Influence of Chest Compression on Amplitude Spectrum Area for the Prediction of the Return of Spontaneous Circulation in a Pediatric Swine Model

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Abstract

Amplitude Spectrum Area (AMSA) is a metric derived from the electrocardiogram (ECG) waveform during ventricular fibrillation (VF). Higher AMSA values have demonstrated strong predictive value for successful defibrillation and return of spontaneous circulation (ROSC) during cardiopulmonary resuscitation (CPR). However, there is no consensus on whether AMSA can be reliably estimated during chest compressions. We hypothesize that AMSA is affected by chest compression artifacts, but its predictive value for ROSC is not affected. We tested our hypothesis in a pediatric swine model of cardiac arrest (N=71). For each subject, AMSA was calculated for a pair of adjacent 4-second ECG VF segments prior to defibrillation, one during chest compressions and another during a pause. AMSA calculated during pause was higher than during compressions, both for ROSC (n=46; P<0.001) and No ROSC subjects (n=25; P<0.001). However, the area under the receiver operating characteristic curve for ROSC prediction did not differ between AMSA calculated during pauses and compressions (0.73; p=0.90). Thus, AMSA values were affected by compression artifacts, but ROSC prediction was not impacted. Our finding supports continuous monitoring of AMSA throughout CPR.

1. Introduction

The Amplitude Spectrum Area (AMSA) has emerged as an important predictor of defibrillation success and return of spontaneous circulation (ROSC) after cardiac arrest. As a metric derived from the electrocardiogram (ECG) waveform during ventricular fibrillation (VF), AMSA offers insights into the underlying physiological state of the heart during cardiopulmonary resuscitation (CPR) [1]. By assessing the frequency-weighted sum of VF waveform amplitudes, AMSA offers a quantitative and dynamic indication of the heart's electrical activity which is associated with electrical responsivity to defibrillation.

This quantitative metric thus enables clinicians to tailor defibrillation strategies based on the patient's actual physiological state rather than relying solely on fixed-time protocols. Consequently, AMSA can serve as a valuable tool in optimizing defibrillation timing, reducing unnecessary shock burden, and enhancing the likelihood of achieving ROSC [2].

Although the significance of AMSA in the context of CPR is widely acknowledged, the determination of the most suitable timeframes for its computation has been a topic with varying perspectives among researchers. Some studies suggest calculating AMSA exclusively during chest compression pauses to mitigate potential artifacts from chest compressions on the electrocardiogram (ECG). Conversely, others have published results which computed AMSA during active chest compressions, demonstrating the lack of consensus in current literature. Continuous monitoring of AMSA during CPR presents a more compelling approach, in contrast to limiting AMSA assessments to short pause periods for rhythm assessment.

In this study, we endeavored to compare AMSA values computed during chest compressions and pauses, and to compare the predictive value of AMSA for ROSC between these two periods. We hypothesized that AMSA values are affected by chest compressions artefacts, and thus significantly differ between chest compression versus pause periods, but that these artefacts would have little or no impact in the predictive value of AMSA for ROSC.

2. Methods

2.1. Animals and Experimental Protocol

In this study, retrospective data was obtained from 1- to 2-month-old, 8-13 kg piglets (*Sus scrofa domesticus*) who underwent an established model of asphyxia-associated cardiac arrest and resuscitation [3], [4]. Experiments were performed between July 2018 and February 2022 in the large animal laboratory of the Resuscitation Science Center at the Children's Hospital of Philadelphia (CHOP). The experimental protocol was approved by CHOP's

Institutional Animal Care and Use Committee (IAC 19-001327), and all procedures were conducted following the NIH Guide for the Care and Use of Laboratory Animals.

Experimental procedures have been previously detailed [3], [4]. Briefly, after anesthesia and intubation, subjects were equipped for physiological waveform monitoring. Baseline recordings occurred for 5 minutes. This was followed by clamping of the endotracheal tube for 7 minutes, induction of VF by ventricular pacing, and initiation of CPR. CPR continued until the animal achieved ROSC or for a maximum period of 10 minutes following the first defibrillation attempt.

Four CPR strategies were observed in the data: hemodynamic-directed, depth-directed, brain-directed, and experimental device CPR. All strategies aimed for 100-110 compressions per minute. Timing of first defibrillation was determined *a priori* (after either 10 minutes or 15 minutes after CPR start) based on CPR protocol, with subsequent shock eligibility every two minutes.

For all subjects, data from the first 10 minutes of CPR was studied. Subjects were excluded if 1) the subject was a control (Sham); 2) there were no ECG or arterial blood pressure waveforms available during CPR; 3) there were no pause period at least 4.8 seconds long (see Section 2.2).

2.2. Waveforms and AMSA Calculation

The ECG and pulsatile arterial blood pressure (ABP) waveforms were recorded at 1kHz using a commercial device (PowerLab, ADInstruments, Sydney, Australia), and block averaged to 100 Hz. Pause periods were identified from the ABP waveform where the ABP area duty cycle was < 10% for any compression peak [5].

Following identification of pause periods, two adjacent ECG segments of 4 seconds were obtained from each subject, one during a pause period and another one during chest compressions, 0.4 seconds prior to the pause onset. To avoid compression artifacts, only pause periods of at least 4.8 seconds were considered, excluding the initial and final 0.4 seconds. The first eligible pause period (i.e., at least 4.8 seconds long) closest to the 10th minute of CPR was used from each subject, as the predictive value for ROSC is greater at later CPR periods [6].

For each 4-second ECG segment, AMSA was derived from the ECG amplitude spectrum calculated using the periodogram with Hann windowing. The amplitude spectrum was frequency-weighted and integrated in the range 5-30 Hz. Mathematically, AMSA was defined as:

$$ \text{AMSA} = \sum_k A_k F_k, \qquad (1) $$

where A_k represents the amplitude of the k-th spectral frequency component F_k, $5\,\text{Hz} \le F_k \le 30\,\text{Hz}$ [1].

2.3. Statistical Analysis

Within-subject differences between AMSA calculated during chest compression versus pause periods were evaluated using Wilcoxon signed-rank test. Differences between ROSC and No ROSC subjects were assessed using Mann-Whitney U test. Statistical significance was assumed when p < 0.05. The area under the receiver operating characteristic curve (AUROC) was calculated for ROSC prediction using AMSA values calculated during compression versus pause periods and compared using DeLong's test.

3. Results

From 189 subjects available, 71 were eligible after applying the exclusion criteria. From these, 46 achieved ROSC and 25 did not (No ROSC). Figure 1 shows the AMSA values obtained during chest compressions versus during pause periods, for ROSC and No ROSC subjects, separately. AMSA is higher during compression versus pause periods, in both ROSC (Fig. 1A) and No ROSC (Fig. 1B) subjects. Moreover, AMSA is higher in ROSC versus No ROSC subjects, regardless of whether AMSA was calculated from a chest compression (Fig. 1C) or pause period (Fig. 1D).

The AUROC for distinguishing between ROSC and No ROSC subjects was 0.73 for both chest compressions and
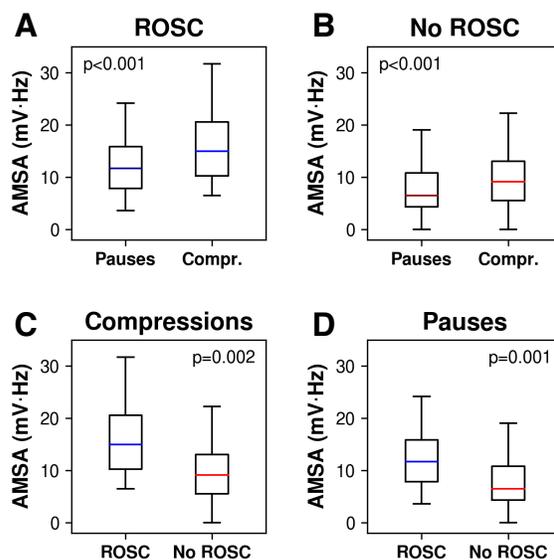

Figure 1. Amplitude spectrum area (AMSA) grouped values. Top plots show the comparison between periods of compressions and pause, for both ROSC (A) and No ROSC (B) subjects. Bottom plots show the comparison between ROSC and No ROSC subjects, both for periods of chest compressions (C) and pause (D). ROSC: return of spontaneous circulation; Compr.: compressions.
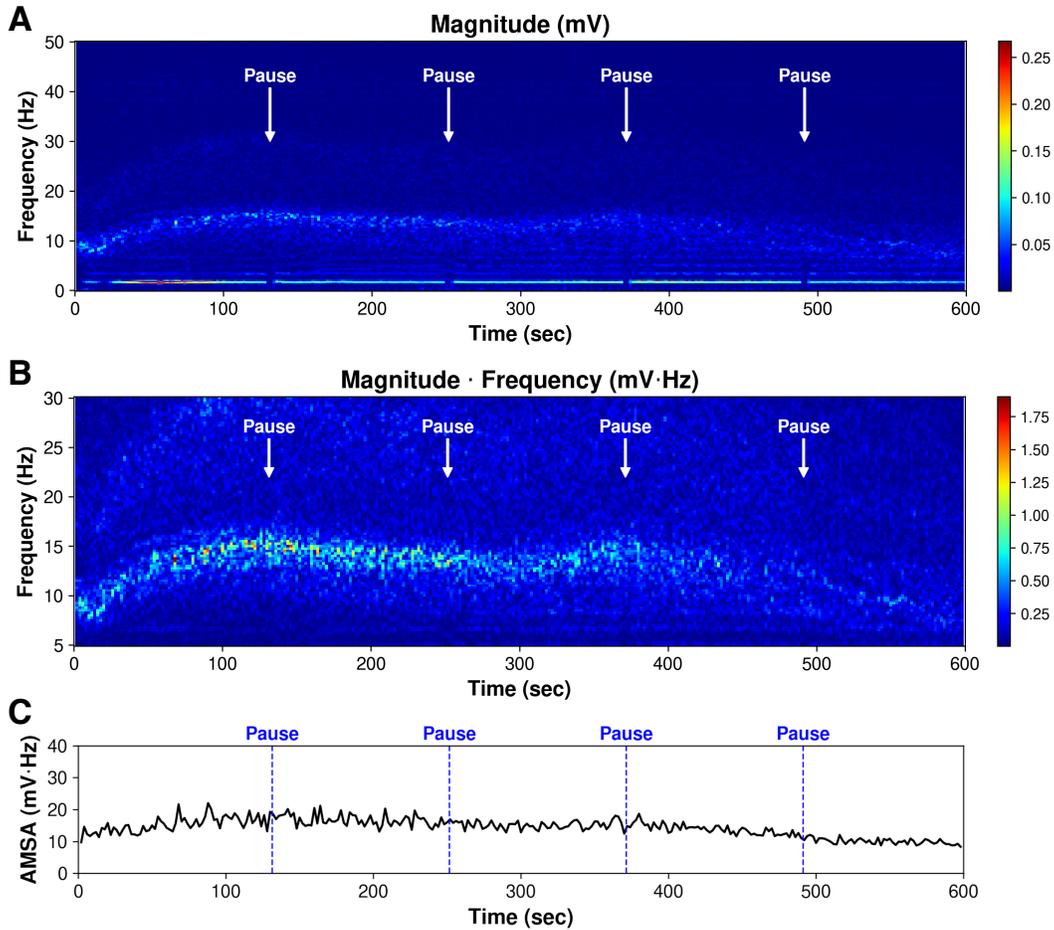
Figure 2. Spectrograms and AMSA values during the first 10 minutes of CPR. In (A) it is shown the amplitude spectrum of the ECG, while in (B) it is shown the magnitudes times the frequency in the range 5-30 Hz. AMSA values at each timepoint (C) are calculated as the sum of values over frequency in (B). The influence of chest compression fundamental frequency (~1.67 Hz) can be clearly observed in (A), along with its harmonics (multiples of 1.67 Hz). During pauses (arrows), these components disappear. Since the compression fundamental frequency is not in the range considered by AMSA, plot (B) shows the small effect caused by compression artifacts. The AMSA series shown in (C) confirms the small influence of compression artifacts on continuous AMSA monitoring. The spectrograms were calculated from windows of 4 seconds (50% overlap), using the periodogram and a window of Hann. Pause periods are highlighted as white arrows (A and B) and blue dashed lines (C).

pause periods (p=0.90). Therefore, although AMSA values were affected by the compressions, ROSC predictive value of AMSA did not change.

Figure 2 shows ECG spectrograms and AMSA series of one subject over the 10 minutes of CPR. The ECG magnitude spectrogram (Fig. 2A) has a strong compression interference near 1.67 Hz (100 compressions per minute), and smaller components on the harmonics of this frequency (i.e., multiples of 1.67 Hz). However, as AMSA considers the amplitude weighted by frequency, slower frequency components are given lower weights. Figure 2B shows how the compression harmonics interfere in the weighted magnitudes. AMSA values obtained from the same period is illustrated in Fig. 2C.

4.   Discussion

Results confirmed our two initial hypotheses, i.e., AMSA values are affected by chest compression artifacts on the ECG, but the predictive value of AMSA for ROSC does not differ between AMSA calculated from periods of chest compressions versus pauses designated for rhythm assessment. This indicates that AMSA remains a valuable predictor of defibrillation success during compressions, which, in turn, supports the creation of advanced CPR algorithms aimed at reducing pause duration and enhancing resuscitation outcomes.

Few studies have compared AMSA between periods of chest compressions and pauses in the same subjects. Coult

et al. [7] evaluated 24 VF features, extracted from 5-sec ECG segments with and without chest compressions, from out-of-hospital cardiac arrest patients [age 61 (52–72), median (IQR)]. Although the authors did not report AMSA values, they calculated the AUROC [95% CI] for discriminating ROSC and No ROSC subjects from periods of chest compressions (0.71 [0.67–0.74]) and pauses (0.72 [0.70–0.75]). The frequency range used to estimate AMSA was selected through an optimization approach, but the selected range was not reported. These AUROC values are consistent with our experimental results.

In another study, Zuo et al. [8] evaluated 4-second ECG segments, with and without chest compressions, in out-of-hospital cardiac arrest patients (subjects' age not available). As observed in our study, AMSA from segments with chest compressions were higher [11.2 (7.7–16.2)] than AMSA from segments without compressions [7.2 (4.9–10.6) mV.Hz, $p<0.01$]. The authors estimated AMSA in the frequency range 2-48 Hz, which includes the fundamental frequency of chest compressions [2.25 (2.0–2.75) Hz]. This methodology likely underlies the large difference in AMSA with versus without chest compressions and the discrepancy in AUROC; the AUROC for AMSA estimated from segments with chest compressions was 0.65 and 0.73 for segments without compressions. Another study from the same group reported similar findings [9]. In comparison, our approach removed frequencies below 5Hz which potentially improved predictive value during compressions.

A critical issue related to AMSA calculation is the lack of guidelines for choosing the length of ECG segment and the range of frequencies to be considered. Both choices vary substantially among studies in the literature, precluding a fair comparison among studies. Another important consideration for comparing our findings to previous studies are differences in experimental models (humans *vs.* swine) and age (adult *vs.* pediatric).

4.   Conclusion

In our pediatric swine model of cardiac arrest, ROSC predictive value of AMSA was the same when calculated during chest compressions or pauses and AMSA was only slightly affected by compression artifacts. This shows the feasibility of continuous AMSA monitoring during CPR to assess eligibility for defibrillation. There is a critical need for guidelines on AMSA estimation, since the frequency range adopted may have a strong influence on the AMSA value during compressions and, consequently, the predictive value for ROSC.

Acknowledgments

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