Analysis of the Ventricular Fibrillation ECG Signal Amplitude and Frequency Parameters as Predictors of Countershock Success in Humans*

Hans-Ulrich Strohmenger, MD; Karl H. Lindner, MD; and Charles G. Brown, MD

Objective: **The purpose of this study was to assess from the ventricular fibrillation ECG signal whether certain amplitude parameters, or frequency parameters derived using fast Fourier transform analysis, are predictive of countershock success (defined as a stable supraventricular rhythm following countershock).**
Design: **Retrospective, descriptive study.**
Setting: **Emergency medical service at a university hospital.**
Patients: **Twenty-six patients with out-of-hospital cardiac arrest, whose initial ECG rhythm was identified as ventricular fibrillation.**
Methods and results: **In all patients, advanced cardiac life support was performed in the out-of-hospital setting and a semiautomatic defibrillator was used for countershock therapy and simultaneous on-line ECG recording. For each patient, ECG data were stored in modules in digitized form over a period of 20 min and analyzed retrospectively. Using fast Fourier transform analysis of the ventricular fibrillation ECG signal in the frequency range of 0.3 to 30 Hz (mean±SD), median frequency, dominant frequency, edge frequency, and amplitude were as follows: 5.17±1.05 Hz, 4.56±0.99 Hz, 10.74±3.46 Hz, and 1.33±0.44 mV before successful countershock (n=20); and 4.21±1.17 Hz (p=0.0034), 3.31±1.57 Hz (p=0.0004), 9.46±2.93 Hz (p=0.5390), and 1.15±0.69 mV (p=0.0134) before unsuccessful countershock (n=134). Using software filters to completely eliminate interference due to manual cardiopulmonary resuscitation from the ventricular fibrillation power spectrum, only amplitude remained statistically different (p≤0.03) in predicting countershock success.**
Conclusions: **We conclude that in patients, median frequency, dominant frequency, and amplitude are predictive of countershock success in humans.** *(CHEST 1997; 111:584-89)*

Key words: cardiac arrest; fast Fourier transformation; ventricular fibrillation

Abbreviations: CPR=cardiopulmonary resuscitation; VF=ventricular fibrillation

Countershock is the method of choice for the treatment of ventricular fibrillation (VF).[1] Although countershock therapy is often successful when applied immediately after the onset of VF, the probability of asystole, electromechanical dissociation, or persistence of VF increases when countershock is applied after more prolonged durations of VF.[2,3] Adequate coronary perfusion pressure during cardiopulmonary resuscitation (CPR) is crucial for successful countershock therapy following prolonged VF and after vasopressor treatment. Countershock therapy applied at the highest myocardial perfusion is a promising therapeutic approach.[4,5] During out-of-hospital cardiac arrest, however, invasive on-line measurement of coronary perfusion pressure cannot be performed and at present, there are no reliable noninvasive parameters to guide countershock therapy and concurrent drug therapy. In animal studies, VF frequency, a variable that can be extracted noninvasively from the VF ECG signal using fast Fourier transformation, has been shown to correlate

*From the Department of Anesthesiology and Critical Care Medicine, University of Ulm, Germany (Drs. Strohmenger and Lindner); and the Department of Emergency Medicine, The Ohio State University, Columbus (Dr. Brown).
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Reprint requests: Dr. Strohmenger, Universitätsklinik für Anästhesiologie, Steinhövelstraße 9, D-89075 Ulm/Donau, Germany.

with myocardial blood flow during CPR and to reflect the probability of successful countershock in particular.[6,7] Therefore, the purpose of this study was to investigate whether in patients with out-of-hospital cardiac arrest, VF frequency and amplitude parameters are predictive of successful countershock. In addition, we investigated the effect of mechanical CPR artifacts on VF ECG spectral analysis.

Materials and Methods

ECG recordings of 26 patients with out-of-hospital arrest were retrospectively evaluated. In all patients, cardiac etiology was presumed as the immediate cause of cardiac arrest and VF was identified as the initial ECG rhythm. Cardiopulmonary resuscitation and countershock therapy were performed in the out-of-hospital setting by the staff of the emergency medical service at a university hospital and all patients were treated in accordance with 1992 advanced cardiac life support recommendations of the America Heart Association. In particular, the first three countershocks were performed at an energy setting of 200 J, 200 J, and 360 J. All further countershocks were performed at an energy setting of 360 J. No further demographic, clinical, or pharmacologic data were available in the study group.

A semiautomatic defibrillator (Heartstart 3000; Laerdal; Stavanger, Norway) was used for countershock therapy and simultaneous on-line ECG recording. The self-adhesive ECG/defibrillation electrodes were attached on the patient's skin to conform with a standard lead II configuration. Resuscitation efforts were stopped at least 12 s before each countershock in an attempt to eliminate potential noise, *ie*, interference from CPR. The ECG data were stored in modules in digitized form (sampling rate, 100 Hz). The frequency bandwidth of the ECG record was 0.3 to 40 Hz. ECG recordings were performed over a period of 20 min for each patient. Using a noncommercial software package (Laerdal) and a postscript printer, all ECG data were later transformed again into analog ECG hard copies, where cardiac rhythm before and after each countershock attempt, as well as periods with or without CPR chest compression, could be identified.

Frequency content for each 3-s period of the VF ECG signal just prior to countershock has been analyzed using fast Fourier transformation. The fast Fourier algorithm is a signal processing method that allows any periodic signal such as the VF ECG signal to be decomposed into its frequency components.[8] Median frequency, dominant frequency, or edge frequency are single-valued parameters that describe the frequency distribution in the resulting power spectrum. In particular, median frequency represents the frequency at which half of the power of the spectrum is above and half below,[8,9] dominant frequency represents the frequency corresponding to the power spectrum maximum,[10] and edge frequency corresponds to the frequency below which 95% of the area under the power spectrum curve resides. The frequency resolution was 0.33 Hz. In addition, measurement of amplitude was made from the original time-domain ECG signal by calculating the difference between the maximum and minimum amplitude for each 3-s segment of the ECG just prior to the countershock using the same computer program. In addition, to assess whether prolongation of the fast Fourier transform window could improve the probability of predicting successful countershock, these same parameters were also evaluated during a 12-s period prior to each countershock.

Countershock was regarded as successful when VF was converted to a supraventricular rhythm (rate ≥60/min and QRS duration <0.12 s) for at least 1 min without any ongoing CPR. Determination of success or failure was done prior to the determination of the frequency and amplitude parameters.

In addition, in 15 of the 26 patients, median frequency, dominant frequency, edge frequency, and amplitude were evaluated during the 12-s interval immediately before and after starting closed-chest CPR to evaluate the effect of closed-chest CPR on the fast Fourier transform analysis and on the time domain VF ECG signal. These analyses were done on separate ECG segments unrelated to the countershock event.

For the calculation of median, dominant, and edge frequency, it was possible to specify the frequency range in the frequency domain. The frequency bandwidth initially chosen was 0.3 to 30 Hz. To eliminate the oscillations due to closed-chest compression (rate 80/min=1.33 Hz) and their first two harmonics (2.66 Hz, 3.99 Hz), the following bandwidths of the digital filter were also selected: 1.7 to 30 Hz, 3.0 to 30 Hz, and 4.3 to 30 Hz.

Each countershock was analyzed as an independent event as it was the purpose of this study to predict the result of each countershock independent of clinical variables that may affect this outcome. The mean (±1 SD), range, and median values for median frequency, dominant frequency, edge frequency, and amplitude were determined for successful and unsuccessful countershocks. A Kolmogorov-Smirnov analysis was used to determine the difference between each of the parameters and the result of the countershock. A Wilcoxon sign-rank test or paired *t* test was used to determine the difference between each of the parameters before and during countershock. Statistical difference was considered when $p \leq 0.05$.

A determination was made of 100% sensitivity and resulting specificity for each parameter. Sensitivity is defined as the capacity of a parameter to predict a successful countershock. It is calculated as the number of successful countershocks that have a parameter value within a specific range divided by the total number of successful countershocks. Specificity is defined as the ability of a parameter to predict an unsuccessful countershock. It is calculated as the number of unsuccessful countershocks that have a parameter value that falls outside a specific range divided by the total number of unsuccessful countershocks.

Results

A total of 154 countershocks were performed in 26 patients. Using a frequency range of 0.3 to 30 Hz, values of median frequency, dominant frequency, and amplitude during the 3-s epoch before successful countershocks (n=20) were significantly higher than those before unsuccessful countershocks (n=134) (Table 1). For the 12-s epoch before each countershock in the same frequency range, values of median frequency, dominant frequency, and amplitude before successful countershocks were also statistically higher than those before unsuccessful countershocks (Table 1). As resuscitation efforts were stopped at least 12 s before each countershock, Table 1 contains only ECG analyses without CPR interference. The range for frequency and amplitude parameters in regards to countershock success, for 100% sensitivity and resulting specificity, are given

Table 1—*VF Frequency and Amplitude Parameters During a 3- and 12-s Period Before Successful or Unsuccessful Countershock in the Frequency Range 0.3 to 30 Hz**

	Successful (n=20)			Unsuccessful (n=134)			p Value
	Mean±SD	Range	Median	Mean ± SD	Range	Median	
3-s period							
MF, Hz	5.17±1.05	3.3−6.9	4.85	4.21±1.17	2.1−9.1	4.1	0.0034
DF, Hz	4.56±0.99	2.3−6.7	4.7	3.31±1.57	0.3−9.7	3.3	0.0004
EF, Hz	10.74±3.46	6.7−21.3	9.85	9.46±2.93	3.3−20.7	9.0	0.5390
A, mV	1.33±0.44	0.61−2.45	1.36	1.15±0.69	0.24−3.59	0.94	0.0134
12-s period							
MF, Hz	5.02±1.02	3.59−6.83	4.91	4.3±1.06	2.69−8.78	4.25	0.0209
DF, Hz	4.44±1.01	3.0−6.43	4.38	3.34±1.22	0.6−6.85	3.19	0.0015
EF, Hz	10.20±2.94	6.5−19.5	9.0	9.41±2.57	4.85−19.93	8.9	0.3931
A, mV	1.40±0.50	0.68−2.89	1.42	1.16±0.68	0.30−3.31	0.95	0.0100

*MF=median frequency; DF=dominant frequency; EF=edge frequency; A=amplitude.

in Table 2 for 3-s and 12-s epochs. At 100% sensitivity, the maximum specificity was approximately 46%, obtained with dominant frequency (12-s epoch).

Median frequency, dominant frequency, edge frequency, and amplitude of the VF ECG signal at different frequency ranges during the 12-s epochs immediately before and after starting closed-chest CPR are shown in Table 3. At the following bandwidths for digital filtering—0.3 to 30 Hz, 1.7 to 30 Hz, or 3.0 to 30 Hz—values of median, dominant, and edge frequency were significantly lower, and amplitude was significantly higher, during CPR than during intervals without CPR. However, when using a bandwidth of 4.3 to 30 Hz, no differences in median frequency, dominant frequency, or edge frequency were found; only amplitude remained significantly higher.

Fast Fourier transform parameters during the 3-s epoch before countershock in the frequency ranges 1.7 to 30 Hz, 3.0 to 30 Hz, and 4.3 to 30 Hz are shown in Table 4. In comparison to the frequency range of 0.3 to 30 Hz, the use of software filters for elimination of CPR interference had the following effects. Using a software filter of 1.7 to 30 Hz, the parameters median frequency, dominant frequency, and amplitude remained statistically different in discerning successful from unsuccessful countershocks. At 3.0 to 30 Hz, only dominant frequency and amplitude remained statistically different; and at 4.3 to 30 Hz, only amplitude remained statistically different.

Table 2—*Frequency and Amplitude Parameters and Their Ranges for Predicting 100% Sensitivity and Corresponding Specificity in the Frequency Range 0.3 to 30 Hz*

Parameter	Range	Specificity, %
3-s epoch		
MF, Hz	3.3≤MF≤6.9	25.37
DF, Hz	2.3≤DF≤6.7	25.37
EF, Hz	6.7≤EF≤21.3	11.94
A, mV	0.61≤A≤2.45	25.37
12-s epoch		
MF, Hz	3.59≤MF≤6.83	32.09
DF, Hz	3.00≤DF≤6.43	46.27
EF, Hz	6.5≤EF≤19.15	8.21
A, mV	0.68≤A≤2.89	25.37

Discussion

In patients with out-of-hospital VF cardiac arrest, the following are notable findings of this study: (1) median frequency, dominant frequency, and amplitude are predictive of countershock success; (2) software filters that completely eliminate interference due to closed-chest CPR deteriorate the predictive value of the frequency parameters examined in this study, although amplitude remains predictive of countershock success; and (3) interference from closed-chest CPR significantly shifts the power spectrum to the left while increasing the amplitude of the VF ECG signal. In addition, using dominant frequency alone in the range 3.00≤dominant frequency≤6.43 Hz, and over a 12-s epoch, in this study sample, 100% of the successful countershock would have been identified and approximately 46% of the unsuccessful countershocks eliminated. This may be particularly important if the cumulative energy imparted to the myocardium following multiple countershocks is an etiologic factor in injuring the heart and thus hindering resuscitation.[11]

In a sense, results from this study confirm older observations that coarse VF fibrillation is more amenable to countershock than fine VF. In particular, VF voltage has been shown to reflect myocardial

Table 3—*Median Frequency, Dominant Frequency, Edge Frequency, and Amplitude of the VF ECG Signal at Different Frequency Ranges During the 12-s Epoch Immediately Before and During Closed-Chest CPR*

	Before CPR			During CPR			p Value
	Mean±SD	Range	Median	Mean±SD	Range	Median	
0.3–30 Hz							
MF, Hz	4.42±0.88	3.3–6.5	4.5	2.49±0.54	1.7–3.5	2.5	0.0001
DF, Hz	3.01±0.86	1.3–4.1	3	1.61±0.58	0.9–2.5	1.5	0.0001
EF, Hz	10.0±2.1	8.1–14.9	9.2	5.85±1.24	3.9–8.6	5.8	0.0001
A, mV	0.68±0.24	0.3–1.0	0.7	2.06±0.63	1.35–3.5	1.9	0.0001
1.7–30 Hz							
MF, Hz	4.83±0.97	3.8–7.1	4.6	3.36±0.46	2.4–3.9	3.5	0.0001
DF, Hz	3.67±1.03	2.2–6.3	3.6	2.42±0.42	1.9–3.3	2.5	0.0001
EF, Hz	10.2±2.13	8.1–15.3	9.4	7.21±1.73	3.9–10.1	7.2	0.0001
A, mV	0.68±0.24	0.3–1.0	0.7	2.06±0.63	1.35–3.5	1.9	0.0001
3.0–30 Hz							
MF, Hz	5.63±0.77	5.0–7.5	5.3	4.91±0.66	3.8–6.2	4.9	0.0014
DF, Hz	4.21±0.78	3.2–6.3	4.1	3.56±0.41	3.0–4.2	3.6	0.0023
EF, Hz	11.31±1.97	8.5–15.7	11.4	9.85±1.9	7.2–13.2	9.6	0.0034
A, mV	0.68±0.24	0.3–1.0	0.7	2.06±0.63	1.35–3.5	1.9	0.0001
4.3–30 Hz							
MF, Hz	6.69±0.82	5.1–8.1	6.8	6.55±0.83	5.1–8.3	6.5	0.1826
DF, Hz	4.97±0.83	3.8–7.1	4.8	4.99±0.41	3.7–6.8	4.9	0.8963
EF, Hz	13.08±2.10	10.1–16.6	12.9	12.77±2.26	9.2–16.0	12.8	0.4691
A, mV	0.67±0.24	0.3–1.0	0.7	2.06±0.63	1.35–3.5	1.9	0.0001

perfusion, myocardial energy metabolism,[12] defibrillation success,[13] and outcome after cardiac arrest.[14] However, VF amplitude depends on the direction of the main fibrillation vector[15] and a great interindividual variety exists.[16] In recent years, several studies have shown that fast Fourier transform analysis of VF in general and median frequency in particular reflect both myocardial blood flow during CPR and the chance of countershock success.[6,9,10] The power spectrum of the fibrillating heart remains constant over many minutes when coronary perfusion is maintained, *eg*, by cardiopulmonary bypass.[9,17] Progressive ischemia due to cardiac arrest results in a rapid depletion of myocardial high-energy phosphates,[18] deterioration of transmembrane potentials,[19] intracellular calcium overload,[20] decline of fibrillation frequency, and increased probability of electromechanical dissociation following countershock.[17,21] Improvement of myocardial perfusion by CPR and

Table 4—*Median Frequency, Dominant Frequency, Edge Frequency, and Amplitude During a 3-s Epoch Before Successful or Unsuccessful Countershock in Selected Frequency Ranges*

	Successful			Unsuccessful			p Value
	Mean±SD	Range	Median	Mean±SD	Range	Median	
1.7–30 Hz							
MF, Hz	5.31±0.96	3.4–6.8	5.05	4.65±1.19	2.5–9.1	4.5	0.0239
DF, Hz	4.56±0.99	2.3–6.7	4.7	3.78±1.39	1.7–9.7	3.7	0.0058
EF, Hz	10.81±2.91	7.3–18.7	10	9.78±2.82	3.3–20	9.3	0.5902
A, mV	1.33±0.44	0.61–2.45	1.36	1.15±0.69	0.24–3.6	0.94	0.0134
3.0–30 Hz							
MF, Hz	5.67±0.76	4.5–7.0	5.6	5.46±1.13	3.6–9.7	5.3	0.3281
DF, Hz	4.71±0.75	3.7–6.7	4.7	4.25±1.15	3.0–9.7	4.3	0.0502
EF, Hz	11.21±2.75	8.3–19.3	10.15	10.91±2.94	1.3–20.3	10.3	0.9651
A, mV	1.33±0.44	0.61–2.45	1.36	1.15±0.69	0.24–3.6	0.94	0.0134
4.3–30 Hz							
MF, Hz	6.63±1.26	5.1–10.6	6.35	6.85±1.03	4.8–10.1	6.7	0.5090
DF, Hz	5.07±0.91	4.3–7.0	4.7	5.12±0.94	4.3–9.7	5.0	0.9756
EF, Hz	12.54±3.75	8.7–26.3	11.7	13.18±3.02	7.3–22	12.7	0.1599
A, mV	1.33±0.44	0.61–2.45	1.36	1.15±0.69	0.24–3.6	0.94	0.0134

vasopressor administration results in an increase of VF frequency and higher probability of successful countershock. Results from our study, which are in general agreement with previous laboratory investigations[6,7] and what has been found in humans,[9,10,22] show that values of both median frequency and dominant frequency before successful countershocks were significantly higher than those before unsuccessful countershocks. Demographic data were not available in these patients and therefore we do not know whether in patients with successful countershock, the supraventricular rhythm was associated with a palpable pulse or BP. Thus, our definition of countershock success differs from that of other studies in humans in which amplitude was not found to be predictive.[22] In the study by Brown and Dzwonczyk,[22] a successful countershock was one in which a palpable pulse or BP was documented within 2 min of the countershock without ongoing CPR. Thus, differences in outcome definitions may account for differences in the predictive value of amplitude parameters.

In some previous investigations that have addressed VF analysis, closed-chest CPR was interrupted to perform noise-free recording of the ECG signal,[6,10] or myocardial perfusion was maintained by technical means.[9,17] Recently, we were able to demonstrate that by using appropriate software filters in a porcine model of VF, interference due to CPR could be removed from the VF power spectrum without impairing the probability of predicting countershock outcome.[23] Results from this study demonstrate that in patients also, interference due to closed-chest compression can be removed effectively from the VF power spectrum by technical means. However, due to the lower absolute values of fibrillation frequency in patients in comparison to animals, filters that effectively eliminate interference due to closed-chest CPR deteriorate the predictive value of the fast Fourier transform analysis, although the parameter amplitude remains predictive of countershock success.

We conclude that in patients, the chance of developing a supraventricular rhythm after countershock is likely to be reflected in specific frequency and amplitude parameters that can be derived from the VF ECG signal. Further prospective studies performed in a greater number of patients will be needed before this method can be applied to the management of human cardiac arrest.

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