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Clinical paper

Evaluation of chest compression artefact removal based on rhythm assessments made by clinicians☆

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ABSTRACT

Aim: To evaluate the performance of a state-of-the-art cardiopulmonary resuscitation (CPR) artefact suppression method by assessing to what extent the filtered electrocardiogram (ECG) can be correctly diagnosed by emergency medicine doctors.

Methods: A total of 819 ECG segments were used. Each segment contained two consecutive 10 s intervals, an artefact free interval and an interval corrupted by CPR artefacts. Each ECG segment was digitally processed to remove CPR artefacts using an adaptive filter. Each ECG segment was split into artefact-free and filtered intervals, randomly reordered for dissociation, and independently offered to four reviewers for rhythm annotation. The rhythm annotations of the artefact-free intervals were considered as the gold standard against which the rhythm annotations of the filtered intervals were evaluated. For the filtered intervals, the rater agreement (κ, Kappa score) with the gold standard, the sensitivity and the specificity were computed individually for each reviewer, and jointly through the majority decision of the pool of reviewers (DPR). These results were also compared to those obtained using a commercial shock advisory algorithm (SAA).

Results: The agreement between each reviewer and the gold standard was moderate ranging between $\kappa = 0.41$–0.64. The sensitivities and specificities ranged between 64.3–95.0%, and 70.0–95.9%, respectively. The agreement for the DPR was substantial with $\kappa = 0.64$ (0.62–0.66), a sensitivity of 90.6%, and a specificity of 85.6%. For the SAA, the agreement was fair with $\kappa = 0.33$ (0.31–0.35), a sensitivity of 90.3%, and a specificity of 66.4%.

Conclusion: Clinicians outperformed the SAA, but specificities remained below the specifications recommended by the American Heart Association. Visual assessment of the filtered ECG by clinicians is not reliable enough, and varies greatly among clinicians. Results considerably improve by considering the consensus decision of a pool of clinicians.

Introduction

The analysis of the heart rhythm during cardiac arrest is determinant because the actions to be taken depend on the ongoing rhythm. Current advanced life support (ALS) guidelines recommend (1) attempting defibrillation and immediately after, resuming cardiopulmonary resuscitation (CPR) in patients presenting shockable rhythms (ventricular fibrillation, VF; or pulseless ventricular tachycardia, VT), and simply resuming CPR in patients with non-shockable rhythms (asystole, AS; and pulseless-electrical activity, PEA) [1,2]. CPR includes, in addition to other interventions, high-quality chest compressions which introduce artefacts in the electrocardiogram (ECG) that make rhythm analysis unreliable [3,4]. Therefore, chest compressions must be interrupted to allow for a reliable rhythm analysis. These interruptions increase hands-off interval which is detrimental for the patient as it negatively affects the probability of return of spontaneous circulation (ROSC) [5,6], and survival [7–11].

The suppression of the CPR artefact would make rhythm analysis

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during CPR possible and consequently, would minimize interruptions in chest compressions and enhance the chance of survival. In the last two decades, different methods have been proposed to achieve this goal. Most of them are based on adaptive filtering techniques that estimate the time-varying artefact using additional reference signal(s), and then subtract it from the corrupt ECG to obtain a filtered ECG free of CPR artefacts [4,12–16]. To evaluate the performance of these methods, the filtered ECG is analysed by a shock advisory algorithm (SAA) to obtain the sensitivity (SE, capacity to correctly detect shockable rhythms) and specificity (SP, capacity to correctly detect non-shockable rhythms) of the method. Despite recent advances [17,18], current methods do not meet the minimum SE/SP requirements established by the American Heart Association (AHA) [19]. Although the great majority of methods showed sensitivities above the 90% minimum value recommended by the AHA, they showed specificities around 85% which is well below the 95% recommended minimum value. Therefore, the combination of CPR artefact suppression method with the SAA of a defibrillator, i.e. a fully-automatic method for a shock/no-shock decision, is not currently feasible [20,21].

In this paper we assess a semi-automatic alternative where a CPR artefact suppression method would be combined with the rhythm diagnosis by experienced clinicians. In ALS, this might be incorporated into monitor/defibrillators as an additional functionality which the healthcare personnel could activate by pushing a button. The filtered ECG would then be displayed together with the corrupt ECG and the estimated CPR artefact. The clinician might continuously assess the rhythm during CPR and only decide to stop CPR in order to (1) advance defibrillation because a shockable rhythm is detected or (2) confirm in an artefact-free interval the suspected shockable rhythm. Therefore, the aim of this study is to evaluate the accuracy of emergency medicine doctors diagnosing the filtered ECG obtained via a state-of-the-art CPR artefact suppression method.

Materials and methods

Data materials

The data used in this study is a subset of an out-of-hospital cardiac arrest database composed of 238 episodes, one per patient, that were collected by the Tualatin Valley Fire & Rescue (Tigard, OR, USA) using the Philips HeartStart MRx monitor/defibrillator between January 2013 and December 2014. Each episode contained the ECG signal acquired through the defibrillation pads and the compression depth (CD) signal extracted from the CPR assist pad. ECG segments were extracted from the episodes when the following two consecutive 10 s intervals were found: an artefact-free interval followed by an interval with CPR artefact, or vice versa. All the available segments, a total of 819, containing ECG and CD signals were used in the study. These numbers are comparable or larger than the number of segments used to assess rhythm analysis during CPR using automatic algorithms [4,14–17,22]. Fig. 1 shows an example of an ECG segment presenting VF. The top panel shows the complete ECG, where the first and last 10 s correspond to the corrupt and artefact-free intervals respectively.

CPR artefact suppression

ECG segments were digitally processed to remove the CPR artefact using an adaptive filtering scheme based on the least mean square (LMS) algorithm [15,23,24]. This method first estimates the CPR artefact, *cpr*(*n*), and then subtracts it from the corrupt ECG to obtain the filtered ECG. In essence, the CPR artefact is considered as a quasi-periodic interference that can be modelled by its Fourier series representation:

$$\mathrm{cpr}(n) = \sum_{k=1}^{N} a_k(n)\cos(2\pi \mathrm{kf}(n)n) + b_k(n)\sin(2\pi \mathrm{kf}(n)n) \quad (1)$$

where N represents the number of harmonics of the model, $a_k(n)$ and $b_k(n)$ correspond to the in-phase and quadrature Fourier coefficients, and $f(n)$, is the instantaneous frequency of the CPR artefact (chest compressions). Note that $f(n)$, $a_k(n)$, and $b_k(n)$ are time-varying, and $f(n)$ varies from compression cycle to cycle, but remains constant within each cycle. The frequency $f(n)$ is computed as the inverse of the time interval between chest compressions which are detected using a simple negative peak detector in the CD signal. On the other hand, $a_k(n)$ and $b_k(n)$ vary from sample to sample, and are computed using the LMS algorithm [23,24]. The CPR suppression method has two design parameters: N, and the step size of the LMS algorithm, μ_0. These values were set to $N = 5$ and $\mu_0 = 0.0178$ following the original authors [15].

Rhythm annotation

Rhythm annotations were made independently by four emergency medicine doctors (authors MD, CC, YL, AI) from different international sites. Doctors are members of resuscitation teams which routinely treat cardiac arrest patients in- and/or out-of hospital. Reviewers classified the rhythm as VF or VT in the shockable category, and as AS or organized rhythm (OR) in the non-shockable category. The rhythm was classified as undecided (UN) if the segment presented: (1) an intermediate rhythm for which there is no clear shock/no-shock recommendation (fine VF and slow VT) [19], (2) a rhythm transition, or (3) large movement artefacts.

Each ECG segment was split into artefact-free and filtered intervals, randomly reordered to dissociate the intervals, and independently offered to each of the reviewers.

Gold standard and dataset of the study

The consensus shock/no-shock diagnosis of at least three reviewers during the artefact-free interval was considered as the correct diagnosis for the whole ECG segment (artefact-free + corrupt). That is, the gold standard against which to compare the shock/no-shock diagnosis of the filtered interval. Since both data subsets (artefact-free and corrupt) were dissociated and randomly reordered, the annotation phases for the gold standard and the rhythm assessment during CPR were considered independent. Segments with split decisions in the artefact-free interval were discarded from the dataset of the study. Panel a of Fig. 2 shows an example of an artefact-free interval (OR) of an ECG segment exactly as it was offered for annotation to the reviewers. Panel b of Fig. 1 depicts an artefact-free interval of an ECG segment included in the dataset of the study as it was annotated unanimously as VF by all the reviewers.

Filtered intervals

The filtered intervals of the dataset of the study were dissociated from the artefact-free intervals and their order randomized before being offered for annotation to the reviewers. For each filtered interval, reviewers were provided with the filtered ECG, the corrupt ECG, and the estimated CPR artefact to make the decision, in the form shown in panel b of Fig. 2. In addition, a consensus decision, designated as the diagnosis of the pool of reviewers (DPR), was defined when at least three reviewers agreed on the shock/no-shock diagnosis of the filtered interval. Filtered intervals without sufficient agreement in the DPR were labelled as UN. The DPR represents the consensus diagnosis of the filtered intervals that would provide the maximum performance (SE/SP) achievable. It is very unlikely that individual performances outperform that obtained by the DPR. Panel a of Fig. 1 represents, from top to bottom, the corrupt ECG, filtered ECG and estimated CPR artefact of a filtered interval annotated unanimously as VF by all the reviewers, and therefore, included in the DPR as shockable.