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Experimental paper

Human ECGs corrupted with real CPR artefacts in an animal model: Generating a database to evaluate and refine algorithms for eliminating CPR artefacts[☆]

M. Granegger[a,*], T. Werther[b], M. Roehrich[a], U. Losert[c], H. Gilly[a]

[a] Department of Anaesthesia, Intensive Care Medicine and Pain Therapy, Medical University of Vienna, Waehringerguertel 18-20, 1180 Vienna, Austria
[b] Faculty of Mathematics, University of Vienna, Vienna, Austria
[c] Department of Biomedical Research, Medical University of Vienna, Vienna, Austria

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ABSTRACT

Aim: For the analysis of ECG rhythms during ongoing CPR, single- or two-channel methods have been proposed to eliminate artefacts from the CPR-corrupted ECG. To refine, test and evaluate these algorithms with a realistic data set, we introduce an animal model with which we created an extended database of human ECGs with real CPR artefacts.
Material and methods: In a pig model real CPR-related artefacts were added to annotated human emergency ECGs. Via a special catheter placed in the oesophagus, ECG sequences (duration > 10 s) were fed in close to the dead pig's heart. The resulting surface potential was recorded on the thorax without and during ongoing chest compressions, which were monitored using a miniature force sensor.
Results: The animals served as a vehicle for human ECGs, making it possible to create a database in which 918 real human ECG sequences (437 shockable and 481 non-shockable) were corrupted with CPR-induced artefacts. The achieved signal-to-noise ratios (SNR) ranged from −17 to +15 dB, sensitivity was 93.5% and specificity was 50.51%. The fed-in ECG and the uncorrupted surface ECG correlated almost perfectly ($r = 0.926 \pm 0.081$; $n = 918$), indicating negligible signal distortion due to the dead pig itself.
Conclusion: As the generated database includes both the original and the corrupted ECG covering a wide range of SNRs as well as the compression force signal, it provides an extended data set to evaluate the reconstruction performance of CPR artefact-removal algorithms.

1. Introduction

CPR-induced corruption of ECG signals is a major limitation for automatic rhythm analysis as performed by state-of-the-art automated external defibrillators (AEDs). At present, manufacturers supply only AEDs in which rhythm analysis is not performed during ongoing CPR. If algorithms like those that have been so far proposed[1–6] could be successfully implemented in an AED, reliable rhythm analysis would be possible also during uninterrupted CPR. One performance measure for ECG reconstruction is the binary classification employing the AED's shock/no shock recommendation. Another parameter commonly used to indicate the performance of the algorithm is the achieved improvement in the signal-to-noise ratio (SNR).

Indeed, various authors claim that their removal algorithms efficiently reduce or even eliminate CPR-induced noise from ventricular fibrillation (VF) and ventricular tachycardia (VT) signals.[2–4,6] However, the performance of several of these algorithms has been tested just with data generated by mathematically modeling the corruption artefact ("additive model"), where the CPR-related noise is linearly added to the ECG.[1,5,7–10] The advantage of this approach is that such test data can be easily generated, that the level of corruption can be predefined in terms of SNR, and that it allows for an explicit comparison between the original (artefact-free) and the reconstructed signal. The clear disadvantage is that the generated data hardly resemble a true CPR artefact as recorded in reality. A recent sensitivity and specificity analysis showed that, when the ECG rhythm is non-shockable, these algorithms could not eliminate CPR artefacts, especially at high corruption levels, without falsifying the shock recommendation[9,11], which is in line with results of previous studies.[2,6]

Here we describe our approach in which we use a dead pig as the source of human emergency ECGs, which are fed in close to the pig's heart. When CPR was performed, realistic CPR artefacts were added to the human ECG rhythms. We generated a database that contains both the corrupted and uncorrupted ECG rhythms, which

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* Corresponding author. Tel.: +43 1404006418.
E-mail addresses: marcus.granegger@meduniwien.ac.at, marcus.granegger@gmx.at (M. Granegger).

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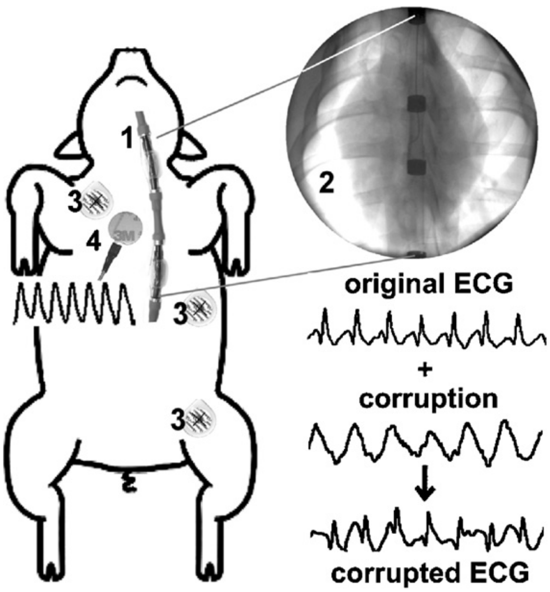

Fig. 1. Outline of the pig model. Uncorrupted human emergency ECGs are introduced close to the pig's heart. These ECGs can be measured on the pig's surface and CPR artefacts can be added by performing chest compression on the pig. (1) Catheter to be inserted into the oesophagus to introduce the original human ECGs. (2) Fluoroscopic image of the inserted catheter. Inflated cuffs ensure proper contact of the stainless steel wires (electrodes) with the oesophagus wall. (3) Standard ECG monitoring electrodes to measure the ECG (3-lead) placed in anterolateral position on the thorax. (4) The Emfit sensor mounted on the sternum at the point of compression and its output, which is related to the force applied to the sternum.

makes it possible to evaluate more precisely the performance of artefact-removal algorithms and enables their refinement.

2. Materials and methods

2.1. Pig model

An overview of the pig model, showing the complete experimental setup, is given in Fig. 1.

2.2. Human original ECG data set

We selected 110 artefact-free ECG signals (duration: 12 s) from real emergency data recorded during resuscitation, either from lead II or from defibrillator pads. All 110 signals were annotated by an experienced emergency physician. Furthermore, 20 VTs were obtained from the Creighton University Database.[12] These 130 signals (in the following denoted as "original" ECG sequences) were analyzed by a Philips Heartstart MRx defibrillator, with the resulting classification in agreement with the annotation (69 non-shockable and 61 shockable).

2.3. Electronic assembly for current injection

The original ECG sequences were converted to an analog voltage. Using a voltage controlled current source[13] the constant current was adjustable between 100 and 200 μA irrespective of changing impedance from 1 Ω to 60 kΩ (due to, for example, the chest compression). In order to achieve a particular SNR the current was set to produce surface potentials between 200 and 300 μV.

The ECG was fed in close to the pig's heart by means of a special catheter which was placed in the oesophagus. A metal ring was fixed at each end of two inflatable cuffs. Stainless steel wires were soldered to the metal ring at one end of the cuff and ended in small holes in the ring at the other end of the cuff. Thus, the wires can slide and arch when the cuff is inflated. Electrical contact with the oesophageal wall is thereby provided. Apart from a 2–4 mm long section of the wires, both the metal rings and the wires were electrically insulated. The correct position of the catheter between the plane of the heart base and the plane of the apex was verified using fluoroscopy.

2.4. Signal recording circuitry

2.4.1. Measurement of the generated ECG

To record the generated surface ECG from the pig's thorax, three standard foam pre-gelled ECG electrodes were used. One electrode was placed 5–10 cm from mid-sternum, the other electrode laterally to the compression point. The reference electrode was positioned on the pig's abdomen. The signal was amplified (1000-fold) and band-pass filtered between 0.6 and 40 Hz.

2.4.2. Recording of the thorax compression

Manual CPR was performed alternately by two MDs, two paramedics and one lay person. Compression rate and depth were largely within the recommended guidelines.[14] To monitor the time course of the compression force applied to the sternum during CPR, an electromechanical film (Emfit) sensor[15] was attached to the point of compression. The Emfit film consists of several polypropylene layers which enclose air voids. Inside the Emfit film a permanent charge creates an intense electric field. If force is applied to the sensor, the thickness of the air voids changes and the charges on the polypropylene/air void interface will move in relationship to each other. As a result a mirror charge is generated at the electrodes.[15]

2.4.3. Data acquisition

The data were acquired using a NIDAQ system NI6036E and a notebook; the sampling rate was 1 kHz. The original ECG, the ECG measured on the pig's thorax (either corrupted or uncorrupted) and the force signal were displayed online; thus their integrity could be checked continuously.

Signal noise pick-up from any other sources of interference was carefully avoided. Thus, to cancel out signal contamination by noise other than CPR and avoid any ground loop, the input (ECG feed-in) and output (recording) circuitry were electrically decoupled: The digital data input was optically isolated, and the ECG amplifier, the data recording and storage device including the notebook were all battery-powered.

2.5. Animal experiments

The University's ethics committee granted permission for the animal experiments (File No. GZ66.009/0124-II/10b/2008). After preliminary experiments to test the complete setup, five experiments with pigs (body weight 70–120 kg) were performed, two aimed mainly at validation of the pig model. In the other three experiments data were collected for the database. The pigs were sedated (ketamine, 20 mg/kg, and acepromazine, 1.75 mg/kg) before arrival in the operating room. Anaesthesia was induced intravenously using 15 mg/kg thiopental.

Subsequently the pigs were intubated. For muscle relaxation tracrium (1.7 mg/kg) was administered and volume-controlled ventilation started. Maintenance of anaesthesia was provided by isoflurane (1.2–2%) in an air–oxygen mixture, supplemented by fentanyl (16 μg/kg/h). Limb ECG, arterial oxygen saturation, invasive blood pressure, airway pressure, and end-expiratory CO_2 were monitored. Ventilation parameters were adjusted according to the results of blood gas analysis.

The catheter for feeding in the original ECGs was properly placed. Standard ECG electrodes were fixed to the pig's thorax after