JOURNAL OF THE AMERICAN COLLEGE OF CARDIOLOGY
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PUBLISHED BY ELSEVIER INC.

VOL. 64, NO. 13, 2014
ISSN 0735-1097/$36.00
http://dx.doi.org/10.1016/j.jacc.2014.07.953

EDITORIAL COMMENT

The Ups and Downs of Ventricular Fibrillation Waveforms*

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In this issue of the *Journal*, Indik et al. (1) describe the predictive value of a spectral method to characterize ventricular fibrillation (VF) waveforms for out-of-hospital survival of cardiac arrest. This work adds to the growing body of evidence that electrocardiographic (ECG) recordings during fibrillation can offer useful information beyond simply identifying VF (2,3). The ECG measurement described in the study holds the potential to provide medical emergency responders with an assessment of the state of the cardiac arrest patient to aid resuscitation efforts.

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A continuous undulating waveform with changing amplitude characterizes VF in the surface ECG. It is often described as a chaotic rhythm compared to the orderly PQRST ECG profile seen during normal sinus rhythm, but the periodic nature of the undulations suggests VF has a spatiotemporal structure. Mapping studies have shown that the fibrillatory activity could be driven by rotors (4-6), which may account for the ECG waveform's periodicity. Prior studies analyzing VF waveforms by using frequency domain techniques have shown that the power spectrum of human VF usually has a dominant peak centered around 4 to 6 Hz that often decreases with increasing duration of VF (3). The frequency of the dominant peak roughly corresponds to the number of fibrillation cycles per second and the reciprocal of the cycle length (e.g., 4 Hz corresponds to a cycle length of 250 ms).

The amplitude-spectral area (AMSA) parameter used by Indik et al. (1) is also a measure derived from the frequency domain of the ECG signal. In order to better understand why AMSA may be predictive of out-of-hospital survival in cases of cardiac arrest, it is useful to relate this measurement back to features of the original ECG waveform and in turn to the VF's underlying pathophysiology. The basic premise of Fourier analysis is that any time domain waveform can be decomposed into a set of sine waves with different amplitudes and frequencies. A frequency domain plot displays either the amplitude or power (proportional to the square of the amplitude) of the sine waves by frequency. Thus, signals are commonly transformed to the frequency domain to allow easy identification of periodicities in the signal. Although the mathematics involved in the transformation (often via a fast Fourier transform algorithm for digital signals) is somewhat complex, there are characteristics from both domains that we can easily relate:

1. The variance of a signal in the time domain equals the overall power in the frequency domain.
2. The frequency of the highest power in the frequency domain represents the predominant periodic component in the time domain.
3. A narrow frequency band indicates a highly periodic waveform with a specific frequency, whereas a wider band indicates a waveform with more complex timings.

Figure 1 illustrates this relationship between the time and frequency domains in the context of ECGs recorded during VF. The signals used in these

*Editorials published in the *Journal of the American College of Cardiology* reflect the views of the authors and do not necessarily represent the views of *JACC* or the American College of Cardiology.

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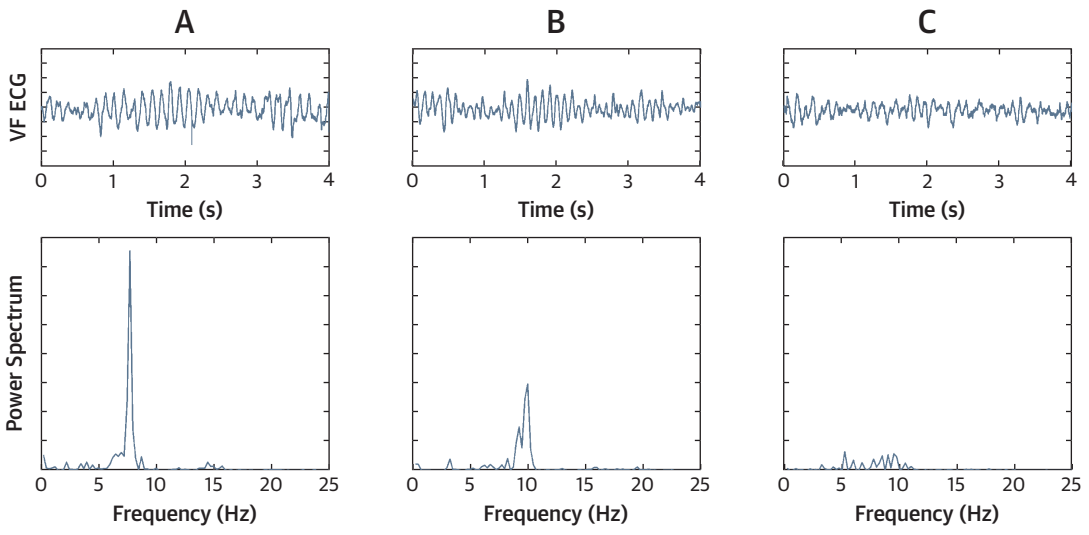

FIGURE 1 Surface Electrocardiographs Recorded During Ventricular Fibrillation From 3 Canine Studies With Corresponding Power Spectra

(A) ECG with clear periodicity of 7 to 8 oscillations per second and a power spectrum with a narrow peak centered at 7.7 Hz. **(B)** ECG having roughly 10 oscillations per second and lower amplitude, and a corresponding power spectrum with a peak at 10 Hz and lower overall power. **(C)** A more complex and lower amplitude ECG with a low and broad power spectrum. VF ECG = ventricular fibrillation electrocardiographic recordings.

examples were obtained during canine experiments. Figure 1A shows a VF ECG with clear periodicity. The corresponding power spectrum below the ECG has a narrow peak centered at 7.7 Hz. Closer inspection of the ECG waveform will confirm between 7 and 8 oscillations per second. Figure 1B shows another VF tracing with faster oscillations (roughly 10 oscillations per second) and lower amplitude overall than the tracing in Figure 1A. The corresponding power spectrum in Figure 1B shows a peak at 10 Hz and lower overall power as expected. The ECG in Figure 1C shows a more complex waveform with even lower amplitude. Although there are some discernable oscillations, they are not as regular as the previous 2 examples. As a result, the power spectrum is very broad, with low power components within the 5- to 10-Hz region. These illustrations serve to demonstrate how information about rate, amplitude, and regularity of VF ECGs can be obtained in the frequency domain.

Indik et al. (1) used AMSA as a measurement with which to characterize VF waveforms. This measurement is derived from the sum of the square root of power for frequencies between 4 and 48 Hz. As we have illustrated, differences in AMSA values could be due to differences in the rate, amplitude, and regularity of the VF oscillations. For example, if amplitude and regularity of the VF waveform were the same, VF with a peak in the power spectrum centered at a frequency less than 4 Hz would have a lower AMSA value than one with a peak centered at a frequency above 4 Hz. Thus, the finding that higher AMSA is predictive of return of spontaneous circulation (ROSC) following defibrillation is consistent with previous studies indicating that patients who had successful defibrillation were more likely to have VF ECGs with higher dominant frequencies.

Goto et al. (7) showed that VF out-of-hospital survivors had a mean VF dominant frequency of 6.45 ± 0.36 Hz, whereas nonsurvivors with some ROSC or no ROSC had significantly lower mean dominant frequencies of 4.77 ± 0.22 Hz and 3.13 ± 0.27 Hz, respectively. Similarly, Stewart et al. (3) demonstrated that the mean dominant frequency of primary VF (no cardiogenic shock or cardiac failure) where survival was greater was significantly higher than that of secondary VF (cardiogenic shock or heart failure), where survival was low (6.2 ± 0.2 Hz vs. 4.0 ± 0.2 Hz, respectively; $p = 0.0001$) (3). Thus, it seems that the 4-Hz cutoff used for AMSA in the study by Indik et al. (1) was well chosen to identify survivors. Interestingly, neither the study by Stewart et al. (3) nor Goto et al. (7) showed differences in VF amplitude between survivors and nonsurvivors. The regularity of the oscillations was not studied.

In the first few minutes of VF, dominant frequency has been shown to fluctuate before progressively decreasing with time. It has therefore been proposed that frequency characteristics could be used to predict duration of VF (8). Cycle lengths of rotor-based fibrillation are bounded by the refractory period of the myocardium. It is likely that the combined effects of sustained VF on the myocardium, ischemia, acidosis, and increased extracellular potassium, contribute to increased refractory periods, thereby decreasing VF dominant frequency (9). Reperfusion and cardiopulmonary resuscitation have been shown to increase VF frequency (10-12).

Additionally, ECG amplitude decreases with VF duration (13). However, unlike ECG dominant frequency, which mostly provides a direct measure of the rate of VF oscillations, ECG amplitude is affected by other factors not related to the arrhythmia itself. For example, amplitude can be influenced by location of the defibrillator patches and impedance of the skin-electrode interface, body dimensions (14), cardiac axis, and others. Therefore, without knowing the amplitude near the onset of VF as a baseline, the use of amplitude to ascertain VF duration is not ideal. This is an important consideration when comparing the AMSA parameter from patient to patient. We recommend further investigation in comparing the predictive value of AMSA with independent measures of dominant frequency, amplitude, and regularity, as all 3 of these features affect AMSA.

We congratulate Indik et al. for advancing our knowledge regarding ECG predictors of ROSC but caution that it is still premature to propose this as a measurement "to determine if continuing the resuscitation efforts would likely be futile." The false negative rate (1 minus the negative predictive value, meaning the test predicts death but the patient attains either ROSC, hospital admission, or hospital discharge) for the various endpoints ranges from 6.5% to 13.1%. In the field of resuscitation, this would still represent a significantly positive outcome worth pursuing. We also recommend further study of how AMSA or other ECG measures relate to VF and the underlying pathophysiology. As ECG waveforms all have their "ups and downs," both literally and figuratively, a better understanding of the strengths and limitations of both the signal processing and the interpretation of the signal itself can make sure that they are optimally designed and implemented in the most appropriate manner.

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KEY WORDS cardiac arrest, ventricular fibrillation, waveform