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Applications of the Transthoracic Impedance Signal during Resuscitation

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Abstract

Defibrillators acquire both the ECG and the transthoracic impedance (TI) signal through defibrillation pads. TI represents the resistance of the thorax to current flow, and is measured by defibrillators to check that defibrillation pads are correctly attached to the chest of the patient. Additionally, some defibrillators use the TI measurement to adjust the energy of the defibrillation pulse. Changes in tissue composition due to redistribution and movement of fluids induce fluctuations in the TI. Blood flow during the cardiac cycle generates small fluctuations synchronized to each heartbeat. Respiration (or assisted ventilation) also causes changes in the TI. Additionally, during cardiopulmonary resuscitation (CPR), chest compressions cause a disturbance in the electrode-skin interface, inducing artifacts in the TI signal. These fluctuations may provide useful information regarding CPR quality, length of pauses in chest compressions (no flow time), presence of circulation, etc. This chapter explores the new applications of the transthoracic impedance signal acquired through defibrillation pads during resuscitative attempts.

Keywords: transthoracic impedance, defibrillator, cardiac arrest, ventilation rate, chest compression rate, circulation detection

1. Introduction

Biological tissues strongly differ in terms of their electrical impedance. For instance, the resistivities of blood, cardiac muscle, and lungs are 150, 750, and 1275 Ω/cm , respectively [1]. This variability makes the measurement of electric impedance useful in understanding the functioning and viability of internal organs. In fact, impedance plethysmography, a

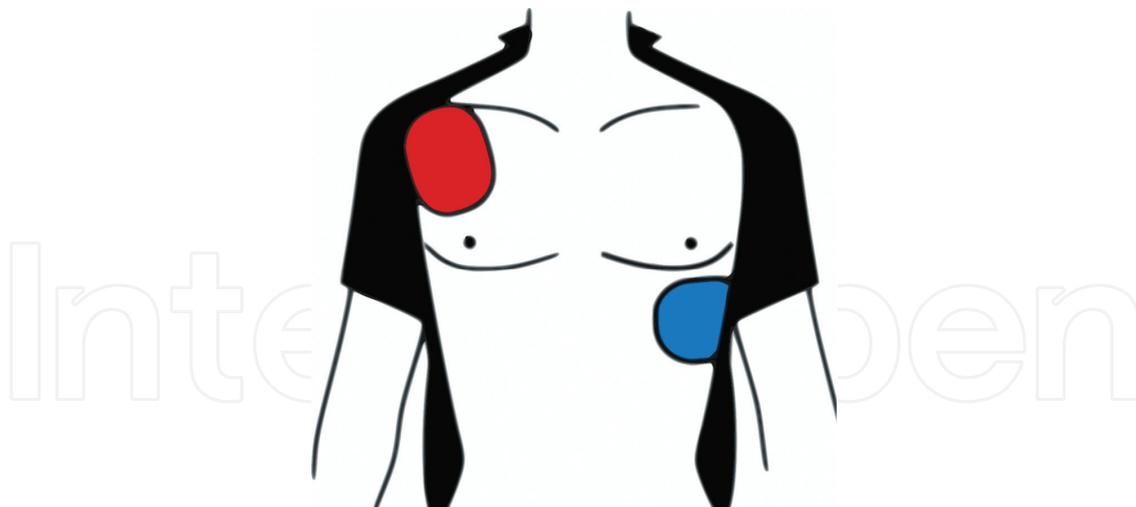


Figure 1. Anterolateral position for self-adhesive defibrillation pads. Source: Bexen Cardio.

well-established technique to determine changing tissue volumes based on the measurement of electric impedance at the body surface, is widely used for multiple applications, including the measurement of lung water content, the diagnosis of deep venous thrombosis, and the determination of cardiac stroke volume.

In the field of resuscitation, transthoracic impedance (TI) is measured by defibrillators through defibrillation pads, together with the ECG signal. **Figure 1** shows the recommended anterolateral position for the defibrillation pads, with one pad placed below the right clavicle and the other one below the left axilla. TI represents the resistance of the thorax to current flow, and can be measured by passing an alternate current through the tissue and measuring the induced voltage drop.

Defibrillators, particularly automated external defibrillators (AEDs), measure the TI to check that the defibrillation pads are correctly attached to the chest of the patient. TI is approximately 70–80 Ω in adults, but it varies considerably between subjects, with a range of 15–150 Ω [2, 3]. Baseline TI is affected by several factors including chest size, distance between the electrodes, electrode size, and the interface between the electrodes and the chest wall [4]. Too high impedance values indicate that the contact between the pads and the skin is inadequate. A good skin-electrode contact is critical for a safe delivery of the electrical shock and for a correct ECG acquisition, essential for a reliable rhythm analysis. AEDs monitor the TI signal and guide the rescuer through the resuscitation process. Typical AED messages prompt rescuers to attach the electrodes to the chest of the patient, to check the contact between the electrodes and the skin if the measured impedance is inadequate, or to avoid touching the patient during AED rhythm assessment.

Additionally, some defibrillators use the TI measurement to adjust the energy of the defibrillation pulse (impedance compensation technique) [5, 6]. Successful defibrillation requires that sufficient current flows through the heart muscle, but excessive current during electrical shock may cause myocardial damage. Thus, shocks should be provided with the lowest amount of energy that will achieve defibrillation. However, the actual current flow is determined not only by the selected energy but also by the TI of the patient. An energy level that is adequate

for a low-impedance patient may not achieve defibrillation in a patient with higher impedance. Modern biphasic defibrillators measure TI and adjust the energy delivery accordingly.

These two applications of the TI signal in defibrillators rely on its baseline value. However, as in the impedance plethysmography, changes in tissue composition due to redistribution and movement of fluids induce fluctuations in the TI acquired through defibrillation pads. During the cardiac cycle, the distribution and amount of blood in the thorax varies, causing small changes in the conductivity of the tissue that are reflected in the TI waveform [7]. Respiration (or ventilation of the patient) also affects TI; impedance increases during inspiration and decreases again during expiration [8]. Additionally, during cardiopulmonary resuscitation (CPR), chest compressions cause a disturbance in the electrode-skin interface, inducing artifacts in the ECG and in the TI signal [9].

This chapter explores the new applications of the TI signal acquired through defibrillation pads derived from the analysis of these variations.

2. Transthoracic impedance for circulation detection

Previous releases of basic life support (BLS) resuscitation guidelines recommended assessing if the patient presented signs of circulation by checking the carotid pulse before starting chest compressions. However, several studies have shown that pulse palpation is time-consuming and inaccurate not only for lay rescuers with basic CPR training [10], but also for healthcare professionals [11]. Based on the existing evidence, resuscitation guidelines removed the pulse check recommendation for laypeople in their 2000 release. However, reliable identification of pulse-generating rhythms would be useful to distinguish cardiac arrest from other collapse states, and to detect the return of spontaneous circulation during a resuscitative attempt.

Circulation induces low-amplitude fluctuations in the TI. **Figure 2** shows an example of the fluctuations induced with each heartbeat for a patient presenting a pulse-generating rhythm. Top panels show the ECG of the patient in mV, and the bottom panel the corresponding TI signal in Ohms (Ω). Several authors have studied the potential of the TI signal to reliably detect the presence of circulation.

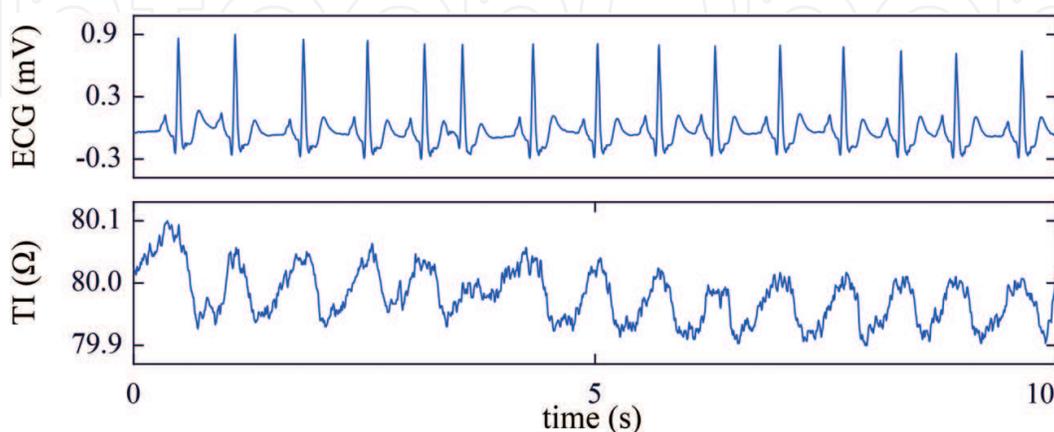


Figure 2. Fluctuations induced by circulation in the TI.

2.1. State of the art

Back in 1998, Johnston et al. showed that the TI acquired through defibrillation pads could be potentially used to discriminate between pulse-generating rhythms and those associated with hemodynamic collapse [7]. Using recordings acquired during cardiac arrest episodes, they extracted four features from the TI signal and evaluated their ability to identify pulse-generating rhythms. Their results were promising, and they suggested using this method to increase the sensitivity of shock advice algorithms in AEDs.

Four years later, Pellis et al. [12] showed in a laboratory study with anesthetized swine that the TI signal measured through defibrillation pads presented fluctuations coincident with cardiac contraction, and larger and slower fluctuations coincident with ventilations. After inducing VF to the animals, all the fluctuations ceased. The authors proposed equipping AEDs with cardiac and respiratory arrest detectors based on the analysis of the TI.

Later, in 2007, Losert et al. proposed a classifier based on neural networks to detect the return of spontaneous circulation during the resuscitative attempt [8]. They extracted several features derived from the circulatory-related waveform of the TI, and evaluated the performance of the classifier using recordings collected from hemodynamically stable and cardiac arrest patients. With their dataset, they could identify patients presenting an arterial blood pressure above 80 mmHg with a sensitivity of 90% and a specificity of 82%.

The following year, Risdal et al. introduced a new classifier based on pattern recognition to discriminate between pulseless electrical activity and pulsatile rhythms [13]. The method used clinical data, and presented a sensitivity and specificity for the detection of pulse-generating rhythms of 91 and 90%, respectively. That same year, Cromie et al. showed in an animal model that the Fast Fourier Transform (FFT) of the impedance cardiogram recorded through defibrillation pads was a potential clinical marker of cardiac arrest [14]. In a subsequent clinical study, they refined the method and evaluated its performance with in-hospital cardiac arrest and nonarrest patients [15]. They concluded that selective filtering of the impedance cardiogram was a powerful hemodynamic sensor of cardiac arrest, with a sensitivity (specificity) of 81% (97%) in the validation set. In 2012, Krasteva et al. showed that the TI recorded through defibrillation pads during cardioversion provides information about the quality of myocardial contraction associated to sinus rhythm, asystole, and different arrhythmias [16, 17].

More recently, in 2013, Ruiz and coauthors postulated that the circulation component of the TI signal acquired through defibrillation pads could be reliably isolated [18]. They proposed an adaptive system based on a least mean square algorithm that used detected QRS complexes as a reference to extract the circulation component of the TI, and obtained several features from the circulation component and its first derivative. When trying to discriminate between pulseless electrical activity and pulsatile rhythms in cardiac arrest victims, all features showed an area under the curve (AUC) higher than 0.96. Later, Alonso et al. proposed another adaptive method, also using the QRS instants as a reference to extract the TI circulation component [19]. They designed a classifier between pulsatile rhythm and pulseless electrical activity based on a multivariate logistic regression model than included six features

extracted from the ECG and from the TI signals. When evaluated with recordings acquired by monitor-defibrillators during advanced life support, they reported a sensitivity (specificity) in the detection of pulsatile rhythms of 92% (92%).

Although several authors have proved that the TI signal recorded by AEDs contains information regarding blood circulation, isolating its circulation component may be challenging. Chest compressions and ventilations induce fluctuations in the TI signal, with amplitudes higher than those attributable to cardiac contraction. In addition, because of the noise caused by patient movement or inadequate electrode-skin contact, the TI signal may become unreliable. To address these challenges, in a later study, Ruiz et al. proposed launching an automated assessment of blood circulation during AED rhythm analysis intervals [20]. Their hypothesis was that, as during those segments nobody should be touching the patient, the ECG and TI signals would not be affected by chest compressions, ventilations, or patient movement, and thus, the algorithm would be more reliable. Additionally, they proposed a very simple method that could be implemented in current AEDs. When evaluated with AED recordings obtained from out-of-hospital cardiac arrest interventions, their method reported a sensitivity (specificity) for detecting pulsatile rhythms of 98% (98%). The authors suggested how the circulation detection algorithm could be included in the AED sequence. After rhythm analysis, in case a nonshockable nonasystole rhythm is detected, the circulation detection algorithm should be launched to assess if the underlying rhythm corresponds to a pulsatile rhythm or to pulseless electrical activity. If circulation is detected, the responder should check if the patient is responsive and breathing normally to confirm the return of spontaneous circulation. If after 10 s the rescuer cannot confirm the presence of circulation, CPR should be resumed.

2.2. Discussion

AEDs are very reliable in detecting malignant arrhythmias, but they cannot distinguish between pulsatile rhythms and pulseless electrical activity. When a nonshockable rhythm is identified, rescuers are prompted to resume CPR, even if the patient has recovered spontaneous circulation.

Since the removal of the pulse check recommendation for laypeople in resuscitation guidelines, several studies have explored the possibility of expanding the functionality of conventional AEDs to reliably detect the presence of circulation. It is widely accepted that the TI signal contains useful information for the identification of pulse-generating rhythms. Some of the published studies suggest launching the circulation detector while the AED is performing a rhythm analysis. This would maximize signal quality, as artifact induced by chest compressions, ventilations, or by patient movement would be avoided. Although some of the proposed methods are complex and computationally expensive, others are much simpler, which lowers the barrier to implementation.

The use of enhanced AEDs able to detect circulation could help BLS providers to confirm cardiac arrest and to identify the return of spontaneous circulation, which would avoid unnecessarily prolonging CPR. However, further validation is still required for the clinical implementation of these methods.

3. Transthoracic impedance for ventilation detection

Medical treatment of cardiac arrest involves early CPR and early defibrillation. Resuscitation guidelines [21] recommend providing chest compressions and ventilations with a 30:2 ratio before intubation and continuous chest compressions with a ventilation rate of 8–12 per minute afterward. Unfortunately, hyperventilation is common both in hospital and out of hospital [22, 23]. In animal studies, these excessive ventilation rates resulted in decreased coronary perfusion pressures and poor outcomes [24, 25], although some conflicting results have been presented [26].

Respiration and ventilation of the patient induce fluctuations in the TI signal acquired by defibrillators; impedance increases about $0.2\text{--}3\Omega$ during inspiration and decreases again during expiration. Mainly, two effects cause these changes: first, during inspiration, there is an increase in the gas volume of the chest in relation to the fluid volume, which causes conductivity to decrease; additionally, during inspiration, the distance between the electrode pads increases because of chest expansion, which also increases resistance.

Figures 3 and 4 illustrate this effect for a patient presenting return of spontaneous circulation and for a cardiac arrest patient who is receiving CPR, respectively. In **Figure 3**, fluctuations induced by circulation and by respiration are observed in the second panel. The baseline impedance of the patient is about 103Ω , but, during inspiration, the impedance value increases between 1 and 2Ω . In this segment, eight breaths are distinguished. The patient presented a pulse-generating rhythm, confirmed by fast and low-amplitude fluctuations in the TI of approximately 0.2Ω , synchronized with every QRS complex; this is the circulatory component of the TI.

Figure 4 shows a segment of the compression depth and TI signals recorded during a resuscitation episode while the patient was receiving 30:2 CPR. In this segment, 4 series of 15 compressions can be observed, with pauses in between for ventilation. Each compression induced a fluctuation in the TI, with a peak-to-peak amplitude of almost 4Ω in this case. During each pause, the patient was ventilated twice, and slower fluctuations were induced in the TI.

The analysis of the TI acquired through defibrillation pads could be useful for ventilation monitoring, either in real time, to guide rescuers during the resuscitation event, or for episode

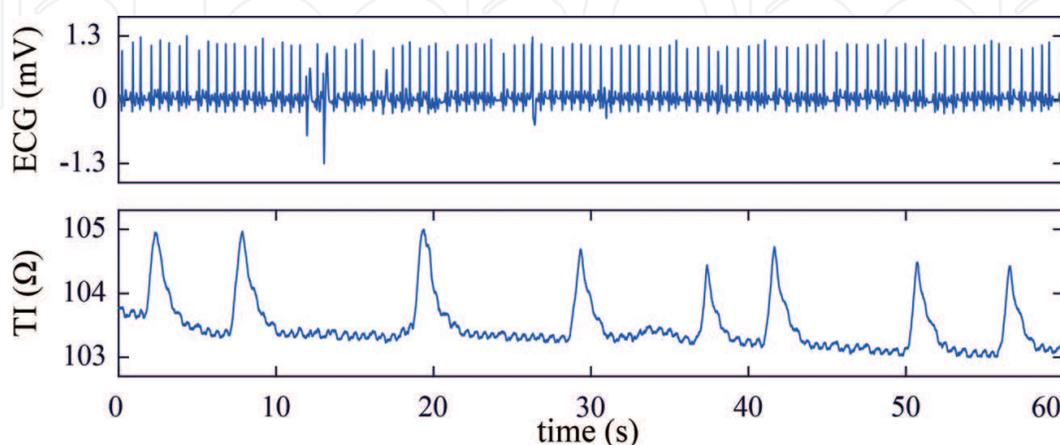


Figure 3. Segment of TI signal with circulatory and respiration-related components.

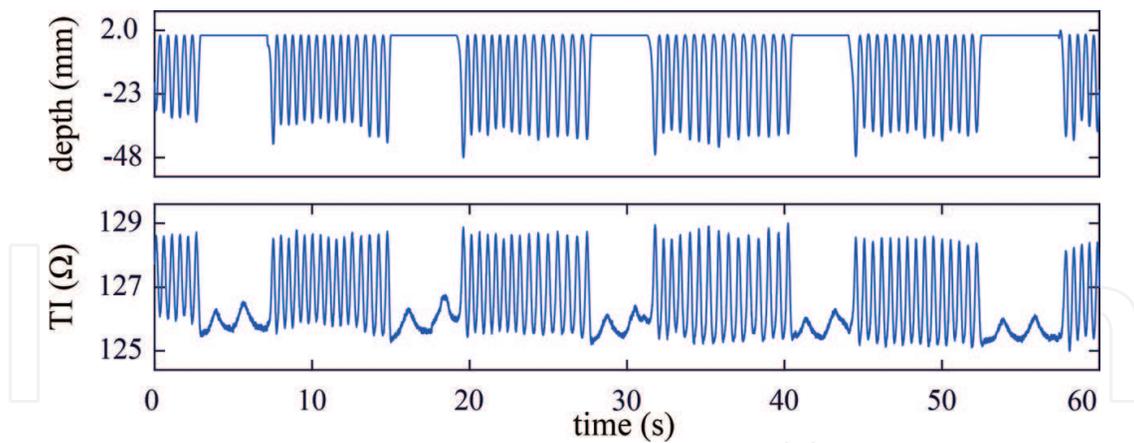


Figure 4. Segment of TI signal with artifact induced by chest compressions and fluctuations induced by ventilations.

debriefing afterward. However, the amplitude and duration of the TI fluctuations vary widely along the resuscitation episode and among different patients. Moreover, patient movement and chest compressions induce artifacts in the TI, which complicate the identification of the fluctuations induced by ventilations, especially when compressions and ventilations are applied simultaneously, as in the case of intubated patients.

3.1. State of the art

Pellis et al. were the first to suggest the ability of the TI signal acquired by defibrillators to determine the presence or absence of breathing, back in 2002 [12]. In an experiment with anesthetized swine, they found that the TI signal acquired through conventional defibrillation electrodes showed large fluctuations time coincident with the ventilations identified in the capnogram.

In 2006, Losert et al. performed a clinical study to investigate the potential of the TI measured via defibrillator pads for measuring ventilation rate and inspiration time [8]. They selected a convenience sample of mechanical ventilated patients, cardiac arrest patients and patients after restoration of spontaneous circulation, and calculated the correlation in waveform between TI and tidal volume given by a ventilator. The median correlation between the impedance waveform and the tidal volume waveform was 0.97 for all patient groups. They concluded that the TI provides information regarding tidal volumes when chest compressions are interrupted, and that it can be useful to quantify ventilation rates and inspiration times.

The following year, Risdal et al. proposed the first automated system to detect ventilation during ongoing CPR by analyzing the TI signal [27]. They developed a pattern-recognition-based detector and used recordings of resuscitation efforts to train it and to evaluate its performance. The annotated ventilations were detected with a sensitivity of 90% and a positive predictive value of 96%. Although the results were good, the method demanded high computational resources, which could limit its practical implementation.

Kramer-Johansen et al. used the TI signal to annotate ventilations in a clinical study about CPR quality before and after endotracheal intubation [28]. In 3% of the episodes, the fluctuations induced by ventilations in the TI signal disappeared after placing the endotracheal tube.

The authors suspected that this was due to accidental esophageal intubation and hypothesized that analysis of the TI could be used to identify incorrect tube placement. Two years later, in a prospective clinical study [29], they confirmed that the TI was useful to detect misplaced endotracheal tubes. With a dataset of 123 esophageal and 178 tracheal ventilations, tube position was predicted with a sensitivity of 99% and a specificity of 97%.

More recently, in 2010, Edelson et al. developed and compared the performance of two methods to detect ventilations during CPR, one of them based on the TI signal and the other one based on the capnogram [30]. They concluded that both methods underestimated ventilation rate, and suggested that the optimal strategy could be combining them. The TI-based detector underestimated ventilation rate because of artifacts induced in the TI signal during chest compressions and patient movement and because low-amplitude ventilations generated too small fluctuations.

González-Otero et al. presented in a conference paper in 2013 a simple impedance-based method for ventilation detection during CPR [31]. Their aim was to develop a method to be implemented in AEDs for ventilation rate monitoring. The detection algorithm first identified fluctuations in the preprocessed TI signal. Then, it characterized the fluctuations by features of amplitude, duration, and slope. Finally, a decision system based on thresholds was applied to decide whether each fluctuation corresponded to a ventilation. When evaluated with out-of-hospital cardiac arrest records, the algorithm presented a sensitivity and positive predictive value of 97 and 95%, respectively.

In 2015, Alonso et al. combined a simple impedance-based method to identify ventilations in the TI with a method to identify chest compressions [32]. Their aim was to evaluate the accuracy and reliability of the TI signal to assess CPR quality metrics. Their combined detector provided good results with out-of-hospital cardiac arrest records, with a sensitivity and positive predictive value of 98 and 81% for ventilation detection.

3.2. Discussion

Respiration and assisted ventilation induce fluctuations in the TI signal acquired through defibrillation pads. Several authors have analyzed the ability of this signal to identify ventilations, and concluded that the TI is an indicator of ventilation rate. However, the technology is not perfect. The main challenges to be addressed are that low-volume ventilations usually generate low-amplitude fluctuations difficult to detect, and that patient movement and chest compressions induce artifact in the TI signal that complicate ventilation detection. Although artifact induced by chest compressions can be suppressed using filtering techniques, residuals in the filtered TI signal may induce errors in the ventilation detection process.

Figure 5 shows two examples of the TI signal before and after being filtered for ventilation detection using the technique described in [31]. In example (a), the patient received six ventilations (depicted with vertical red lines), the first two overlapped with chest compressions. After the filtering process, the artifact induced by chest compressions was suppressed, and the ventilations could be correctly identified. In example (b), the onset and the offset of the chest compression interval altered the filtered TI and induced fluctuations that were incorrectly identified as ventilations (false positives).

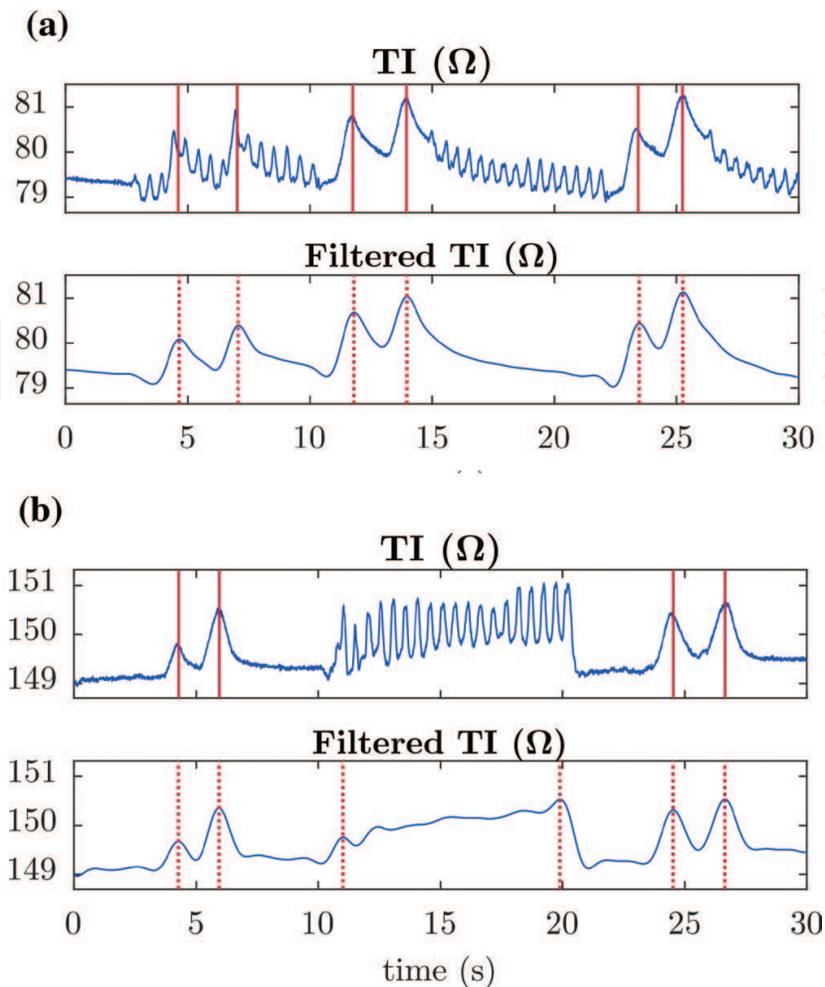


Figure 5. Examples of TI signal before and after being filtered for ventilation detection. Example (a) illustrates correct ventilation identifications, while example (b) illustrates false-positive detections.

Although there is still room for improvement, it is widely accepted that the TI signal is a reliable indicator of ventilation rate, and a good option when no other signal such as capnography is available for ventilation monitoring. In fact, various commercial AEDs analyze the TI in real time to provide feedback to the rescuer regarding ventilation rate during the resuscitative attempt. Additionally, some manufacturers use the TI signal to compute ventilation rate in offline applications for episode debriefing.

4. Transthoracic impedance for chest compression characterization

Resuscitation guidelines emphasize the importance of providing high-quality chest compressions during CPR, that is, compressions with an adequate rate and depth, completely releasing the chest after each compression, and minimizing interruptions [21]. During CPR, chest compressions induce fluctuations in the TI. These fluctuations are caused both by true variations in the impedance value associated to the thoracic volume change and by motion artifact induced by the disruption of the electrode-skin interface. Several researchers have

investigated the feasibility of using the TI signal to extract information about chest compressions during CPR. Some of the proposed applications include identification of chest compression pauses, calculation of chest compression rate, and estimation of chest compression depth. The following sections present an overview of the state of the art in those three topics.

4.1. Automated detection of pauses in chest compressions

Interruptions in chest compressions are frequent during out-of-hospital cardiac arrest. Following current resuscitation guidelines, chest compressions are interrupted for assisted ventilation (BLS sequence), to assess the rhythm, to defibrillate, and to change rescuers. These interruptions compromise the blood flow to the heart and brain and have an adverse effect on defibrillation success, and, consequently, on survival [33, 34].

The automated detection of pauses in chest compressions would be relevant for two main reasons. First, in the field of CPR quality, it would enable AEDs to provide feedback to the rescuer when too long interruptions in chest compressions are detected. Second, it would allow detecting CPR artifact-free ECG intervals (for example, pauses for ventilation of the patient or rescuer switch) in which the AEDs could reliably assess the ECG rhythm, without requiring an additional interruption of chest compressions for rhythm assessment.

Chest compressions and ventilations induce fast and slow fluctuations in the TI signal, respectively. In 2012, González-Otero et al. published in a conference proceedings a simple method for the automated detection of pauses in chest compressions using the TI acquired by defibrillators [35]. **Figure 6** illustrates the application of the method. The fluctuations induced by chest compressions (first panel) are first isolated by applying a filter that suppresses the fluctuations induced by ventilations. The result of this filtering process is shown in the second panel. Then, chest compressions are emphasized by computing the slope of the signal as the first difference, scaled and squared (third panel). Finally, the fluctuations are smoothed by applying a first-order low-pass filter of a cutoff frequency of 0.6 Hz, and using an adaptive threshold, the intervals without chest compressions are identified (fourth panel). A small delay correction is applied to the detected onset and offset of the chest compression pauses to compensate the delay introduced by the process.

The performance of this method was evaluated using 600 out-of-hospital cardiac arrest records. In the test database, sensitivity and positive predictive value for the detection of pauses in chest compressions were 93.9 and 96.2%, respectively. The difference between the durations of the detected and of the annotated pauses was 0.24 ± 0.73 s.

Some AEDs implement similar algorithms to identify too long pauses in chest compressions, and to prompt the rescuer to resume CPR. Additionally, the detected pauses, which are free of motion artifact induced by chest compressions, could be used by AEDs to launch a rhythm analysis, avoiding additional interruptions in chest compressions, as proposed by Ruiz de Gauna et al. in 2012 [36]. In 2013, Ruiz et al. analyzed the accuracy of a fast shock advice algorithm able to provide a shock/no shock decision in 3 s when it was launched during chest compression pauses [37]. Their algorithm was evaluated with 110 shockable and 466 non-shockable segments extracted from 235 out-of-hospital cardiac arrest episodes. This dataset

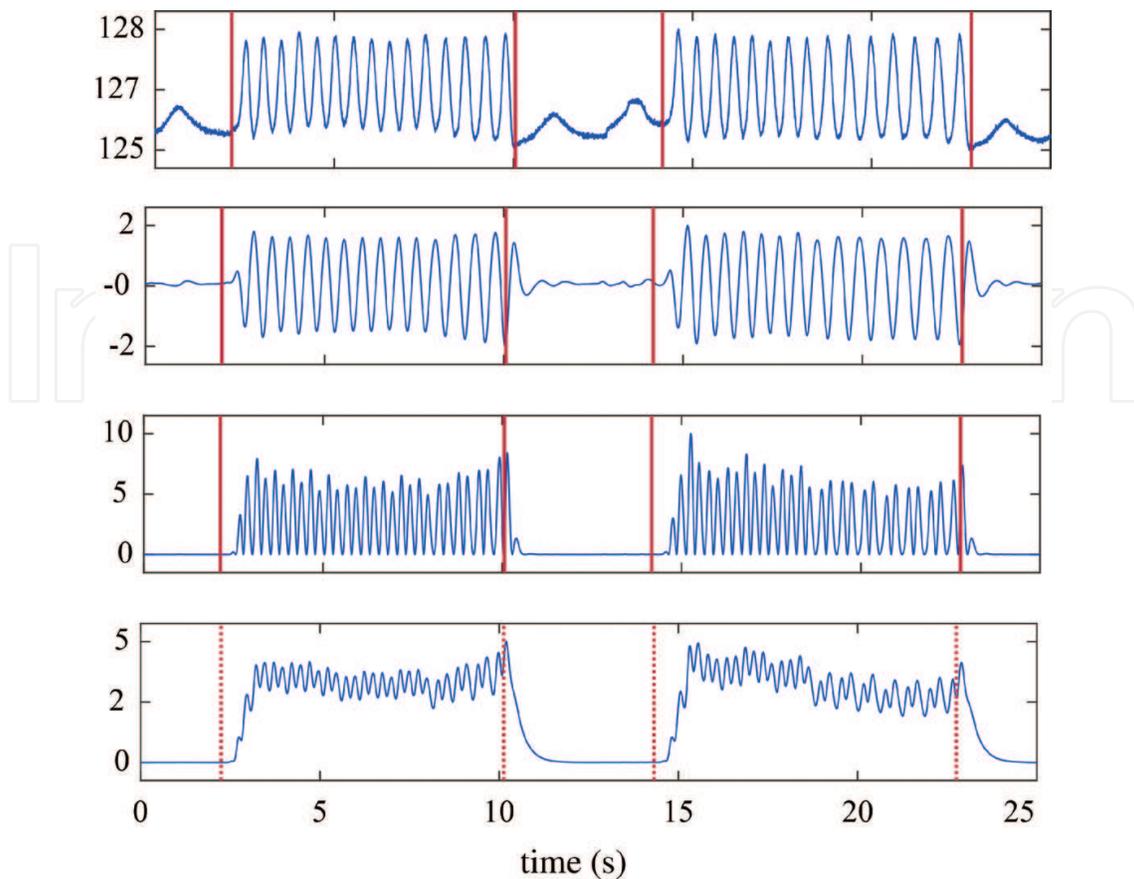


Figure 6. Signals involved in the chest compression pauses detection method described by González-Otero et al. [34].

comprised 4476 pauses, 2183 of them containing two ventilations. A total of 92% of the pauses and 95% of the pauses with two ventilations were long enough to launch the shock advice algorithm. The overall sensitivity and specificity of the shock advice algorithm for the detection of shockable rhythms were 96 and 97%, respectively.

When CPR is provided at the standard 30:2 compression-ventilation ratio, this method would allow the AED to diagnose the rhythm after each series of 30 chest compressions, that is, approximately every 20 s. Current resuscitation guidelines recommend interrupting CPR every 2 min for rhythm assessment. These preshock pauses would be eliminated by analyzing the rhythm during ventilation pauses. Additionally, a rhythm assessment would be performed every 20 s instead of every 2 min, so more information regarding rhythm evolution would be available. This could potentially be useful to guide the therapy, for example, by early recognition of recurrent ventricular fibrillation.

4.2. Chest compression rate estimation

Resuscitation guidelines recommend providing chest compressions at a rate between 100 and 120 compressions per minute (cpm) during CPR. Two studies found higher survival among patients that received compressions at those rates compared to those who received slower or faster compressions [38, 39]. Additionally, very high chest compression rates were associated

with reduced compression depths, which are detrimental to survival. However, studies on CPR quality have shown that providing high-quality chest compressions is challenging both for laypeople and for well-trained rescuers [40].

The use of metronomes and real-time CPR feedback devices can improve adherence to CPR quality guidelines [41]. Metronomes generate regular audible beats that help rescuers to follow a rhythm, for example, recommended compression rate. Feedback systems are more sophisticated, and measure CPR performance in real time [42, 43]. Most of them are accessory devices that are placed between the hands of the rescuer and the chest of the patient during CPR. This adds complexity to the equipment and limits the widespread of feedback systems, particularly in BLS settings.

Chest compressions induce fluctuations in the TI signal. Analyzing these fluctuations could be a simple way to monitor chest compression rate without requiring additional devices. Several authors [32, 44–47] have suggested using the TI signal to compute chest compression rate either online, to provide feedback to the rescuer during a resuscitation attempt, or offline, for episode debriefing.

The main challenge in computing compression rate from the TI signal derives from the fact that an important component of the fluctuations induced in the TI is an artifact generated in the electrode-skin interface. As an artifact, its characteristics are influenced by many factors including the TI acquisition front-end, the electrode type, the stiffness of the patient's chest and CPR performance (rate, depth, applied force and acceleration). **Figure 7** shows two segments of TI signals acquired by different defibrillators with different TI acquisition front-ends. In both segments, the chest compressions were provided at a similar rate (about 100 cpm). However, in example (a), the fluctuations induced in the TI signal were quite sinusoidal, while in example (b), they had a very strong second harmonic component, causing a distinct waveform.

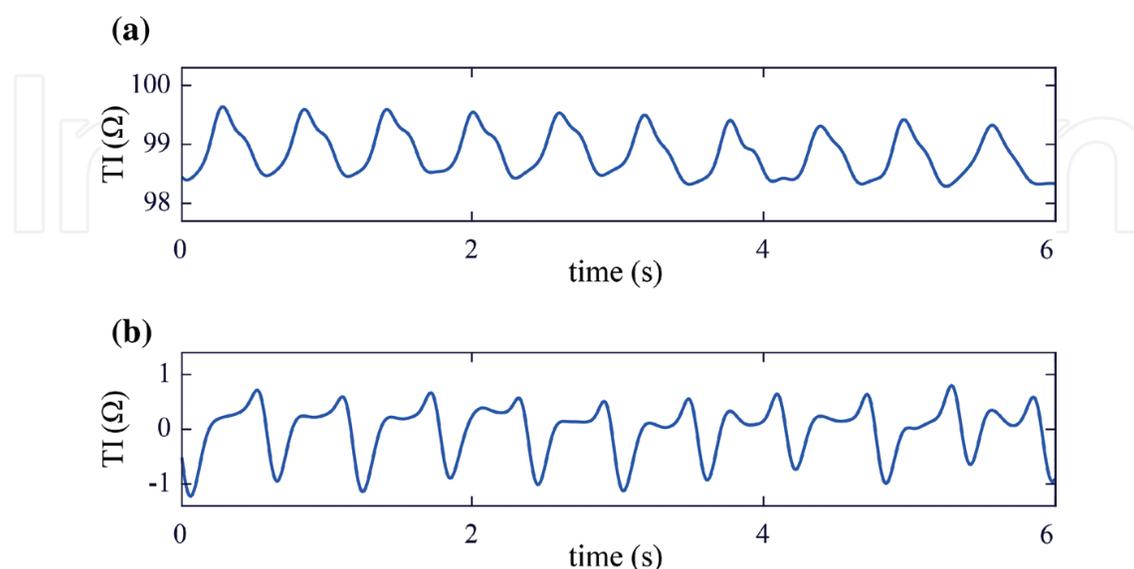


Figure 7. TI signals obtained from two different defibrillators during chest compressions.

Most of the methods to compute compression rate from the TI signal that have been published in the literature were optimized and tested with subsets obtained from a single monitor-defibrillator, and thus the variability introduced by the signal acquisition front-end was not taken into account. A later study [47] presented a general method to calculate chest compression rate, and evaluated its accuracy with three different databases of out-of-hospital cardiac arrest records. The authors concluded that it is possible to reliably estimate compression rate by processing the TI, although the performance of the method will vary with the characteristics of the TI fluctuations.

Methods to measure compression rate based on the TI signal are being commercially used both in applications for episode debriefing and in defibrillators to provide feedback to the rescuers in real time.

4.3. Chest compression depth estimation

Feedback devices can be used during CPR to guide chest compression depth and improve CPR quality, but this implies using an additional device [42]. Some authors suggested that fluctuations induced in the TI could be a potential indicator of compression depth [48, 49]. Unfortunately, those studies were published in short communications, and details on the analytical methods and the datasets used were not provided. In 2012, Zhang et al. investigated the relationship between TI fluctuations and compression depth in an animal study [50]. Two experts provided chest compressions with different depths, suboptimal (35 mm) and optimal (50 mm), to 14 anesthetized swine. They evaluated the correlation between the peak-through amplitude of the fluctuations induced in the TI during chest compressions and the compression depth, and found a high correlation (Pearson correlation coefficient $r = 0.89$). Additionally, they found great differences in TI amplitude between optimal and suboptimal depth groups. These results were promising, and suggested that TI could be useful for monitoring compression depth.

Two years later, Alonso et al. [51] studied the correlation of TI with compression depth using a large database of out-of-hospital cardiac arrest recordings. They extracted three morphologic features of the TI signal and analyzed their correlation with compression depth. This correlation was evaluated for the whole population, for each patient individually, and for segments corresponding to a single patient and a single rescuer. Additionally, trying to replicate the experiments of Zhang et al., they included the correlation when only series of optimal or suboptimal chest compressions (no intermediate values) were included. In their study, the prediction of compression depth based on any of the morphologic features of the TI was highly unreliable. When only optimal and suboptimal chest compressions were included, the correlation coefficient increased, but there was still a high variability. The authors concluded that when a wide variety of patients and rescuers are included, chest compression depth could not be reliably estimated from features extracted from the TI signal.

5. Conclusions

The TI signal is potentially available in any resuscitation attempt in which adhesive defibrillation pads are used. This signal was customarily acquired to check if the defibrillation pads

were correctly attached to the chest of the patient and to adjust the energy of the defibrillating shock. In the last years, new applications have been suggested. Respiration (or assisted ventilation), changes in blood flow during the cardiac cycle, and chest compressions induce fluctuations in the TI. By analyzing these fluctuations, useful information can be extracted regarding CPR quality and patient status. Some of these new applications, such as TI-based ventilation rate and chest compression rate computation, have been thoroughly validated and are implemented in AEDs or in offline programs for episode debriefing. Other applications, such as circulation detection, require further studies before clinical use. Finally, with the current technology, compression depth cannot be accurately computed from the TI signal. In any case, the TI signal has the potential to serve as a real-time noninvasive indicator of CPR quality and of patient status, and has the advantage of being widely available.

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Conflict of interest

No potential conflict of interest was reported by the authors.

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