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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.

Keywords: Cardiopulmonary resuscitation (CPR), Rhythm analysis during CPR, CPR artefact suppression, Adaptive filter

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

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Results: The agreement between each reviewer and the gold standard was moderate ranging between κ=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 κ=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 κ=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.

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1. 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 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 analyzed 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.

2. MATERIALS AND METHODS

2.1. 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, Oregon, 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 viceversa. 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.

2.2. 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:

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

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 μ_0=0.0178 following the original authors.[15]

2.3. 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.

2.3.1. 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.

2.3.2. 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.

2.4. Diagnostic accuracy and statistical analysis

The reviewers' accuracy for shock/no-shock diagnosis was evaluated in terms of SE and SP, and was compared to that obtained by the SAA currently running on the Reanibex R-series defibrillators (Bexen Cardio, Ermua, Spain). The SAA is AHA compliant and diagnoses the rhythm in less than 9.6 s by analyzing 2 or 3 consecutive 3.2 s intervals of the ECG.[25] Finally, for the shock/no-shock annotation the inter-rater agreement, and the agreement between raters and the gold standard were measured using the Fleiss' Kappa coefficient (κ) and its 95% confidence interval.

3. RESULTS

From the 819 segments annotated, only 755 (611 non-shockable and 144 shockable) were included in the dataset of the study, and 64 were discarded because of the lack for a shock/no-shock decision in the artefact free interval. Fig. 3 shows five examples of ECG segments not included in the dataset of the study. From top to bottom, (1) an interval with two shockable and two non-shockable diagnoses, (2) a border case where half of the reviewers could not make a decision and the other half disagreed, (3) a rhythm transition from VF to AS, (4) a VT which was misdiagnosed as OR by half of the reviewers, and (5) a noisy interval that half of the reviewers annotated as UN.

Table 1 summarizes the results obtained for the artefact-free intervals. The agreement achieved between reviewers for the 755 segments that composed the dataset of the study was almost perfect with κ=0.89 (0.89-0.90). The agreement between each reviewer (A, B, C and D) and the gold standard ranged between κ=0.91-0.98. The SE and SP of the reviewers ranged between 90.2%-100%, and 96.4%-99.7%, respectively. The mean proportion of intervals diagnosed as UN by the reviewers was very low (1.3%). The performance of the SAA was AHA compliant resulting in a SE and SP of 94.4% and 95.4% respectively. The agreement of the SAA with the gold standard was also almost perfect with a Kappa score of κ=0.85 (0.83-0.87).

Table 2 summarizes the results obtained for the filtered intervals. The agreement between each reviewer (A, B, C and D) and the gold standard was moderate, the mean kappa score of the four reviewers was κ=0.53 (range 0.41-0.64). The SE and SP of the reviewers ranged between 64.3%-95.0%, and 70.0%-95.9%, respectively. The mean proportion of intervals diagnosed as UN by the reviewers was 7.8%. The agreement of the consensus decision (DPR) and the gold standard was substantial with a κ=0.64 (0.62-0.66), a SE of 90.6%, an SP of 85.6%, and a proportion of intervals diagnosed as UN of 16.2%. Finally, the performance of the SAA was AHA compliant only for the SE (90.3%), while SP decreased to 66.4%. The agreement of the SAA with the gold standard was fair with a Kappa score of κ=0.33 (0.31-0.35). In order to make a fair comparison between the DPR and the SAA, the latter was run on the 633 segments diagnosed by the DPR resulting in a SE/SP of 93.7%/73.7%.

4. DISCUSSION

In this paper, the feasibility of rhythm analysis during ongoing CPR was evaluated through the visual assessment of the ECG made by experienced emergency medicine doctors. A state-of-the-art method was used to eliminate the artefact due to chest compressions and the resulting filtered ECG, together with the estimated CPR artefact and the corrupt ECG, was diagnosed by four emergency medicine doctors. The diagnoses were compared with the consensus diagnosis of the adjacent artefact-free ECG segments, and the SE, SP, and the rater agreements computed.

4.1. The dataset of the study and the gold standard

The dataset of the study contained 755 ECG segments in which a consensus shock/no-shock diagnosis was reached in the artefact-free interval. The remaining 64 segments provided no consensus and were excluded in an effort to obtain a robust gold standard. The artefact-free intervals of those excluded intervals were not further reviewed to reach a consensus shock/no-shock diagnosis because a reliable rhythm annotation cannot be obtained by forcing an agreement in intervals presenting rhythm transitions, borderline rhythms and/or artefacted ECGs. The robustness and reliability of the resulting gold standard were evident as both the agreement achieved between the four reviewers (κ=0.89), and the agreement of the SAA with the gold standard (κ=0.85) were almost perfect.

4.2. Rhythm analysis accuracy

Overall, the assessment of the filtered intervals by the reviewers reported better results than those obtained by the SAA. The agreement with the gold standard was moderate (mean κ=0.53) for each reviewer individually, and substantial (κ=0.64) for the DPR, while the agreement between the SAA and gold standard was just fair (κ=0.33). The SE and SP showed by reviewers individually and by the DPR were also above those obtained by the SAA. However, the results reported for the reviewers and for the DPR did not take into account the proportion of intervals diagnosed as UN, a mean of 7.8% and 16.2% respectively. The UN diagnoses reflect a situation in which the clinician decides that a diagnosis is not possible based on the traces displayed. Conversely, in the results reported for the SAA, all the intervals were analyzed since defibrillators are programmed to always give a shock/no-shock diagnosis and cannot postpone the decision. When the SAA was run on the 633 segments diagnosed by the DPR, the performance of the SAA improved (SE/SP of

93.7%/73.7%) but remained well below that obtained by the DPR. Nevertheless, the SAA used in this study runs on a commercial defibrillator and was therefore designed to diagnose artefact-free intervals. It is possible that a SAA optimized to diagnose filtered ECGs, such as that proposed by Ayala et al.,[18] may show better performance.

The mean values of the SE and SP obtained by the clinicians were good, but the individual performance varied significantly among them. The balanced accuracy, the mean of the SE and SP, was similar for all clinicians (between 80.4%-83.8%), but the differences in SE and SP were large among clinicians. Reviewers A (SE/SP 88.1%/79.3%) and C (86.3%/81.3%) showed balanced SE and SP, whereas Reviewer B (95.0%/70.0%) and D (64.3%/95.9%) showed marked tendency to either shock or not-shock, respectively. These differences in the individual performance might be caused by variations in training and treatment strategies among sites.

This is the first time that rhythm analysis during CPR is assessed based on the decisions made by clinicians, so there is no other similar study against which to compare our results. However, to get the sense of a comparison, our results in terms of SE/SP are similar to those reported for other authors that used SAAs to carry out the evaluation: Eilevstjønn et al.[4] (96.7%/79.9%), Ruiz de Gauna et al.[14] (90.1%/80.4%), Aramendi et al.[22] (95.4%/86.3%), Li et al.[26] (93.3%/88.6%), Tan et al.[27] (92.1%/90.5%), or Krasteva et al.[28] (90.1%/86.1%). In all these studies specificities were well below the 95% goal recommended by the AHA. However, this comparison must be considered carefully as each work (1) was carried out on a different dataset with different rhythm prevalences, and (2) used its own SAA which may diagnose the filtered ECG in a different way. Fig. 4 shows the main reasons for the misdiagnoses. In panel a, the main reason of the low specificity of this and previous studies is illustrated, an AS diagnosed as shockable due to the residue left by the filtering process. In panel b, a source of erroneous non-shockable decisions is shown, spiky filtering residuals interpreted as QRS complexes for a VF.

4.3. Current state and potential application

Currently, to the best of our knowledge, there are two commercial technologies that offer rhythm assessment during ongoing CPR. The first one corresponds to the CPR artefact suppression method proposed by Tan et al.[27] (known as 'See-Thru CPR') which has been incorporated into commercial defibrillators, namely Zoll Medical Corporation (Chelmsford, Massachusetts, USA) defibrillators. It displays on defibrillator's screen both the filtered ECG and the estimated CPR artifact during ongoing chest compressions and only if the operating mode is set to manual. Thus, only professional rescuers able to operate in manual mode can see the filtered ECG during chest compressions. According to the manufacturer, the filtered ECG is not suitable for making treatment decisions because the 'See-Thru CPR' is not able to remove all the CPR artefact. Therefore, CPR must be always stopped to reassess the rhythm and make a decision.

The second and most recent one is the 'cprINSIGHT' analysis technology incorporated in the automated external defibrillator LIFEPAK CR2 by Physio-Control (Redmond, WA, USA). The technology is proprietary and few details have been disclosed, only that it processes both ECG and thoracic impedance during ongoing compressions, and one of the following three decisions is made: shock, no shock, or to pause chest compressions because further analysis (in an artefact-free interval) is required.[29]

Given the SE/SP values observed for individual reviewers and for the DPR, our study confirms that the filtered ECG should be used as a decision support tool during ALS. That is, the combination of CPR artefact suppression and visual assessment of filtered ECG by doctors is quite good, but not enough to meet AHA requirements. Nevertheless, if applied correctly our method can be helpful to minimize hands-off intervals and advance defibrillation in ALS. For instance, during 2 min chest compressions series ALS providers could monitor the rhythm at any time and make one of the following decisions: (1) charge the defibrillator and immediately after, stop CPR before the end of the series to confirm the suspected shockable rhythm in an artefact-free interval. If so, deliver a shock and otherwise, discharge the defibrillator and resume chest compressions; (2) prolong chest compressions because a clear OR is detected. Only stop chest compressions when a rhythm transition occurs and a rhythm reassessment is needed, or when pulse must be checked; (3) if none of the previous actions take place, complete the chest compression series and then make a diagnosis in an artefact-free interval. Future studies must validate this application proposal with simulations of real cardiac arrest episodes to quantify the reduction of hands-off intervals (shortening pre-shock pauses or avoiding unnecessary rhythm analysis intervals) and advance of defibrillation. In a second stage, shock outcome prediction[30–32] might also be incorporated to this application proposal to only deliver defibrillations with high probability of success and thus, avoid unnecessary unsuccessful defibrillations that can cause myocardial damage.

4.4. Limitations of the study

This study was conceived to measure the accuracy of rhythm analysis by experienced emergency medicine doctors when assessing the rhythm in a relaxed scenario, i.e. in optimal conditions without the time restriction, stress and pressure that are present in a real cardiac arrest scenario. Accuracy in rhythm assessment obtained in more stressful scenarios (with time restriction or in a real scenario) is expected to be lower. Future studies must evaluate how visual ECG assessment by emergency medicine doctors is affected with limited time for a decision.

Another limiting factor is that the study was carried out using data acquired from a particular site and exclusively by the Philips MRx monitor/defibrillator. Therefore, results obtained should be confirmed using data from different sites and ECGs recorded from a wide variety of defibrillators.

5. Conclusions

In this study, the reliability of rhythm analysis during ongoing CPR has been evaluated through the visual assessment of the ECG by experienced emergency medicine doctors. An adaptive filtering scheme based on the LMS algorithm has been used to suppress the CPR artefact, and the accuracy of four experienced clinicians to diagnose the filtered ECG has been evaluated and compared to that of a commercial SAA. Reviewers outperformed the SAA, but specificities remained below the specifications recommended by the AHA. The decision of a pool of reviewers increased the accuracy considerably.

Ethical Approval

The CPR process files used in this study were collected as part of an effort to develop an airway check algorithm using the capnography signal. Since these raw data files have no identifying information, the Institutional Review Board at the Oregon Health & Science University determined that the proposed activity is not human subject research because the proposed activity does not meet the definition of human subject per 45 CFR 46.102(f).

Conflict of interest

Authors declare no conflict of interest.

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Figure Legends

Figure 1 — Example of a segment presenting VF which was included in the dataset of the study. On top the complete ECG where the first 10 s correspond to the corrupt interval and the following 10 s to the artefact-free interval. Panel a shows, from top to bottom, the corrupt ECG (ECG_c), filtered ECG (ECG_f), and estimated CPR artefact (CPR), while panel b represents the artefact-free ECG (ECG_{af}).

Figure 2 — Dissociated segment as it was presented to the reviewers for annotation. The top panel shows 6 s of the artefact-free interval, while the bottom panel shows 6 s of the filtered ECG which included the corrupt ECG, the filtered ECG and the CPR artefact. The intervals were numbered differently and delivered in separate booklets to guarantee the dissociation.

Figure 3 — Examples of artefact-free intervals of segments not included in the dataset of the study. Annotations made by the four reviewers are shown in the left-top side of the ECG.

Figure 4 — Examples of ECG segments misdiagnosed after removing the CPR artefact. In both panels, from top to bottom, the raw ECG where the first 10 s correspond to the artefact-free interval and the last 10 s to the corrupt interval, and the filtered ECG after removing the CPR artefact. Panel a shows an AS misdiagnosed as shockable due to large disorganized filtering residuals, and panel b depicts a VF incorrectly diagnosed as non-shockable due to post-filtering spikes which were interpreted as QRS complexes by the reviewers.

Table Legends

Table 1	Summary of the results obtained for the artefact-free intervals. The SE, SP, proportion of intervals diagnosed as UN and the agreement with the gold standard are reported for each reviewer (A, B, C, and D), and for the SAA. The numbers in parenthesis indicate the positive decisions for each category out of the total number of decisions. Kappa scores with 95% confidence intervals are reported to measure the agreement.
Table 2	Summary of the results obtained for the filtered intervals. The SE, SP, proportion of intervals diagnosed as UN and the agreement with the gold standard are reported for each reviewer (A, B, C, and D), for the DPR, and for the SAA. The numbers in parenthesis indicate the positive decisions for each category out of the total number of decisions. Kappa scores with 95% confidence intervals are reported to measure the agreement.