Comparison of Countershock Prediction Features based on Autoregressive and Fourier transformed Spectral Analysis

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Abstract

Spectral analysis of ventricular fibrillation (VF) ECG has been used for predicting countershock success, where the Fast Fourier Transformation (FFT) is the standard spectral estimator. Autoregressive (AR) spectral estimation should compute the spectrum with less computation time. This study compares the predictive power and computational performance of features based on FFT and AR methods. In an animal model of VF, 41 shocks were delivered in 25 swine. Two new AR based prediction features were developed in this study. For a proof of concept a microcontroller program was implemented. Calculating the area under the receiver operating characteristic (ROC) curve (AUC), the results of the features using AR modeling (85 %; 89 %) are better than common parameters based on FFT (72 %; 78 %). In the calculation time comparison the AR based parameters yield better results (nearly 2.5 times faster) than FFT based parameters. Summing up, AR spectral estimators are an attractive option compared to FFT due to the computational speed and the better prediction outcome.

1. Introduction

Electrical defibrillation is the treatment of choice of ventricular fibrillation (VF) [1]. When applied early after the onset of VF, a countershock usually results in return of spontaneous circulation (ROSC) [2]. With prolonged duration of VF, the chance of successful defibrillation decreases dramatically with an increasing likelihood of asystole, pulseless electrical activity or persistent VF following the countershock [1]. Thus, optimal timing of defibrillation therapy and adjunct drug therapy is highly warranted to improve the probability of ROSC with less injury of the heart [3].

In recent years, considerable efforts were made for developing features that help the emergency physician guiding countershock therapy and timing during cardiopulmonary resuscitation (CPR) [3], [4], [5], [6]. Spectral analysis of the VF ECG, the classical Fast Fourier Transformation (FFT) in particular, has been a central tool used for computing prediction parameters of the VF ECG [3], [4], [5], [6]. A computationally efficient spectral estimator, which has been successfully applied in various other biomedical applications, e.g. in [7], is the autoregressive (AR) spectral estimation method. Less computation time and less memory requirements of the AR modeling should be of advantage when implementing a spectral analysis on the microprocessor system of a commercial semiautomatic defibrillator. Thus, this study compares the predictive power and the calculation time of parameters obtained by FFT and AR estimation.

2. Methods

2.1. Experimental data

A subset of animal data (25 healthy, 12- to 16-week-old swine) originally allocated to compare the effects of epinephrine or vasopressin on coronary perfusion pressure and countershock success during CPR was used to investigate the predictive power of AR spectral analysis. Details on these experiments can be found in [8].

Shortly, After 4 minutes of untreated cardiac arrest, closed chest CPR was performed (80 compressions per minute). Epinephrine, vasopressin or placebo was applied after 3, 8 and 13 minutes of CPR, whereas the choice of the drug was randomly assigned. After 22 minutes of VF including 18 minutes of CPR, countershocks were administered with energies of 3, 4 and 6 J/kg, respectively. In total, forty-three countershocks were applied. The number of shocks varied between one and maximal six shocks per animal. Two shocks had to be excluded because of a too short duration between the two shocks. For calculating the different prediction features, 2.5 s intervals of the pre-countershock VF ECG were used.

Successful countershock resulting in ROSC was defined as an unassisted pulse giving rhythm with an systolic arterial blood pressure > 80 mmHg lasting for at least 10 s [8]. All the other countershocks were defined as unsuccessful (NoROSC).

2.2. Signal processing and analysis

For signal preprocessing purposes the VF ECG intervals were down-sampled from 1000 Hz to 100 Hz, which is similar to the sampling frequency used by most commercial defibrillators (100 Hz to 500 Hz). Moreover, for avoiding aliasing effects, a 3 Hz to 40 Hz Butterworth band-pass filter of order four was applied [9].

For calculating the prediction features, the FFT and an AR modeling was used [10], respectively. Here, the estimation of the AR parameters is executed recursively by the Yule-Walker algorithm [10]. For choosing the best model order p of the AR model, the Akaike Information Criterion (AIC) is used [10]. Moreover, as described by Baselli et al. [11], it is possible to subdivide the entire power spectral density (PSD) of one signal in bell-shaped curves, whose characteristics can be obtained from the position and the residual of each pole. By knowing the pole distribution inside the unit circle, the center frequency of each peak, called pole frequency f_{pole}, and the pole power p_{pole} of each pole [11] can be defined. This indicates that each spectral component of the PSD can be described only by its pole frequencies and pole power.

The receiver operating characteristic (ROC) curve and the underlying area under the curve (AUC) were used to compare the predictive power of the VF features investigated [4]. The AUC values indicate the possibility of discrimination of the prediction features between ROSC and NoROSC (AUC value = 100 %, perfekt discrimination; AUC value = 50 %, randomly stochastic decision).

2.3. AR based prediction features

In this study new prediction features based on AR spectral estimation were defined as follows:

2.3.1. Spectral pole power (SPP)

SPP represents a combination of all f_{pole} and p_{pole} of each PSD:

$$SPP = \sum_{i=1}^{T} f_{pole}(i) \cdot p_{pole}(i), \qquad (1)$$

where T corresponds to the number of p_{pole}. Note the physical similarities of its calculation compared to the AMSA parameter (see 2.4.2).

2.3.2. Spectral pole power with DF weighing (SPPDF)

SPPDF is calculated by multiplying the SPP with the DF for getting another weighting.

$$SPPDF = DF \cdot \sum_{i=1}^{T} f_{pole}(i) \cdot p_{pole}(i), \qquad (2)$$

where T corresponds to the number of p_{pole}.

2.4. FFT based prediction features

For validation and comparison purposes two previously studied prediction features based on FFT were evaluated, here.

2.4.1. Centroid Frequency (CF)

CF is calculated as the point of mass in the spectrum [6], so that the low-frequency contents of the VF ECG are highlighted:

$$CF = \frac{\sum F_i \cdot P_i}{\sum P_i}, \qquad (3)$$

where F_i is the i^{th} frequency component and P_i is the relative power at F_i.

2.4.2. Amplitude spectrum analysis (AMSA)

AMSA represents the whole area under the PSD curve for countershock outcome prediction [5]:

$$AMSA = \sum (A_i \cdot F_i), \qquad (4)$$

where A_i is the amplitude at the i^{th} frequency F_i.

2.5. Implementation of a microcontroller

An ATmega32-16PU microcontroller (Atmel Corporation, San Jose, California) was implemented for calculating two prediction features (SPPDF and AMSA) with speed improving algorithms as a proof of concept. For generating the FFT based features, the source code for the spectral estimator was adopted from [12] that is an established, numerically optimized tool. The Yule-Walker and the Levinson-Durbin-algorithm were implemented for the calculation of the AR based parameter [10]. The calculation duration of the prediction features from all datasets was measured and the mean and the standard derivation of the time were built in each case.

3. Results

3.1. Prediction feature over time

The time course during the whole experiment of two swine (one with ROSC, and one with NoROSC outcome) is presented in Figure 1. Only one prediction feature calculated with AR modeling (SPPDF, upper panel) and one with FFT calculation (AMSA, lower panel) are shown.

During the first 4 min of untreated VF, the features investigated decrease due to growing ischemia in the animal heart. Ninety seconds after resumption of CPR (i.e. 5.5 min after induction of VF) the feature values increase again. After the first drug administration, the animal with ROSC gets vasopressin and the other one only a placebo. There is a difference in the feature value distributions: While there is still an increase approximately one minute after the first drug administration in the ROSC data, the prediction values of the NoROSC data decrease.

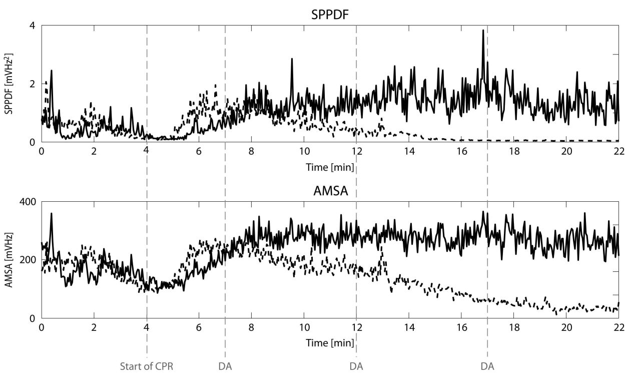

Figure 1. The change of the prediction features over the time and the differences of a ROSC (solid line, three vasopressin administrations) and NoROSC (dashed line, one placebo administration followed by two epinephrine administrations) data can be seen, respectively. The upper panel shows the values of the SPPDF parameter and the lower panel the outcome of the AMSA feature.

All four prediction features discussed in this study work with a threshold criterion. If the parameter value is greater than a certain threshold as can be seen in Table 1 for each feature, it predicts that an applied countershock may result in ROSC.

Table 1. Threshold of the prediction features.

Prediction Feature	Threshold
SPP	0.05 mVHz
SPPDF	0.4 $mVHz^2$
CF	0.1 mV
AMSA	230 mVHz

3.2. Comparison of the prediction power

Forty-one countershocks were evaluated, where 12 of them resulted in ROSC. For AR based features, a mean model order of 22.0 (range 7 to 49) was acquired. The ROC AUC values of the prediction parameters with its sensitivity and specificity are summarized in Table 2. The best prediction features were those calculated with AR based spectral estimation (SPP and SPPDF), resulting in a ROC AUC of 85.9 % and 89.4 %, respectively.

Table 2. ROC AUC values with its sensitivity and specificity of the prediction features 2.5 s before applying the countershock.

Parameter	AUC value [%]	Sens [%]	Spec [%]
SPP	85.9	92	62
SPPDF	89.4	92	72
CF	72.1	92	51
AMSA	78.0	92	59

Sens, Sensitivity; Spec, Specificity; SPP, Spectral Pole Power; SPPDF, Spectral Pole Power with DF weighing; CF, Centroid Frequency; AMSA, Amplitude Spectrum Analysis;

3.3. Calculation time measurements

The microcontroller calculated the SPPDF and AMSA parameters of all 41 datasets. The time for calculating the AMSA parameter amounts 9.5 $\pm$ 0.7 s (range 8.9 s $-$ 10.6 s) and it is 3.9 $\pm$ 0.1 s (range 3.8 s $-$ 4.1 s) for the SPPDF feature, respectively. This means that calculating the new parameters is nearly 2.5 times faster than parameters with Fourier-based techniques.

4. Discussion

For evaluating the new prediction features, they are compared with previous studied parameters based on FFT. Notably, despite the physical similarities of their calculation, the ROC AUC values of the AR based features SPP and SPPDF, which amounted to 85.9 % and 89.4 %, yield better results than AMSA with an AUC value of 78.0 % with a sensitivity of 92 % and a specificity of 59 %. Also the CF parameters has only a prediction power of 72.1 %. Thus, it can be stated that the two AR based parameters have a better predictive power with a higher specificity in opposite to the FFT bases features.

Moreover, the AR method is a powerful and computationally fast method that is frequently used in clinical research or in established medical products [7], which performs well for spectra with pronounced peaks, as present in the VF ECG. Thus, as the proof of concept study shows, beside the better predictive power the AR based features are calculated 2.5 times faster than the FFT based parameters. Due to this fast computation and its marginal memory requirements, its calculation does not require much computational effort [10]. Accordingly AR based prediction features could be easily integrated on the microprocessor of a commercial defibrillator.

5. Conclusion and outlook

Summing up, the two new AR based parameter SPP and SPPDF show higher predictive accuracy with respect to countershock success rate compared to the established FFT based features CF and AMSA. Rapid computation resulting in reduced computational effort is moreover a great advantage of the AR method that would facilitate its implementation on the microprocessor of a commercial defibrillator. The performance of the proposed predictors in human data must be confirmed in future studies.

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