Use of the Impedance Cardiogram in Public Access Defibrillators as an Indicator of Cardiopulmonary Resuscitation Effectiveness

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Abstract

An algorithm has been developed for a Public Access Defibrillator which utilizes distinctive features from the impedance cardiogram (ICG) recorded via defibrillator pads to advise both lay users and minimally trained bystanders to ensure CPR effectiveness. Following ethical approval, data were collected and marked. CPR was administered by trained personnel. 211 cases were gathered and the training set included 106 cases. A retrospective analysis was carried out of simultaneously recorded ECG and ICG. The speed of compressions was calculated by counting the outstanding waves in the ICG during CPR. Also if the base-to-peak amplitude of the ICG is greater than a minimum threshold, the corresponding compressions were classified as being applied with adequate force. For the validation set, adequate speed was detected with 91.45% sensitivity and 96.27% specificity (79826s) and adequate force with 99.94% sensitivity and 97.91% specificity (91973s).

1. Introduction

Impedance cardiograms (ICG) have been studied for more than 40 years as a non-invasive method in estimating stroke volume and particular cardiac events [1,2]. However ICG are not widely used in comparison to ECG.

Kubicek et al. [1] used tetrapolar band electrodes which turned out to be difficult to use in clinical settings [3]. Different configurations and placement of electrodes have been attempted. These have resulted in discrepancies in the methods to estimate the stroke volume [4,5] and in the ICG morphology itself. Improved ICG recording methods have recently enabled their widespread use in critical care [6]. Also, ICG can be measured in portable defibrillators using two defibrillation electrodes, which overcome the cumbersome application of multiple electrodes and provide additional information apart from the ECG to assess a patient in suspected cardiac arrest [7-9]. Cromie et al. reported that using two defibrillation pads the ICG could detect differences in stroke volumes from gated myocardial perfusion imaging scans [8]. They also reported an embedded frequency analysis of the derivative of the impedance signal which provided additional information about circulatory arrest [7,8]. Risdal et al. presented an algorithm based on ICG and ECG recorded from defibrillator pads in order to distinguish between Pulseless Electrical Activity and perfusing rhythms [9]. ICG measured in a defibrillator can also be used to improve the management of high rate ventricular tachycardia [10].

Distinctive changes in the morphology of ICG related to the compressions during Cardiopulmonary Resuscitation (CPR) can be used to assess the process. Alternatively, there are devices which use accelerometers in addition to defibrillator pads to evaluate and guide the compressions. Accelerometers allow the estimation of compression depth [11]. The current 2010 AHA guidelines suggest a minimum depth of 2 inches to guarantee effective chest compressions [12]. However, apart from the two defibrillator pads, the application of an accelerometer presents an added complication in the critical time window available to both assess the patient and provide a fast and adequate therapy. In this paper an algorithm that can provide real-time indications about the force and the speed of compressions is presented which is based uniquely on the ICG measured via defibrillation electrodes. It has been developed from the analysis of the ICG during in-hospital CPR administrated by nurses.

2. Materials and methods

2.1. Equipment

An in-house fully functional defibrillator was constructed (Samaritan AED; HeartSine Technologies, UK) which in addition to the ECG, included the recording of ICG using a low amplitude sinusoidal current (30 kHz; 0.05 mA) via 2 adhesive defibrillator pads (Samaritan, SDE 201, Heartsine Technologies, UK). Its CPU is a Motorola 68336, the sample rate is 170.66 samples per second, 8 bits are used to represent the data: ECG

(±3mV), ICG (±0.66Ω from the baseline impedance). The ECG and ICG signals were monitored, digitized and stored for retrospective analysis [8].

2.2. Clinical studies

Most of the ECG with ICG clinical data used in this research has been reported by Cromie et al. [8] and collected by Darragh et al. [13]. The ICG was recorded in 210 patients attending within the Royal Victoria Hospital and in the community of greater Belfast, by an Emergency Medical Team (EMT) from 1st May 2003 – through 2004 and after 2006. The defibrillator was used with adhesive ECG/ICG pads applied in standard cardiac arrest positions (inferior to the right clavicle in midclavicular line, to the right of the upper sternum and over the left lower chest). The study complied with the Declaration of Helsinki. The Local Regional Ethical Committee approved the study. All survivors and the next of kin of non-survivors were informed retrospectively, and could withdraw consent for the use of their data. There was no interruption in patient management during this study.

Data were marked, using EMT documentation, by an investigator blinded to the ICG. CPR was identified in the recordings in addition to Sinus Rhythm, and different arrhythmias. A total of 105 cases were randomly chosen for the Training set for CPR analysis. Not all of the cases contained CPR. An additional case was later added to the training set.

2.3. Algorithm for evaluating CPR

Following retrospective analysis of 106 cases in the training set, it was observed that the changes in impedance during compressions are of higher amplitude when compared to the changes in normal perfusing rhythms. There was evidence that the amplitude of the ICG varied according to the force applied to compressions. A significant reduction in the ICG amplitude can be observed close to a pause in the compressions. This reduction in amplitude is consistent with the bystander's increasing level of fatigue. Also at the beginning of the compressions it can be appreciated that the amplitude starts to increase gradually as the bystander achieves a more consistent rate and depth. Also it was observed that each compression generated a wave in the ICG. When the compressions are kept at a particular pace the main frequency component of the ICG coincides with the rate of compression.

The peak-to-baseline amplitude of the ICG when CPR was administered by trained personnel was analysed. If it is greater than 0.35Ω, it was classified as adequate CPR. The algorithm to calculate the instantaneous amplitude (based on an envelope) at an arriving sample from the ICG (Z) is given by:

```
1. read sample
2. calculate absolute value of sample  (abs_sample)
3. if (abs_sample > amplitude) then
  3.1 if (abs_sample > maximum_peak) then
    3.1.1 amplitude = maximum_peak
  else
    3.1.2 amplitude = abs_sample
  end-if
  3.2 last_peak = amplitude
  3.3 amplitude_decrease = amplitude/(sample_rate* t)
  (t is time in seconds the ray would be zero)
  3.4 if (amplitude_decrease=0) then
        amplitude_decrease = 1
  3.5 clearance = 0
end-if
4. amplitude = amplitude - amplitude_decrease
5. clearance = clearance +1
6. if(clearance=9) then maximum_peak = factor*last_peak
  (factor is usually greater than 1)
```

Figure 1 shows an ICG (Z) trace recorded before and during compressions and an example of the envelope (and its mirror) is shown by dotted lines.

Wave detection is implemented by detecting a particular "feature" of the wave. It means that by detecting this feature in the signal we are detecting the occurrence of a wave. In this case we have chosen the local maximum as the feature to be detected. We have used the following four conditions all of which must be fulfilled in order to detect a "strong" local maximum and therefore a wave:

a) Not in a refractory period

b) Previous condition and after a significant negative value has been reached (negative swing).

c) Previous conditions and significant positive slope and higher than a minimum value.

d) Previous conditions and change of sign of consecutives slopes from positive to negative.

A local maximum needs to be anticipated by a significant positive slope -higher than 70% of the average of positive slopes and with significant amplitude. Significant negative values are lower than -0.2 previous local maximum. "Saddle" points are mostly avoided according to condition d). Local maxima in low amplitude signals or below zero can produce false positives which is important to avoid. In figure 1 "Strong" local maxima delimiting waves coinciding with compressions can be seen. Labelled markers show local maxima and saddle points which the algorithm avoids. Marker A points to a saddle point, B is a local maximum of low amplitude, C is a local maximum of low amplitude and no significant previous slope, D is a local maximum with no previous significant negative swing (and low amplitude), E is a local maximum but it is detected inside the refractory period set by a close previous local maximum. The algorithm to detect a local maximum at an every arriving sample is presented:

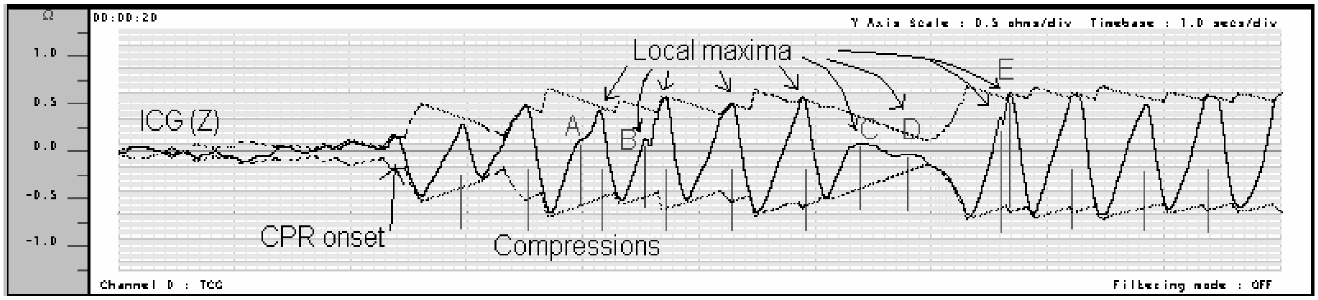

Figure 1. ICG signal morphology before and during CPR. Different maxima are depicted. Dotted lines show an envelope.

```
1. initialise values
  1.1 save previous_slope
  1.2 update slope
  1.3 update average_positive_slope
  1.4 local_maximum_found = false
2. if ( refractory_counter = 0 )  then   //Condition a
  2.1 if ((!completed_negative_swing)
        and (sample<-0.2*previous_peak))  then //Cond b
          2.1.1 completed_negative_swing = true
    end if
   2.2 if ((completed_negative_swing)
        and  (slope > 0.7 * average_positive_slope )
        and (sample > low_limit)) then     // Condition c
           2.2.1 high_slope_found = true
      end if
    end if
    2.3 if ((previous_slope >= 0) and (slope <= 0) ) then
      2.3.1 completed_negative_swing = false
      2.3.2 if (high_slope_found) then   //Condition d
         2.3.2.1 local_maximum_found = true
         2.3.2.2 refractory_counter= MAX_REFRACTORY
         2.3.2.3 average_positive_slope = 0
         2.3.2.4 previous_peak = sample
      end if
    end if
  else
    2.4 refractory_counter = refractory_counter - 1
  end if
```

It is still possible to pick up saddle points when both the previous and the current slopes are zero. A false positive is obtained in this case but the following true local maximum would be ignored by failing to pass conditions a) and b) thereby preventing the wave being counted twice. The maximum refractory period (MAX_REFRACTORY) is the number of samples that will elapse without searching for a local maximum. Its value depends on the sample rate and the rate of good compressions set for the algorithm.

The optimal rate of compressions (speed) was defined as between 84 and 120 compressions per minute and can be calculated by counting the number of waves in the ICG signal during CPR. The lower limit comes to a count of 14 waves in 10 seconds whereas the upper limit arises when 20 waves are counted in that window. This rate of compressions would require an update in light of the 2010 Guidelines which recommend more than 100 compressions per minute.

3. Results

Table 1 shows the results of the algorithm in assessing compressions in terms of force and speed. Sensitivities and specificities are presented alongside their 90% lower confidence interval (CI) value.

Table 1. Assessment of compressions in 1s blocks.

	Total Blocks	Sensitivity (%) (90% lower CI)	Specificity (%) (90%lower CI)
		Training Set	
Good Speed	82377	95.38 (83.40)	93.11 (82.19)
Good Force	108728	99.96 (99.54)	98.47 (96.29)
		Validation Set	
Good Speed	79826	91.45 (75.28)	96.27 (88.43)
Good Force	91973	99.94 (98.94)	97.91 (92.18)

4. Discussion

Results are encouraging especially for the detection of adequate force. For detection of good speed it is important to note that at the time the data were collected the recommended rate of compression was slower than the current recommended rate [12].

The results for the assessment of compressions during CPR are encouraging when compared to the performance of CPR carried out by trained personnel. As can be seen in table 1, the sensitivities and specificities for the training and validation sets are higher than 90%. The algorithm, to detect speed and force based on the ICG measured by the two defibrillation pads, runs in real time and non trained bystanders could benefit from the audio-visual feedback that the defibrillator can provide. No additional accelerometer is required which simplifies the process of providing the therapy to the patient. However, the current guidelines indicate a depth of more than 2 inches for adequate compressions and depth was not studied or measured during the interventions. There are some questions that need to be addressed that represent the limitations of this study: What is the exact relationship between the ICG amplitude (used in the algorithm presented) and depth in a clinical setting? Is depth the best indicator of CPR effectiveness taking into account differences in chest volume, age and size? Our group is attempting to answer these questions in an ongoing study [14]. We found strong correlations (>0.8) between amplitude and depth and depth and thrust in experiments using controlled compressions by a thumper at 6 different thrusts in 12 swine. Also we explored other physiological markers during CPR such as End Tidal CO_2, SpO_2 and Coronary Perfusion Pressure. The answers to those questions have the potential to further validate the presented algorithm using the current guidelines in terms of depth of compressions.

The presented algorithm using ICG amplitude retrospectively validates the compressions during CPR administrated in the controlled environment of a hospital. However data collected in a mobile coronary care scenario instead of a hospital setting is required to further assess the algorithm. Also a comparative study with technologies using accelerometers is recommended.

5. Conclusion

The algorithm presented for the assessment of compressions during CPR using the ICG measured in a defibrillator offers encouraging results. Such an algorithm embedded into a defibrillator has the potential to provide accurate real-time feedback to the rescuer in order to provide effective compressions. The results provide tools for further development of applications for the use of ICG in defibrillators during emergency practice.

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