Characterising Resuscitation Events Using Wavelet Transforms of Digital Stethoscope Recordings During Cardiac Arrest

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Abstract

Out-of-hospital cardiac arrest is a time sensitive condition to be treated initially by non-medically trained bystanders through the application of cardiopulmonary resuscitation (CPR). Rescuers may non-invasively check the person's pulse using their hand, which can be unreliable. Our objective was to assess the potential of recording and using thoracic audio to automatically identify resuscitation events.

Twelve (12) digital stethoscope recordings from a porcine cardiac arrest study were annotated according to simultaneous physiological signals. Normal sinus rhythm (NSR), ventricular fibrillation (VF), CPR and defibrillation. A 5-second audio epoch was extracted for each annotation. The time and frequency composition of the exported epochs were characterized using continuous wavelet transforms.

During NSR sound pulses were identifiable corresponding to S1 and S2 activity in the 10 to 100 Hz frequency range. Upon VF induction, the audio signal displays no distinct physiological features. CPR resulted in sound signatures in the frequency range of 10 to 1000 Hz; however, motion caused by CPR disturbed the contact between the stethoscope and the skin of the test subjects.

Thoracic audio shows potential in classifying events during resuscitation and may provide a non-invasive method for detecting the return of spontaneous circulation.

1. Introduction

There are many devices capable of providing information about patient condition during cardiac arrest (CA). The primary goal when providing therapy to a CA patient is to achieve the return of spontaneous circulation (ROSC) in the shortest time possible. The electrocardiogram (ECG) alone does not provide enough detail to determine if a rhythm is associated with delivering cardiac output. To confirm ROSC, advanced life support guidelines detail that manual pulse checks, of no longer than 10 seconds should be carried out [1]. It has previously been reported that pulse checks are inconsistent and decrease hands-on time - the proportion of a CA event where chest compressions (CC) are being delivered to the patient [2], [3]. Maximizing hands-on time is associated with a higher incidence of ROSC and improved survival outcome, thus, minimizing hands-off time is paramount [4], [5]. Moreover, pulse check methods, such as point of care ultrasound or blood pressure monitoring, are required to be undertaken by trained medical professionals [2], [3]. This requires additional equipment for determining ROSC, leaving minimally trained bystanders without a reliable method of detection during out-of-hospital CA.

Auscultation has previously been used to differentiate between normal sinus rhythm and pulseless electrical activity, which are examples of pulsatile and non-pulsatile rhythms respectively. Luong et al. [6], Johnson et al. [7] and Solevåg et al. [8] used stethoscope data to confirm that the piglets had descended into pulseless electrical activity (PEA) after a period of asphyxiation. Audio data was used as a secondary truth marker, as ECG alone was not able to differentiate between the presence or absence of cardiac output.

The objective of the investigation was to characterize audio recorded via a digital stethoscope according to specific CA events, such as the presence of a pulse, CC and ventilations. Furthermore, defibrillation outcome may be determined by confirming the presence of a pulse after the termination of a shockable rhythm.

2. Methods

2.1. Data collection

Data were collected from 12 porcine models of CA. Ventricular fibrillation was induced in each animal via electrical stimulation of the heart and left in an untreated state for 5 to 7 minutes. Continuous CC were applied for 2 minutes followed by a defibrillation shock if advised by the automated external defibrillator (AED; SAM 350P, HeartSine, UK).

During the experiments, ECG, invasive arterial blood pressure (BP) and capnogram signals were recorded (Datex-Ohmeda AS3, GE Healthcare, USA). ECG data was sampled at 300 Hz, BP was sampled at 100 Hz and the capnogram was sampled at 25 Hz. In addition, 2 acoustic sensors were used to capture audio during the experiment

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- a digital stethoscope (ThinkLabs One, ThinkLabs, USA) to capture the intrathoracic audio of the animals, and an external condenser microphone (NW-410, Neewer, China) to capture ambient room audio. The stethoscope had a frequency range of 20 Hz to 2 kHz and the room audio microphone had a frequency range of 30 Hz to 18 kHz. Both the stethoscope and room audio signals were sampled at 44.1 kHz.

2.2. Definitions

Pulseless electrical activity (PEA) was defined as organized electrical activity of the heart without a pulse (systolic blood pressure of >60 mmHg) [9], [10]. By extension, ROSC was defined as periodic systolic blood pressure pulses, >60 mmHg, coordinated with organized electrical activity in the ECG.

2.3. Annotations

The acquired physiological signals were annotated to identify events indicating the presence of sinus rhythm, VF, CC and post-defibrillation outcome.

Sinus rhythm was identified using the ECG signal in conjunction with the BP signal with a sustained systolic BP of >60 mmHg. VF was identified using the ECG and confirmed by observing an immediate drop in systolic BP. Chest compressions were identifiable as oscillations in the BP signal with a fundamental frequency of 1.83 Hz. Defibrillation shocks were identified using the ECG, as a voltage spike was visible upon delivery. A combination of the ECG and BP signals was used to determine the presence of a pulsatile rhythm, where an organized ECG rhythm and systolic BP >60 mmHg was indicative of a pulsatile rhythm.

2.4. Data processing

The physiological and audio devices were synchronized by finding the first compression in the BP and stethoscope signals. The audio data corresponding to the annotated events of interest were characterized and reviewed for the presence of identification signatures.

Audio signal epochs were extracted from the intrathoracic audio channel corresponding to each of the identified annotated events. The audio signals were denoised and compressed via discrete wavelet transform using the Wavelet Daubechies 4 mother wavelet and resampled to 1378 Hz, maintaining the low-end frequencies reflective of the phonocardiogram range. A 2-second blanking period was applied to the denoised signals immediately after each annotation marker, and 5-second epochs were extracted.

2.5. Signal characterisation

Epochs of thoracic audio were subject to qualitative analysis. A continuous wavelet transform was applied to the denoised audio data for each epoch. The epochs were grouped into annotation categories and visually inspected to identify if common frequency and amplitude signatures were present, for sinus rhythm, VF, CC and post-defibrillation outcome events. Descriptive features such as time-period between signatures, the frequency of identifiable audio pitches and the variability of the waveform over time were reported. Additional signals such as ECG, BP and capnogram were used to identify instances of shock delivery, ROSC and presence of pulsatile rhythms.

3. Results

A total of 192 five-second epochs were extracted for the combined sinus rhythm (30), VF (30), CPR (77) and post-defibrillation (55) events. Example epochs belonging to the annotated events are presented in Figure 1.

Sinus rhythm: The stethoscope audio recorded frequencies associated with relatively high magnitudes between 10 and 100 Hz. Where heartbeats are present in the thoracic scalogram the time-position of the frequency signatures coincided with R-waves in the ECG signal and arterial pulses, seen as oscillations in the BP signal. In addition, to heartbeat signatures, mechanical ventilations were also apparent at frequencies between 100 to 300 Hz. Audible ventilation signatures appear in the inspiratory downstroke phase of the capnogram.

Ventricular fibrillation: During VF, organized electrical and mechanical activity of the heart ceases, however, audible noise was generated by both the motion of the chest or body and air filling the lungs. There was no coordination between the stethoscope audio and either ECG or arterial BP because of the absence of coordinated electro-mechanical function. Frequency signatures were present in the stethoscope audio which were coincident with the time period of the mechanical ventilator.

Chest compressions: Distinctive frequency signatures were visible and are typically made of low and high frequency bands. The low frequency band was of relatively high magnitude and was sustained when compressive force was applied to the chest during. This low frequency band consisted of frequencies between 10 to 30 Hz, and the high frequency band contained several short pulses ranging from approximately 50 Hz to the Nyquist frequency.

Defibrillation: Post defibrillation there are two possible outcomes of interest, pulsatile and non-pulsatile. For defibrillation attempts which resulted in a pulsatile rhythm, the stethoscope audio was not coordinated with either the ECG or BP signals. Features observed during sinus rhythm may have been expected. Pulsatile and non-pulsatile

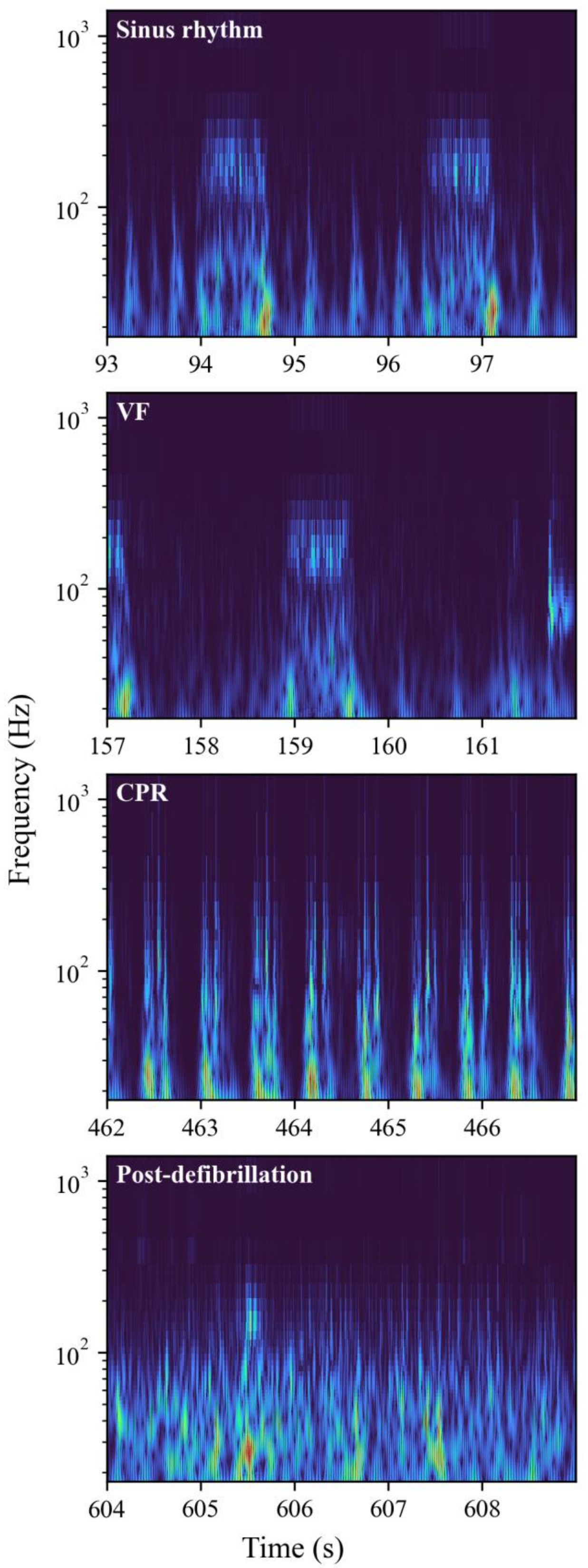

Figure 1. Scalograms representing stethoscope audio epochs captured during each of the annotated events.

segments shared common features. The stethoscope audio frequencies in the range of 10 to 100 Hz exhibit the greatest magnitudes.

4. Discussion

The present investigation was a first look into characterizing thoracic for the purposes of detecting a range of events which may occur during CA, from which a series of hypotheses were created (Table 1). Identifiable signatures were found for sinus rhythm, VF and CC epochs, however, scalogram data for post-defibrillation outcome was not characterizable. A theory for the discrepancies between sinus and pulsatile rhythms may be due to the maturity of the rhythm. Sinus epochs are captured when the animal is observed to be stable and is consistently registering vital signs parameters within an acceptable range. On the other hand, pulsatile rhythms recorded after defibrillation are captured within 2-seconds of ROSC. Therefore, there may not have been enough time for the stabilization of the animal or audio signal for signatures to be found.

A confounding factor which may obscure the differentiating signatures between pulsatile and non-pulsatile rhythms is that the epochs were captured after

Table 1. Hypothesized thoracic audio scalogram characteristics for the annotated events.

Event	Audio Hypothesis
H_1: Sinus rhythm	Scalogram displays periodic frequency signatures, time aligned with R-waves and blood pressure oscillations
H_2: VF	No obvious pattern observed in audio scalogram
H_3: CPR	Periodic frequency signatures which correspond to blood pressure artifacts
H_4: Post-defibrillation (resulting in pulsatile rhythm)	Scalogram displays periodic frequency signatures, time aligned with R-waves and BP oscillations
H_5: Post-defibrillation (resulting in non-pulsatile rhythm)	No obvious pattern observed in audio scalogram

CPR was delivered to the animals. The motion created by CC may dislocate the position of the stethoscope on the animal's body or remove the contact interface completely. Perhaps the identification of clear speech messages, emitted from the AED, in both the stethoscope and room audio data is an indication of the quality of the stethoscope to skin interface. If messages emitted by the defibrillator are clear in the stethoscope recordings, this may indicate the stethoscope is no longer flush with the skin of the animal, like it was at the beginning of each experiment. This may also explain why shocks which result in a non-pulsatile rhythm, most notably VF, do not share similar signatures observed after the induction of VF.

5. Limitations

The quality of the audio captured by the stethoscope may have varied across the animals in the study and the magnitude of the audio signal was dependent on the exact positioning of the sensor, the interface between the stethoscope and the animal and physiological variance between subjects.

6. Conclusion

Thoracic audio shows potential in classifying events during resuscitation and may provide a non-invasive method for detecting the return of spontaneous circulation.

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