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Clinical paper

The performance of a new shock advisory algorithm to reduce interruptions during CPR

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Abstract

Objective: To explore a new algorithm and strategy for rhythm analysis during chest compressions (CCs), and to improve the efficiency of cardiopulmonary resuscitation (CPR) by minimizing interruptions.

Methods: The clinical data and ECG of patients with sudden cardiac arrest (CA) from three hospitals in China were collected with Philips MRx monitor/defibrillators. The length of each analyzed ECG segment was 23 s, the first 11.5 s was selected to contain CPR compressions, the next 5 s had no compressions, and the last 6.5 s had no requirement. Three experienced emergency doctors annotated the ECG segments without compression artifacts. A two-step analysis through CPR (ATC) algorithm was applied to the selected data. The first step was analysis during chest compressions. If a shockable rhythm was not detected, compression-free analysis followed. The results of the ATC algorithm were compared with the annotations by the physicians, to determine the sensitivity and specificity of the algorithm.

Results: In total 166 CA patients were included with 100 out-of-hospital cardiac arrest (OHCA) patients and 66 in-hospital cardiac arrest (IHCA) patients. A total of 1578 ECG segments were analyzed, including 115 (7.3%) shockable rhythms, 1278 (81.0%) non-shockable rhythms, and 185 (11.7%) intermediate/unknown rhythms. The specificity of all non-shockable rhythms was 99.8% at the end of chest compressions, and 99.5% after analysis without compression artifact. 70.5% of ventricular fibrillation (VF) rhythms were detected by the end of chest compressions. After the CC-free analysis, 93.6% of VF was identified.

Conclusion: The ATC algorithm achieved sensitivity of 93.6% and specificity of 99.5% after the two-step analysis, and 70.5% of the patients with shockable rhythms did not require CC-free analysis. Such an approach has the potential to substantially reduce CC interruptions when identifying shockable rhythms.

Keywords: Rhythm analysis, Algorithm, CPR, Cardiac arrest

Introduction

Early defibrillation and high-quality cardiopulmonary resuscitation (CPR) are elements of the chain of survival for patients with cardiac arrest (CA). Studies have shown that the main factors resulting in poor prognosis after cardiac arrest include delayed CPR, low quality CPR with ineffectiveness and frequent interruption of chest compressions (CCs), and delayed defibrillation.[1–5] On the contrary, significantly better outcomes were achieved when the no flow time (NFT) or interruption of chest compression was minimized.[6–9] Cardiac rhythms may change during cardiac arrest and CPR,[10] and the artifacts produced by CCs

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reduce the accuracy of rhythm analysis in the current automatic external defibrillators (AEDs). Therefore, CCs are mandated to be interrupted repeatedly for rhythm analysis.[11] The pre-shock interruptions last 5.2–28.4 s,[12] which may reduce the patients' survival rate.[13] Therefore, the latest resuscitation guidelines of the American Heart Association (AHA) emphasized the importance of high-quality CPR with minimal interruptions in chest compressions.[14,15]

To date, most shock advisory algorithms in AEDs require interruptions for rhythm analysis.[16] If these algorithms are applied on CPR corrupted data, the sensitivity may meet the requirement of the American Heart Association (AHA) (≥90%),[16] while specificity rarely exceeds 85%, well below the 95% value recommended by the AHA.[17] Reduced specificity will lead to a large number of incorrect "shock decision" during CPR, and unnecessary CPR interruptions for non-shockable rhythms. Some solutions to perform rhythm analysis during CCs, such as adaptive filters[18–20] or new shock advisory algorithms (SAA) are designed to analyze either the artifacted[21,22] or the filtered ECG.[23] Esibov et al.[24] reported a novel analysis through CPR (ATC) algorithm with high sensitivity and specificity. However, 29% of the rhythms were put into an undecided group and excluded from the calculation of sensitivity/specificity during CCs. The actual performance of the algorithm with the undecided rhythms included was not reported. Although researchers have made advances in rhythm analysis with artifact filtering during CPR, the current performance is not very satisfactory, especially for non-shockable rhythms.[25]

In this study, we report a new algorithm and strategy for analyzing cardiac rhythms during CCs to improve the efficiency of rhythm analysis, especially specificity. Compared with previous studies, this method greatly improved the specificity without reducing the sensitivity.

Materials and methods

Design of the ATC protocol

As shown in Fig. 1, the ATC protocol includes two steps. STEP 1 analyzes ECG rhythm during CPR by employing an algorithm robust to CPR artifacts. Most shockable rhythms are identified in STEP 1 and a shock can be delivered right after the end of the CPR interval. If the rhythm is undecided in STEP 1, CPR is paused and a traditional algorithm will analyze the CPR-free ECG in STEP 2 to further identify a small group of shockable rhythms and the other non-shockable rhythms. The STEP 2 analysis in the ATC protocol is essentially the same with the standard protocol shown in Fig. 1.

It's worth noting that the proposed ATC protocol does not depend on the particular algorithms. Adapting this ATC protocol to any

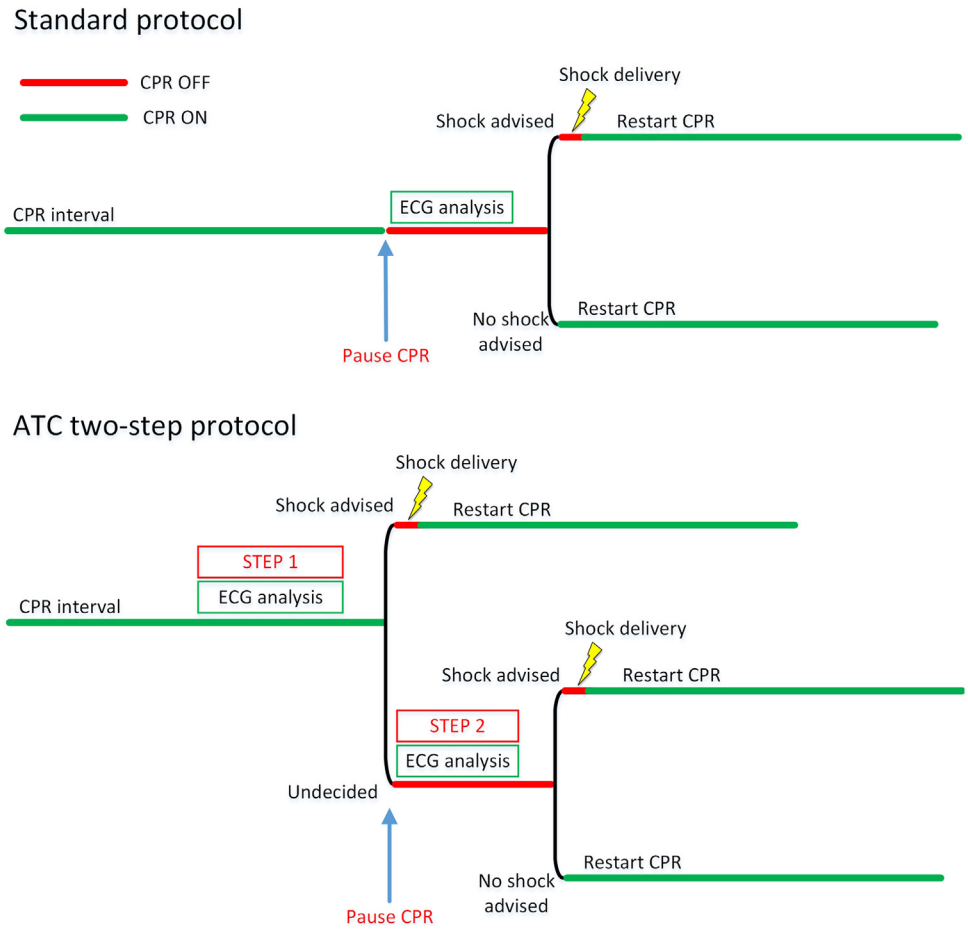

Fig. 1 – Flowchart of the analysis through CPR algorithm. (A) A standard AED protocol, which requires interruptions of chest compressions for ECG analysis. (B) The two-step analysis through CPR (ATC) protocol, where heart rhythm analysis is conducted during CPR in STEP 1, and shock can be delivered as soon as the CPR interval ends; If shock is not advised during CPR, the STEP 2 rhythm analysis is performed.

algorithm, which can appropriately analyze CPR artifacts, would help minimize the CPR interruptions in a percentage of shockable patients.

Clinical data collection

This was a multi-center study which was registered in the United States clinical trial database (registration number: NCT02952105). This study was approved, with an informed consent exemption, by the Medical Ethics Committee of The First Affiliated Hospital and College of Clinical Medicine of Henan University of Science and Technology. The anonymized data were collected for retrospective analysis. All patients enrolled received standard patient care. From April 1, 2016 to October 31, 2017, 166 CA patients were enrolled from the emergency departments of three hospitals including Peking Union Medical Hospital, the First Affiliated Hospital of Henan University of Science and Technology, and the Central hospital of Jinhua City in Zhejiang province.

CA patients ≥14 years of age who were admitted to the Emergency Departments were enrolled. CA patients were excluded if they (1) had a Do Not Resuscitate (DNR) order; (2) were pregnant; or (3) had incomplete data. According to the Utstein model,[26] CA is defined as the cessation of cardiac mechanical contraction activity. CPR refers to the measures to restore the spontaneous circulation through chest compressions and/or airway ventilation. Restoration of spontaneous circulation (ROSC) is defined as pulse or blood pressure that can be obtained and maintain at least 30 s, with agonal gasping respiration. All the study physicians treating enrolled patients were trained according to the AHA 2015 Guidelines. The physician in charge of CPR filled out the case report form.

ECG data extraction

Philips MRx monitor/defibrillator (model 3536A), disposable defibrillation pads, and Q-CPR meter were used during the resuscitation. Chest compression waves were acquired by the Q-CPR meter (Fig. 2). The following data were collected: transthoracic impedance (TI) recorded at a 200 Hz sampling rate, ECG recorded at a 250 Hz sampling rate, the depth of CCs recorded at a 50 Hz sampling rate. All data were stored in the Philips MRx monitor/defibrillator.

Data review and annotation

ECG segments were extracted from the recordings (Fig. 2 Upper Panel). The length of each segment was 16.5 s. The first 11.5 s of data was selected to contain CCs, followed by 5 s of ECG data without compressions. The 5-s CC-free ECG segment was used for annotating the heart rhythm by the physicians. Actual waveforms of ECG were recorded by the monitor/defibrillator. The thoracic impedance waves and Q-CPR compression waves (Fig. 2 Upper Panel) were also collected and were used to confirm the presence or absence of compressions. ECG segments free of chest compression artifacts (Annotated ECG in Fig. 2 Upper Panel) was plotted in the style of ECG strips for annotation purpose.

In Atkins's research, a three-second ECG segment was sufficient to describe the rate, stability, and morphology of the rhythm for SAA to make a decision for shock or non-shock.[27] In brief, adapted from the guidelines of AHA,[17] cardiac rhythms were divided into four categories: (1) shockable, including ventricular fibrillation (VF), polymorphic ventricular tachycardia and ventricular flutter (VT); (2) non-shockable, including asystole (ASY), organized and other non-shockable non-asystole rhythms (ORG), normal sinus rhythm (NSR), near normal sinus rhythm (NNSR); (3) intermediate rhythm, including low amplitude or low frequency ventricular fibrillation (LVF), unspecified ventricular tachycardia (UVT); and (4) unknown rhythms.

In this study, it was assumed that the rhythm of the 5 s of ECG with no CC was consistent with that of the previous 11.5 s with CCs. It's worth noting that because the segments are chosen at the transitions from CC to CC free, NSR is rare. If a patient is receiving CPR, it is less likely that the present rhythm is NSR. In order to increase the number of NSR segments, a category of Near NSR (NNSR) was created, which includes organized rhythms with similar characteristics to NSR. When evaluating the performance of the ATC algorithm, the NSR group and NNSR group were combined. According to the criteria described in AHA guidelines, three experienced physicians (two emergency physicians and one cardiologist) independently annotated the artifact-free ECG rhythms seen during the 5-s hand-off period. When the annotators did not agree, a review meeting was held in order to reach consensus. If consensus was still not reached, that ECG segment was put into the "Unknowns" category.

Assessment for the efficiency of the ATC algorithm

The ATC algorithm was trained as reported previously using a separate database.[28] This study aimed to apply the algorithm using ECG segments from our database. We evaluated the two-step ATC algorithm protocol (Fig. 1). STEP 1 analyses the rhythm in the 11.5-s CPR corrupted ECG. If an underlying shockable rhythm is identified, the analysis is complete; otherwise the STEP 2 will analyze the following artifact-free ECG. The decisions of the ATC algorithm were compared with the physician annotations and the sensitivity and specificity of the algorithm were evaluated during CCs and after the CC-free analysis.

Statistical analysis

All statistical analyses were performed using SPSS 20.0 software (IBM Corporation, New York, NY, USA). Quantitative variables were presented as means ± standard deviation or frequencies and qualitative variables as percentages (%). The performance of the ACT algorithm is presented as sensitivity and specificity.

Results

There were 166 CA patients enrolled, including 100 out-of-hospital cardiac arrest (OHCA) and 66 in-hospital cardiac arrest (IHCA) patients. There were 119 males and 47 females with an average age of 64.3 ± 15.5 years. CPR was performed with manual compressions, and the Philips MRx monitor/defibrillator was used for defibrillation and data collection. The data of OHCA patients were recorded only after their admission to the hospitals. The defibrillators were used in manual mode. 55 (33.1%) patients returned to spontaneous circulation at least once, and 6 (3.6%) patients survived to the 28th day. The median rate and depth of chest compressions were 113 (83–150) compressions per minute (cpm) and 45 (25–64) mm, respectively (Table 1).

The clinical data were retrospectively processed and then analyzed by the ATC algorithm. 1578 ECG segments were extracted from recordings of 166 CA patients, including 115 (7.3%) shockable rhythms, and 1215 (77.0%) non-shockable rhythms (Table 2).

Examples of the compression-free ECG used for annotations are presented in Fig. 2 (Lower Panel), including shockable, non-shockable and intermediate rhythms. As shown in Table 2, 7.8% of

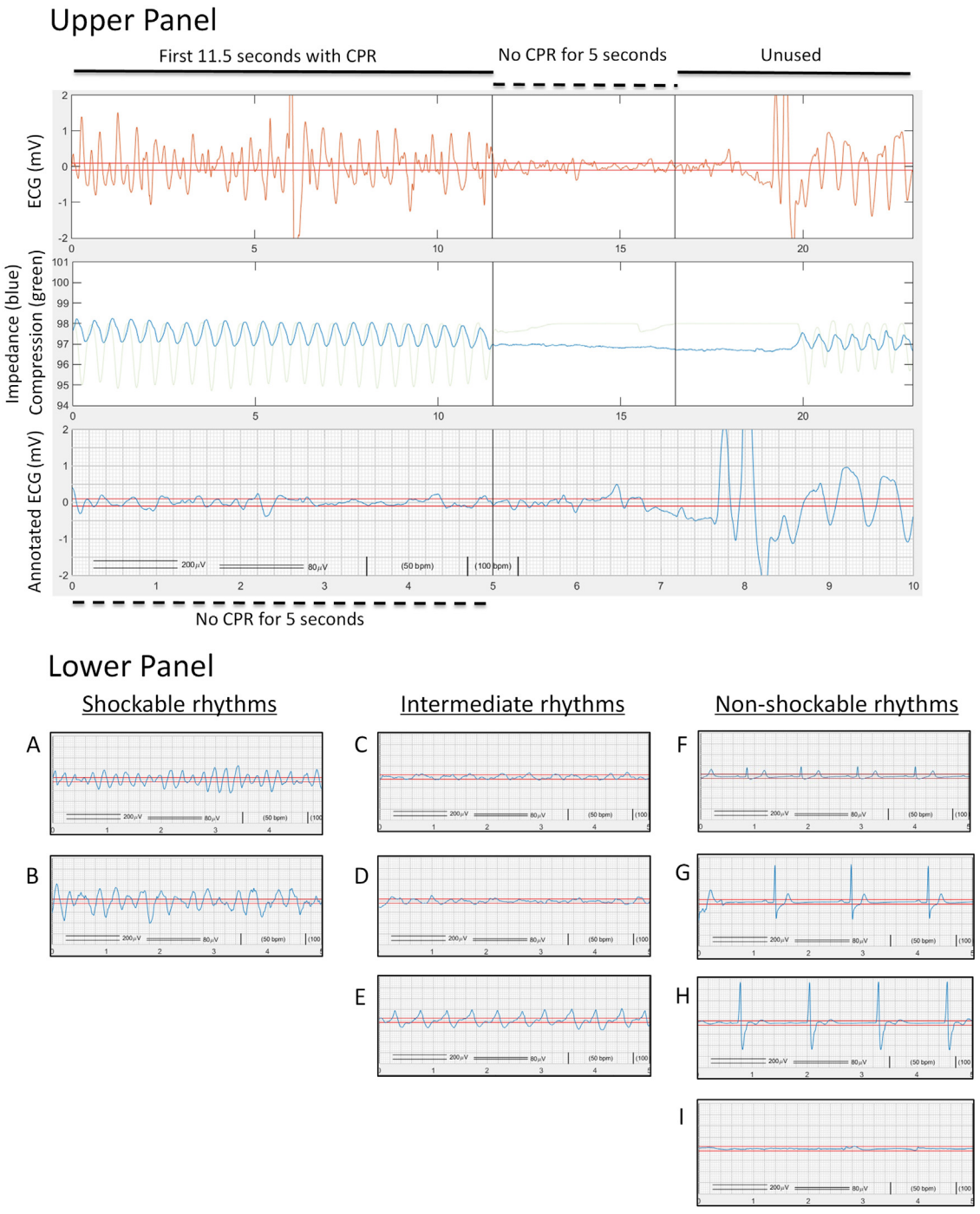

Fig. 2 – Upper panel: the ECG annotation tool. Top: the 16.5-s ECG consisting of 11.5 s ECG with CPR followed by 5 s without CPR; middle: the compression waveform (green) and the impedance waveform (blue) which indicate the status of CPR; Bottom: the 5-second CPR-free ECG plotted in ECG strip style. Lower Panel: Examples of shockable rhythms, including Ventricular Fibrillation/VF (A), Ventricular Tachycardia/VT (B); intermediate rhythms including low rate VF (C), low amplitude VF (D), Unspecified VT/UVT (E); non-shockable rhythms including Normal Sinus Rhythm /NSR (F), Organized rhythm with similar characteristics to NSR/NNSR (G), Organized rhythm and other non-asystole non-shockable rhythms/ORG (H), Asystole /ASY(I) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

all rhythms are LVF. This is probably caused by relatively long time for OHCA patients treated by defibrillators.

After STEP 1 of the ATC protocol analyzing the rhythm during CPR, 70.5% of VF segments were successfully identified. After STEP 2 of CPR-free rhythm analysis, a total of 93.6% VF segments were correctly identified. The specificity of all non-shockable rhythms was 99.8% after STEP 1 during CCs, and 99.5% after STEP 2 CPR-free analysis, exceeding the

Table 1 – The clinical demographics, CPR characteristics and prognosis of CA patients.

	Number of Patients (n/%)	Number of Segments (n/%)
Clinical demographics		
Male	71.7%(119/166)	/
Age (mean ± std)	64.3 ± 15.5	/
Location of CA		
OHCA	60.2%(100/166)	/
IHCA	39.8%(66/166)	/
Cardiac origin	63/166(38.0%)	/
Rhythm		
Non-shockable		
ASY	81/166(48.8%)	613/1578(38.8%)
NSR + NNSR	26/166(15.7%)	84/1578(5.3%)
ORG	138/166(83.1%)	581/1578(36.8%)
Shockable		
VF	24/166(14.4%)	78(4.9%)
VT	21/166(12.6%)	37(2.3%)
Intermediate		
LVF	42/166(25.3%)	123(7.8%)
UVT	11/166(6.6%)	14(0.9%)
Unknown	29/166(17.5%)	48(3.0%)
CPR characteristics		
Mean compression depth (mm, mean ± std)	45.1 ± 10.5	/
Mean CCs rate (cpm, mean ± std)	113.1 ± 12.9	/
Medical treatment		
Shock	45/166 (27.1%)	/
Adrenaline administration	164/166 (98.7%)	/
Advanced airway	98/166 (59.0%)	/
Prognosis		
ROSC	33.1% (55/166)	/
Survival to 28th days	3.6% (6/166)	/

Table 2 – The efficiency of ATC in rhythm analysis.

Rhythm	Performance during CCs	Performance after hands-off analysis
Non-shockable		
ASY (Specificity)	99.7% (611/613)	99.7% (611/613)
NSR + NNSR (Specificity)	100% (84/84)	100% (84/84)
ORG (Specificity)	99.8% (580/581)	99.3% (577/581)
Shockable		
VF (sensitivity)	70.5% (55/78)	93.6% (73/78)
VT (sensitivity)	43.2% (16/37)	83.8% (31/37)
Others		
LVF (sensitivity)	0% (0/123)	19.5% (24/123)
UVT (sensitivity)	14.3% (2/14)	21.4% (3/14)
Unknown(Specificity)	97.9% (47/48)	95.8% (46/48)

requirements of the AHA.[17] The detailed performance of the ATC algorithm is shown in Table 2.

Two non-shockable and two shockable rhythm examples are shown in Fig. 3. Rhythm diagnosis in Fig. 3A and B: non-shockable rhythm (ORG, ASY), no defibrillation recommendations were made in the first 11.5 s segment with compressions and 5 s segment without compressions. The asystole in Fig. 3B looks like VF during chest compressions, and the ATC algorithm correctly avoids a shock decision during the chest compressions. For the rhythm diagnosis of Fig. 3C: shockable rhythm (VF), the defibrillation decision was made in the first 11.5 s segment with compressions. Rhythm diagnosis of Fig. 3D: shockable rhythm (VF), no defibrillation decision was made in the first 11.5 s segment with compressions, but a shock decision was made in the 5 s segment without compressions.

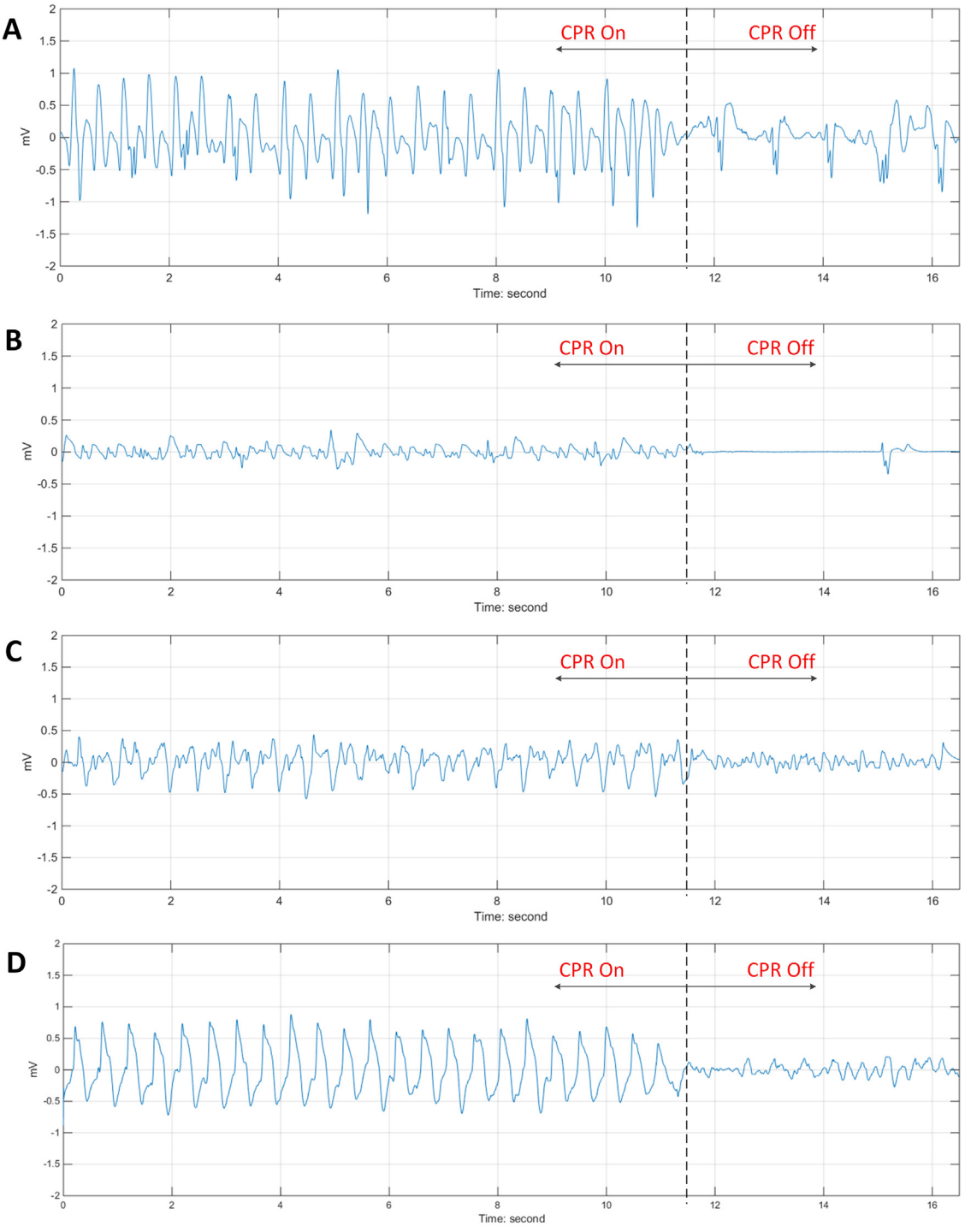

Fig. 3 – Examples of rhythms sequentially analyzed by the ATC algorithm. (A) Organized rhythm. STEP 1: undecided; STEP 2: no shock advised. (B) Asystole. STEP 1: undecided; STEP 2: no shock advised. (C) Ventricular fibrillation. STEP 1: shock advised; STEP 2: not applicable. (D) Ventricular fibrillation. STEP 1: undecided; STEP 2: shock advised.

Discussions

Reduction of pauses in CCs is one of the key elements of high-quality CPR in the 2015 AHA Guidelines. In order to achieve this goal, a number of methods have been proposed to minimize the interruptions of CCs, especially during pre- and post-shock pauses. These methods fall into two main categories: (1) charging the defibrillator during chest compressions or analyzing the rhythm during ventilations[15,29–31]; and (2) using adaptive filters to suppress chest compression artifacts on performance of ECG (artifact-free or artifact-contaminated ECG), or a combination of

both. However, the performance of most algorithms does not meet the AHA guidelines.

The methods using digital signal processing techniques to suppress artifacts induced by the chest compression to analyze the filtered rhythm have significantly improved the signal to noise ratio (SNR) of the CPR corrupted ECG signals. The accuracy of rhythm classification has also been improved but still suffers from the filtering residuals.[18,22,32–34] On one hand, non-shockable rhythms are occasionally identified as VF when the amplitude of disorganized residuals are large enough to cover the underlying rhythm; on the other hand, VF may also be misclassified as non-shockable rhythms when the chest compression induced spiky artifacts are interpreted as QRS complexes.[23,34] The electrical activity in the heart and thoracic muscles or the movement of the electrode pads during compressions may affect the specificity of SAAs.[18] An inaccurate method could have an adverse effect on survival with long hands-off time or incorrect shock decisions. False positive shock decisions could lead to an unnecessary pause in CCs or an unnecessary shock, and false negative classification could delay defibrillation.[32] In one simulation study, a method with a sensitivity of 94% and a specificity of 81% resulted in unnecessary CPR interruptions in 42% of non-shockable rhythm episodes.[35] Therefore, researchers are still working on improving the accuracy of rhythm classification during CPR.

In this study, a two-step algorithm analyzing ECGs during CPR obtained a very high specificity, and a sensitivity meeting the requirement in AHA guidelines.[17] In the 1278 non-shockable rhythms, the specificity of rhythm analysis during CCs was 99.8%, and slightly dropped to 99.5% after the CC-free analysis. Fig. 3A shows an ECG segment of organized rhythm, and Fig. 3B shows an example of asystole. As shown, the ECG waveforms in the first 11.5 s are contaminated by CC-caused artifacts. The contaminated rhythms are visually similar to VF. The ATC algorithm correctly recognized this segment as "undecided" instead of "shockable". In Fig. 3C, the ATC algorithm made a correct defibrillation decision during CCs, although the artifacts are prominent. The shock advice can be made without interruption of CCs, and so the duration of pre-shock pause is minimized. In Fig. 3D, the algorithm did not make a shock decision during CCs, but the shock decision occurred in the subsequent CC-free analysis. It is obvious that the artifact generated by CCs overwhelms the VF signal, and the ATC algorithm conservatively used the CC-free analysis for accurate classification of the rhythm. Over 70% of the VF cases in this study were recognized as shockable rhythm without the need of CC-free analysis, which implies that 70% of the VF patients could have minimized CC interruptions because the pre-shock pause can be reduced to near zero. Another 23% of the VF cases were further detected with CC-free analysis, which demonstrates that about 23% of the shockable patients may receive the standard diagnosis like what is provided in existing AEDs.

Overall 93.6% of the VF cases were identified by the ATC algorithm meeting the sensitivity requirement in the AHA guidelines. 43.2% of the VT segments were recognized as shockable rhythm during CCs, and 83.8% of them were identified as shockable rhythm by the ATC algorithm after CC-free analysis, which was higher than the required sensitivity of 75% in the AHA guidelines.[17] In addition, intermediate rhythms (UVT and LVF) include low-rate ventricular tachycardia, low-frequency and low-amplitude ventricular fibrillation. The effects of shocking on these rhythms are unclear. The proposed ATC algorithm is conservatively designed to analyze intermediate rhythms.

Some recently developed algorithms tackling CC-corrupted data are compared in Table 3,[23] the specificities of most of them were below 90% (the AHA guidelines are 95% for ASY and ORG, and 99% for NSR).In a recent publication, Esibov's[24] study had the highest specificity, using a novel algorithm to analyze the rhythm during ongoing chest compressions. However, a 29% undecided group was excluded from the calculation of sensitivity/specificity. With enhanced adaptive filter technology and the multi-channel reference signal, researchers[36,37] found that the signal-to-noise ratio of the filtering signal was significantly improved, and the filtering efficiency was further enhanced. They obtained sensitivity and specificity of 96.9% and 100% for artifact-free signals, and 88.7% and 69.4% when the signals were corrupted by CPR artifact, and improved to 90.8% and 83.5% when enhanced adaptive filtering methods were applied. However, this method required use of multi-channel reference signals, which may not be suitable for bystander AEDs for use during OHCA.

In this study, the compression rate was 113.1 ± 12.9/min. The mean value is within the range of the 2015 AHA guidelines (100–120/min). The average compression depth was 45.1 ± 10.5 mm, which is slightly lower than the recommended depth (50–60 mm) in the guidelines. In actual practice, the subjects were mostly elderly patients and most of them had osteoporosis. The medical staff reported they routinely would reduce compression strength and depth to reduce complications from CCs. During manual CPR, injures were more common when compression depth was greater than 60 mm.[14] Fifty-five (33.1%) of 166 patients had ROSC at least once in the present study. Six patients (3.6%) survived to the 28th day. These results are comparable to a previous epidemiological study of cardiac arrest patients reported by our group (ROSC rate: 33.9%, 28 days survival rate: 3.26%).[38]

There were some limitations of this study. Both the total number of patients and the number of VF patients were small, and the requirement of 200 patients with coarse VF by AHA was not reached[17]

Table 3 – Comparison the effectiveness of rhythm analysis methods in sudden cardiac arrest patients.

Author	Method	Accuracy		Testing datasets	
		Sensitivity (%)	Specificity (%)	Shockable	Non-shockable
Li et al.[17]	Direct analysis	93.3	88.6	1256	964
Krasteva et al.[18]	Direct analysis	90.1	86.1	172	721
Eilevstjønn et al.[14]	MC-RAMP	96.7	79.9	92	174
Aramendi et al.[16]	LMS filter	95.4	86.3	87	285
Tan et al.[33]	ART filter	92.1	90.5	114	4155
Ayala et al.[19]	Filtering + SAA	91.0	96.6	622	3350
Esibov et al.[20]	SAA	96.3	97.7	603	2338
This study	ATC protocol	93.6	99.5	185	1278

due to characteristics of the enrolled patients. The out-of-hospital CA patients were not treated with a defibrillator until hospital arrival. It reflects the current workflow of the ALS systems in three big cities in China. The time from patient collapse to the application of the defibrillator was long resulting in a low percentage of shockable patients, and a relatively high number of patients with LVF. The analysis was on 11.5 s ECG with CCs and 5 s ECG without CCs. A database with longer segments would better evaluate the performance of the proposed ATC algorithm reflecting real-world continuous analysis.

Conclusions

The proposed ATC algorithm resulted in a high specificity and sensitivity, with 70.3% of shockable rhythms were identified without interruption of CCs. Application of this algorithm may minimize CC interruptions and improve the quality of CPR and the prognosis of CA patients.

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Conflict of interest

None.

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