Chapter

The Influence of Transthoracic Impedance on Electrical Cardioversion and Defibrillation: Current Data

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Abstract

Sudden cardiac death (SCD) is a leading cause of death globally, often caused by malignant ventricular arrhythmias. Rapid termination by direct current defibrillation (DF) is the best way to treat pulseless ventricular tachycardia and ventricular fibrillation. Atrial fibrillation (AF) is the most common sustained arrhythmia in clinical practice. External cardioversion (ECV) is an immediate, effective, and safe procedure for the treatment of arrhythmias with high ventricular rate, for example, AF. The success of both ECV and DF is dependent on the delivery of sufficient current, influenced by energy and transthoracic impedance (TTI). TTI depends on patient characteristics, and the exact factors affecting it are still a matter of debate. Influencing factors such as respiration phase, contact pressure, coupling agent, and total energy delivered are commonly identified. However, there are multiple studies with controversial results concerning the effect of age, gender, body mass index, hemoglobin concentration, the presence of chronic heart failure, and fluid accumulation as independent predictors of TTI. The review emphasizes refining energy dosage during ECV and while minimizing complications caused by an unnecessarily high energy delivery. The value of TTI should be predicted to optimize the energy dosage and the number of shocks for successful ECV and DF.

Keywords: transthoracic impedance, defibrillation, cardioversion, electric current, delivered energy

1. Introduction

1.1 Sudden cardiac arrest and atrial fibrillation

Sudden cardiac death (SCD) is a major cause of death worldwide and the third leading cause of death in Europe [1]. In the European Union, there are 155,000–343,000 estimated SCD cases annually, with an incidence rate of 48.6 per 100,000 inhabitants. The number of SCD cases accounts for approximately 70% of the total annual expected number of Out-of-Hospital Cardiac Arrest (OHCA) cases in the

European Union [2]. In the United States, SCD accounts for 7–18% of all deaths, or between 185,000 and 450,000 fatalities annually [3, 4].

The electrophysiological causes of SCD include shockable rhythms such as ventricular tachycardia (VT), ventricular fibrillation (VF), and other nonshockable rhythms. Ventricular arrhythmia therapy and SCD prevention involve managing underlying and concomitant conditions and diseases while preventing acute and progressive worsening [5]. In most cases, pharmacological therapy only has not been shown to be effective therapy enough; therefore, the proper consideration and implementation of device and pharmacological therapy are of paramount importance in the management of ventricular arrhythmias. The most effective device-assisted method of treating malignant ventricular tachycardias is the rapid termination by direct current defibrillation (DF).

Atrial fibrillation is the most common sustained cardiac arrhythmia, with a prevalence of up to 4% in the population over 20 years old. Treatment options include both pharmacological and nonpharmacological methods. In hemodynamically unstable patients with atrial fibrillation, an emergency electrical cardioversion (ECV) should be the preferred choice, while in stable patients, antiarrhythmic drugs preceding ECV can also be attempted. The benefits of rhythm control therapy include improving hemodynamics and quality of life, as well as reducing the time in arrhythmia, therefore the risk of potential thromboembolism, beside pharmacological therapeutic measures [6].

The success of both ECV and DF is dependent on the delivery of sufficient current. Current is determined by energy and transthoracic impedance (TTI). TTI largely depends on the patient's characteristics, and the exact factors affecting it are still a matter of debate.

1.2 Relevance of the chapter

Accurate identification of the exact influencing factors of TTI may lead to an increase in the efficacy of ECV and DF while minimizing the risk of complications. Adjusting the delivered energy according to identified clinical variables that independently influence the thoracic electrical impedance and hence the trans-myocardial current might result in more adequate defibrillation strategies, thus, better defibrillators in the future.

The importance of TTI is further supported by a recent meta-analysis, concluding that skeletal muscles shunt away 82% of the electrical current while lung tissue shunts away 14% of the heart so that only 4% of the total level of electrical current reaches the heart [7]. This, besides raising some clinical questions, reinforces the need to gain a better understanding and insight into the factors that influence the level of TTI, hence the extent of electric current flow.

1.3 Definition and background of transthoracic impedance

The history of electrical defibrillation dates back to 1956, when a patient was successfully treated for ventricular fibrillation. A few years later, the delivery of an electric shock proved to be effective in atrial fibrillation and atrial flutter [8, 9].

Several factors have been investigated to make defibrillation therapy more effective, highlighting the paramount importance of the current application and the current delivery distribution [10]. Effective defibrillation is based on the delivery of an electrical shock to a critical amount of myocardial cells, which is determined by the flow of electrical current that is influenced by the shock energy modified according to the measured TTI. If the electrical current is too low, defibrillation will fail, so the objective should be to reduce the level of TTI as much as possible [11].

With the development of cardiac implantable devices, it has become possible to measure a variety of parameters, enabling healthcare specialists to provide telemedical treatment and monitoring. One of these parameters is the monitoring of the intrathoracic impedance in a special setup of implantable cardioverter defibrillators (ICDs) to monitor fluid overload in chronic heart failure patients. A recent meta-analysis has shown that reduced intrathoracic impedance is a significant risk factor for developing both atrial and ventricular arrhythmias [12]. However, in the present chapter, we focus on the factors affecting transthoracic impedance and do not address intrathoracic impedance because of the different measurement characteristics.

The factors that influence TTI can be divided into two subgroups, modifiable (extrinsic) and nonmodifiable (intrinsic) factors. Although the latter are not alterable, knowledge of them allows us to approximate the value of a TTI more accurately.

1.4 Methodology of transthoracic impedance measurements

The available datasets involving TTI measurements are derived mainly from implantable defibrillator devices and external defibrillators in the setting of electrophysiological conditions requiring the delivery of an electric shock to patients. The other technique is high-frequency impedance estimation. This is a built-in feature of all modern defibrillator devices, estimating what the current TTI value might be according to the so-called test-pulse method by delivering a minimum current electrical pulse.

2. Factors influencing transthoracic impedance

2.1 Paddle force, contact pressure

Several studies have examined the influence of electrode contact on the TTI, highlighting an inverse relation between electrode pressure and TTI [13–18]. When holding conventional, hand-held defibrillator paddles, by increasing the pressure force, the electrical contact surface at the electrode-skin contact level increases, while the air volume in the lungs may decrease [15]. The optimal paddle force is different for adults and children: 8 kilogram-force (kgf) for adults, 5 kgf for children, and 3 kgf for infants [13, 14].

Since 2020, the ERC guidelines have recommended the use of self-adhesive defibrillation pads instead of defibrillation paddles to improve defibrillation performance and increase the safety of the providers [19]. Although the importance of paddle force has been marginalized by the widespread use of defibrillation pads, studies indicate that the force applied to self-adhesive defibrillation pads may as well contribute to reduced TTI [17, 18, 20].

In addition to the absolute force applied, the size of the defibrillator electrode is also important, as it is a key element in the distribution of the pressure. This may be especially important in the case of defibrillating infants and children weighing less than 10 kg [7].

2.2 Pad/paddle placement

Human studies have failed to prove the role of the pad position as a determinant of Return of spontaneous circulation (ROSC) in the setting of ventricular tachycardias [19]. According to the ILCOR 2020 systematic review, trans-myocardial electrical flow is highest when the fibrillating myocardial area is located between the defibrillator electrodes. This indicates that the optimal position of the electrodes is the region located close to the left ventricle in cases of ventricular arrhythmia. Where feasible, anterolateral (sternal-apical) positioning is recommended; however, anteroposterior, bi-axillary, and right posterior-apical positionings are also acceptable. In large-breasted individuals, the electrode may be shifted to the lateral or inferior side, selecting the one closest to the optimal placement if possible [19, 21]. Deakin et al. found that the use of the apical defibrillation paddle in a longitudinal orientation resulted in a significantly lower TTI compared to the transverse placement during shocks in cardioversion [22].

2.3 Repeated shocks

The change in TTI during multiple shocks is also a topic of debate [23]. In their study, Deakin et al. conducted electrical cardioversion on 58 patients. TTI significantly decreased with each consecutive shock, initially averaging 92.2 Ohms, while for patients receiving five shocks, the average was 85.0 Ohms [24]. Similarly, Fumagalli and colleagues found a significant difference in TTI, which decreased by 6.2% after 2 or more shocks from the starting value [25]. However, Walker and colleagues analyzed data from 863 out-of-hospital cardiac arrest patients treated with AED shocks for ventricular fibrillation and found no significant change in TTI between consecutive shocks. In the study, they examined both the high-frequency impedance and the shock impedance; all patients were initially administered 200 J for their first shocks, with the second shocks being either 200 J or 300 J, using preprogrammed AEDs by the local protocols [26]. Niemann and colleagues also found similar results in their animal model, as TTI did not change significantly in animals receiving 4 or more shocks compared to the first shock to eliminate ventricular fibrillation [27].

2.4 Hypothermia

The beneficial role of induced hypothermia (HT) is still a widely debated issue, mainly as a measure to protect the heart and brain after cardiac arrest following resuscitation. According to Rhee and colleagues, severe HT enhanced the success of transthoracic defibrillation in a swine model. After inducing ventricular fibrillation for 30 s, the pigs were defibrillated using biphasic waveform at various energies in both normothermic and HT conditions. Results showed that severe HT (30°C) led to a higher success rate in terminating ventricular fibrillation compared to normothermia, even though impedance increased and current decreased during HT. No significant differences were found between normothermia and HT in the other groups [28]. Similarly, the moderate HT (33°C) group showed a significant increase in first-shock success, with a trend toward improvement in the severe HT group in another swine model [29]. The rise in defibrillation success despite the increased TTI in hypothermic conditions suggests that other factors besides current delivery may contribute to improved shock success.

2.5 Respiration phase

Sirna and colleagues observed 28 patients who underwent elective cardioversion and were monitored for 48 h after shock delivery and compared them with 10 control subjects who did not receive a shock. TTI was 9% lower at end-expiration compared to end-inspiration [15]. Kim and colleagues also confirmed that impedance seems to be sensitive to changes in lung volume and body position [30]. According to a study published in 2004, TTI drops as thoracic volume decreases, but this only accounts for a maximum of 16% of the total TTI reduction [31]. Deakin and colleagues also observed that TTI increased linearly with increasing positive end-expiratory pressure [32]. Furthermore, in another study, they examined 10 healthy people while they breathed different respiratory gas mixtures and concluded that TTI is unlikely to be affected by different breathing gases during defibrillation [33].

2.6 Coupling agent

The proper alignment and connection of electrodes to the skin are vital for achieving accurate TTI measurements. Sirna et al. found that using a salt-free adhesive gel (ultrasound gel) led to a 20% higher TTI compared to a salt-containing gel (Redux paste). When no adhesive was used, TTI was significantly higher than the control [15]. In a study, 80 patients were examined and received 267 shocks using self-adhesive electrode paddles. The researchers compared the effectiveness of these pads to traditional manual electrode paddles. The transthoracic impedance during defibrillation did not significantly differ between the self-adhesive pads and manual pads (75 ± 21 Ohm vs. 67 ± 36 Ohm). The initial shock success rate of 64% for ventricular fibrillation of self-adhesive pads using 150–200 J shock energy was found to be comparably good [34] to the defibrillation rates achieved in a large prospective study that achieved successful first shock in 61% of the total OHCA patients, delivering 175 J shock energy by defibrillation paddles [35]. Thus, self-adhesive pads were found to be effective for both defibrillation and cardioversion [34]. However, Dodd and colleagues found that using manual paddles resulted in lower TTI than using self-adhesive paddles in both the anterior-anterior and anterior-posterior positions [36]. This may be due to the pressure set on the paddles and body by defibrillation providers.

2.7 Age

The relationship between age and TTI is not well understood, and there is a lack of agreement among experts. Several studies have reported that TTI values are higher in older adults. This can be attributed to a variety of factors, including altered body posture as a result of musculoskeletal diseases associated with aging and decreased lung function [7, 37]. However, in a study by Fumagalli and colleagues, there was no correlation between age and chest impedance. This discrepancy may be explained by their study population being restricted to a narrow age range, with 75% of patients being around 70 years old [38]. Additionally, there was a high prevalence of chronic heart failure in the patient population, which is associated with lower chest impedance. Seung-Young Roh and colleagues performed a total of 683 direct current cardioversions in 466 patients with atrial tachyarrhythmias. In their study, they found that age did not affect TTI [39].

2.8 Gender

In a meta-analysis, Heyer and colleagues obtained contradictory results regarding the relationship between TTI and gender and found no clear trend. Body fat increases with age, to a greater extent, in women than in men [7]. From this, one might conclude that chest electrical impedance is higher in women; however, many other factors also differ between the two sexes, which makes the picture more nuanced. For example, chest hair also affects TTI. It has been shown that after shaving, chest impedance decreases significantly [40, 41]. In the 2020 ILCOR overview paper, the authors conclude that the removal of chest hair before electrode placement may be considered if it does not delay the shock delivery [42]. Overall, it can be said that factors that affect TTI, such as the amount of subcutaneous fat, or hair, and breast size, also show a high degree of variability within gender and that knowledge of these factors together would be necessary to tailor the delivered shock energy level to the individual.

2.9 Body mass index (BMI)

The results of the studies suggest that as BMI increases, chest impedance also increases [22, 38, 39, 43, 44]. The exact mechanism behind this is currently unknown. It is believed that increased amounts of fat tissue may lead to higher chest impedance values. Body composition measurement methods (InBody) also utilize this characteristic in their measurements [45].

2.10 Hemoglobin concentration

Studies have shown a connection between hemoglobin concentration and the electrical properties of blood [46]. Plasma is believed to be the conductive element of blood, with red blood cells interfering with current flow and increasing blood viscosity [47]. The microvascular tree itself alone acts as an electrical insulator due to the presence of endothelial and red blood cells along the capillary wall [48].

Studies have shown a correlation between hemoglobin oxygen saturation and TTI [25, 38]. According to one study, a $1.9 \pm 0.6\ \Omega$ increase in TTI with higher Hb concentration is related to the electrical properties of blood and the insulating layers around capillaries [38]. Another study found a $0.2 \pm 0.1\ \Omega$ increase in TTI with higher Hb O2 saturation, partially attributed to Chronic Obstructive Pulmonary Disease symptoms [25]. An animal study observed that hypoxia can affect TTI by changing cytoplasmic resistance and intercellular impedance [49]. Higher Hb O2 saturation results in a small increase in TTI, with clinical significance dependent on other pathological symptoms.

2.11 Presence of chronic heart failure

In chronic heart failure, transthoracic impedance also changes in parallel with the symptoms of heart failure, such as pulmonary congestion, decreasing the TTI value. Research has found that a decrease in TTI or intrathoracic impedance, as measured by Cardiac resynchronization therapy (CRT) and ICD devices, is linked to the severity of heart failure and the patient's prognosis [38, 50–52]. Measuring TTI can aid in predicting the severity of heart failure and the patient's prognosis, as well as assessing the effectiveness of the treatment (**Table 1**).

Influencing factor	Chapter section	Change of transthoracic impedance
Electrode pressure	2.1.	Decreases with pressure
Electrode size	2.1.	Decreases with electrode size
Electrode position	2.2.	Decreases in anteroposterior position
Repeated shocks	2.3.	Decreases with multiple shocks
Respiration and lung volume	2.5.	Increases with lung volume
Coupling agent	2.6.	Decreases for good coupling
Age	2.7.	Increases with age
Body size, Body Mass Index (BMI)	2.9.	Increases with body dimensions
Hemoglobin saturation	2.10.	Increases with Hemoglobin O2 saturation

Chapter sections: 2.1. Paddle force, contact pressure, 2.2. Pad/paddle placement, 2.3. Repeated shocks, 2.4. Hypothermia, 2.5. Respiration phase, 2.6. Coupling agent, 2.7. Age, 2.8. Gender, 2.9. Body mass index (BMI), 2.10. Hemoglobin concentration.

Table 1.
Influencing factors of TTI supported by a recent meta-analysis [7].

3. Conclusion

Defibrillators are one of the most important devices that can potentially save a person's life in emergency medical situations of SCD or AF by restoring normal heart rhythm. The TTI plays a key role in determining the current flow during defibrillation and should be monitored and used for current modulation, to improve the success and safety of the procedure. In this chapter, we have analyzed and discussed the most important factors that can affect TTI and, thus defibrillation success.

Conflict of interest

The authors declare no conflict of interest.

Acronyms and abbreviations

AF	atrial fibrillation
CRT	cardiac resynchronization therapy
DF	defibrillation
ECV	electrical cardioversion
HT	hypothermia
ICD	implantable cardioverter defibrillator
kgf	kilogram-force
OHCA	out-of-hospital cardiac arrest
ROSC	return of spontaneous circulation
SCD	sudden cardiac death
TTI	transthoracic impedance
VT	ventricular tachycardia
VF	ventricular fibrillation

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