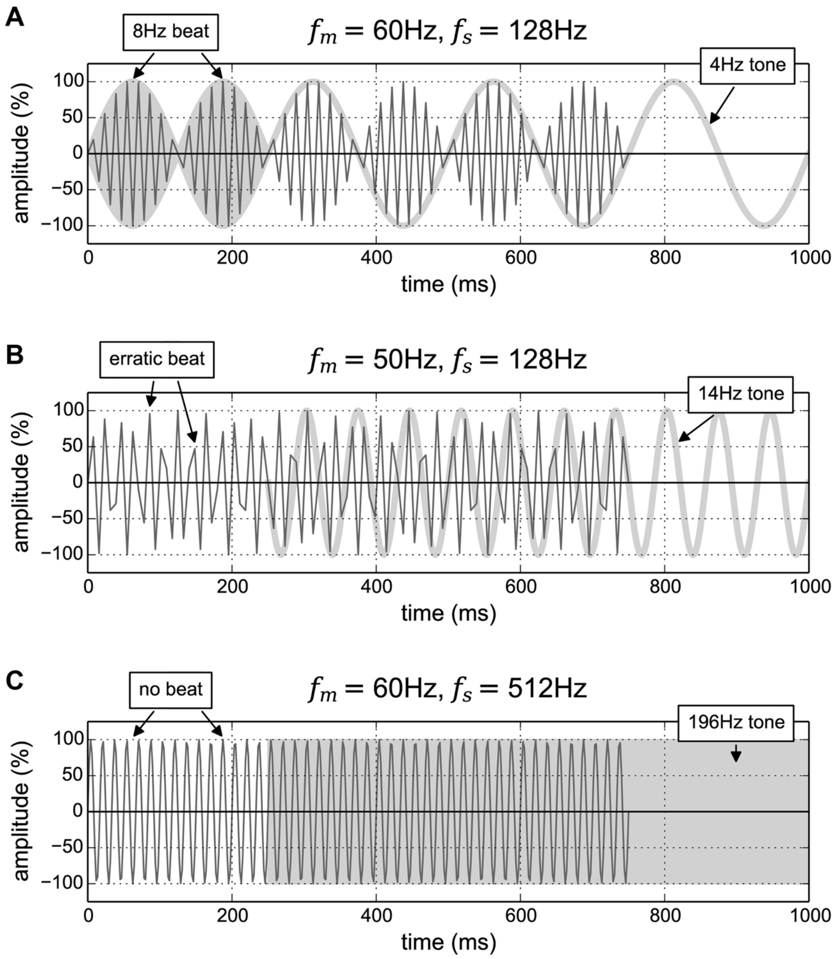

Figure 2. *Simulation of (A) a 60 Hz mains signal sampled at 128 Hz. The reconstructed signal is DSB-modulated with the envelope of a 4-Hz tone. An 8-Hz beat, corresponding to twice the tone frequency, is clearly visible. (B) A 50-Hz mains signal sampled at 128 Hz. The reconstructed signal is DSB-modulated with the envelope of a 14-Hz tone. The beat is very erratic. (C) A 60-Hz mains signal sampled at 512 Hz. The reconstructed signal is DSB-modulated with the envelope of a 196-Hz tone. No beat can be discerned. DSB = double-sideband.*

frequencies. Before storage in device memory, these IEGMs are sampled down to 128 Hz, thereby reducing memory consumption by a factor 4. Manufacturer-specific sampling rates for real-time analysis and IEGM storage are given in Table II.[4–8] Downsampling of IEGMs not only lowers the time resolution, it also may result more readily in sampling-induced artifacts. Nonetheless, manufacturers could improve the reconstruction of recorded signals without having to increase memory size. Beat tone artifacts would be entirely eliminated if the signals were reconstructed using cardinal sine waveforms instead of the currently employed square wave impulses.[3] After all, the Nyquist–Shannon sampling theorem states that a time-continuous, band-limited signal can be recovered exactly from its samples, only when the Whittaker–Shannon interpolation formula is used.[9] This interpolation formula employs cardinal sine-shaped impulses. For now, physicians should be aware that stored IEGMs do not entirely correspond to the higher quality intracardiac signals as analyzed by the device. In a case of electrocution, recorded IEGMs may provide forensic evidence of the mains frequency and hence geographical area of the event.

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