Experimental paper

Electrical features of eighteen automated external defibrillators: A systematic evaluation

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ABSTRACT

Aim: Assessment and comparison of the electrical parameters (energy, current, first and second phase waveform duration) among eighteen AEDs.

Method: Engineering bench tests for a descriptive systematic evaluation in commercially available AEDs. AEDs were tested through an ECG simulator, an impedance simulator, an oscilloscope and a measuring device detecting energy delivered, peak and average current, and duration of first and second phase of the biphasic waveforms. All tests were performed at the engineering facility of the Lombardia Regional Emergency Service (AREU).

Results: Large variations in the energy delivered at the first shock were observed. The trend of current highlighted a progressive decline concurrent with the increases of impedance. First and second phase duration varied substantially among the AEDs using the exponential biphasic waveform, unlike rectilinear waveform AEDs in which phase duration remained relatively constant.

Conclusions: There is a large variability in the electrical features of the AEDs tested. Energy is likely not to be the best indicator for strength dose selection. Current and shock duration should be both considered when approaching the technical features of AEDs. These findings may prompt further investigations to define the optimal current and duration of the shock waves to increase the success rate in the clinical setting.

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1. Introduction

More than thirty years have elapsed since the first report on the use of automated external defibrillation into clinical practice. Since then, automated external defibrillators (AEDs) have been widely spread not only in the emergency medical service setting but also among lay people in public places. Technology has been greatly improved and the AEDs adopt a biphasic waveform strategy, in contrast to the traditional monophasic defibrillators, to promote an increased success of defibrillation by concurrently reducing the myocardial damage due to the shock itself. Biphasic waves exploit less energy than monophasic wave and achieve greater defibrillation efficacy.

Two main types of biphasic waveforms are available: biphasic truncated exponential (BTE) and rectilinear biphasic (RLB). Among these, some companies developed some variations, like the pulsatile truncated exponential and the rectangular waveform. Based on scientific data, the ILCOR recommendations stated that “...there is no evidence of greater effectiveness of one biphasic waveform or device on another”. The guidelines for cardiac arrest and CPR thus recommend that “the initial biphasic shock should be no lower than 150 J for BTE and 120 J for RLB”. Under the clinical point of view, there is as yet no evidence on the best biphasic waveform nor on the best energy to achieve a successful defibrillation. Accordingly, companies have developed their own technology and features based on the international recommendations.

Energy has traditionally been the parameter used to estimate the strength of the shock although it is the current flowing through the heart that defibrillates the myocytes. Biphasic defibrillators modify the delivered current in relationship to trans-thoracic impedance. Thus far, however, the precise amount of current required to achieve a successful defibrillation is still unknown. This...
accounts for the variability of waveforms, peak and average current and of the duration of the first and second phase.

We therefore decided to systematically test several commercially available AEDs sold on Italian land following a large investment from the National Ministry of Health to the Italian Regions for a wide spread diffusion of AEDs in our country.

2. Methods

Overall, eighteen AEDs from twelve different manufactures were tested:

- SaverOne (Ami Italia, Napoli, Italy);
- G3 Pro (Cardiac Science, Bothell, WA, USA);
- G5 Pro (Cardiac Science, Bothell, WA, USA);
- Lifeline AED (Defibtech, Guilford, CT, USA);
- Responder AED (General Electric, Schenectady, NY, USA);
- Sam300P (HeartSine, Belfast, Ireland);
- Lifepak 1000 (Physio Control, Redmond, WA, USA);
- Lifepak express (Physio Control, Redmond, WA, USA);
- Cardiolife 2100 (Nihon Kohden, Shanghai, China);
- FR2+ (Philips, Eindhoven, Netherlands);
- FRx (Philips, Eindhoven, Netherlands);
- FR3 (Philips, Eindhoven, Netherlands);
- RescueSAM (Progetti, Trofarelo, Italy);
- AED HeartSave (Primedic, Rottweil, Germany);
- FRED Easy (Schiller, Baar, Switzerland);
- FRED Easyport (Schiller, Baar, Switzerland);
- AED Plus (Zoll, Chelmsford, UK);
- AED Pro (Zoll, Chelmsford, UK).

Tests were performed by using a defibrillator analyzer (Impulse 7000D, Fluke Biomedical, Everett). This device allows three different functions: defibrillation, ECG, pacing. Peak and average current (the maximum and average values of current delivered during the shock) and shock duration were measured in defibrillation mode. Each shock was delivered by the AEDs by increasing sequentially the impedance from 25 ohm (Ω) up to 200 Ω by incremental steps of 25 Ω. The AED was turned off at every shock and the impedance was changed. Changes of impedance were obtained through an impedance simulator (Impulse 7010D, Fluke Biomedical, Everett). This device allowed variation of impedance since the 7000D model is set at fixed 50 Ω impedance.

Biphasic waveforms were displayed on a 2 channel oscilloscope (THS720P model, Tektronix, Beaverton) which had a sensitivity from 5 millivolt (mV) to 50 volt per division (V/div) and a 8 bit vertical resolution with a scale of time which can be set from 5 nanoseconds (ns) to 50 second per division (s/div).

Tests were made at the Engineering Laboratory of the Lombardia Regional Emergency Service. In order to avoid bias measurements, all test were made by a single biomedical electronic engineer who consistently performed all evaluations. All but one tests were conducted between January 2012 and May 2012, with the exception of a newly introduced device which came out on the market in summer 2012. Measurements of this device were performed at the end of September 2012. The pads of each model were cut, replaced with suitable plugs and connected to the defibrillator analyzer.

The following parameters were measured at every shock:

- Delivered energy (E), [joule].
- Peak current of first and second impulse phase (I_p1, I_p2), (A) [ampere].
- Average current of first and second impulse phase (I_avg1, I_avg2), (A) [ampere].
- Duration of first and second impulse phase (T_1, T_2) and total duration (T_total), (ms), [milliseconds].

For measurements we maintained the energy default settings. All tests were repeated three times.

Additional measurements included peak and average voltage, size, weight, time required to analyze the ECG signal and time elapsed between turning on the AED and the ready-to-shock moment. These data, however, are not herein presented as they are part of separate reports. Preliminary results were reported in abstract forms.15–17

3. Results

Highly consistent data in terms of precision of measurements were registered. Accordingly, due to the negligible standard deviation, the data in the tables reported values without the standard deviation. Overall, there were four types of trends. In the first one, including 6 AEDs, an energy decline ranging from 5 to 36.5% from 25 to 200 Ω was identified. A second group (two defibrillators) showed a raise in energy in relationship to an impedance increase with, however, a large difference among their percentage energy increase, from 5 to 26.9%. In a third group four AEDs maintained approximately the same energy value at every impedance level. In the fourth group there was an initial increase in energy which then declined steadily. Overall, despite the large energy variation, the majority of the energy delivered was within the range declared by each manufacturer for every given impedance level. The results of energy measurements are shown in Table 1.

The peak current of the first phase showed marked decreases in all eighteen AEDs concurrent with the increases in impedance value (Fig. 1). The greatest variation was seen in FRED Easyport AED that delivered a peak current of 95.5 A at an impedance value of 25 Ω and ended up with a peak current of 14 A when the impedance was 175 Ω. Conversely, the AED Pro and AED Plus showed a minor range of variation by maintaining a relatively low peak value. More specifically, the peak current of these two AEDs varied from 25.6 to 8 A from 25 to 200 Ω. The diversity in peak current among the AEDs was more evident at low impedance values than at high impedance levels. At impedance values greater than 100 Ω, the peak current was similar for all tested AEDs. The second peak current showed a similar trend to that of the first one, but I_p2 maintained lower values as compared to those of I_p1.

The first and second phase average current delivered during the shocks showed a similar trend to that described for peak current (Fig. 2).

The first phase, second phase and total wave duration varied among the AEDs in relationship to the impedance (Table 2). The greatest variation in the first phase duration was observed in the Cardiolife AED. This parameter, indeed, increased from 3.9 ms at 25 Ω to 18.7 ms at an impedance value of 175 Ω. Instead, the greatest variation in the total duration of the shock was seen in Sam 300P, in which the T_total varied from 6.5 ms at an impedance value of 25 Ω to 31.9 ms at an impedance value of 200 Ω. Fig. 3 represents the FRx waveform showing a larger variation in time duration in contrast to the AED Plus which maintained the same duration regardless of the changes in impedance.

4. Discussion

The Truncated Exponential and the Rectilinear are the most common biphasic waveforms currently available in the automated external defibrillators. The recommendations of both guidelines on CPR, American Heart Association and European Resuscitation Council, however, only relate to the energy that should be
delivered being slightly different from BTE (no lower than 150J) to RLB (no lower than 120J). Based on these recommendations, the AED manufactures defined different settings of default energy level. By measuring every device we identified four different energy trends: a steady decline, a progressive increase, an approximately stable value and a dual response characterized by an increase followed by a decrease of energy concurrent with the increase in impedance. Overall, several AEDs delivered an amount of energy higher than the recommended values raising up to more than 300J in one model. Other devices delivered energy values lower than the minimum limit indicated by the guidelines throughout the range of impedance (from 25 to 200Ω). It is likely that these differences are related to the engineering solutions chosen by each manufacturer. A high energy delivery, however, does not imply a comparable amount of current delivered during the shock. Indeed, it has to be taken into account that energy depends also on the time over which the shock is given. According to its mathematical representation \( E = \int_{0}^{t} P \cdot R \, dt \), which is the integration of the square current multiplied by the resistance over time) a high amount of energy may be either the result of high current delivered in a very short time or the result of low current given over a longer period of time. This concept accounts for the reason why energy is not the proper parameter to indicate the “strength” of the discharge and, ultimately, of the appropriate measure of shock effectiveness. These observations were already reported in earlier studies\(^{18–20}\) and have been re-emphasized by more recent investigations.\(^{21–23}\) Despite these observations, joules have traditionally remained the unit of the shock “strength”.

The current is delivered by the capacitor which is the principal component of AED electronic circuit. It can store a different quantity of energy and can deliver the current through the resistance of the circuit. This is related to the capacitor capacitance (in term of Farad unit), and to trans-thoracic resistance (in term of Ohm unit).

The first phase peak current is the highest value of current delivered by the capacitor. In our measurements we observed that it largely varied among the AEDs with differences that were more evident at low impedance than at higher impedance. The effects of very high peak current at low impedance are unknown although a previous study by Lerman indicated an optimal amount of current ranging between 30 and 40 A.\(^{24}\) At an impedance value of 100 Ω, which is consistent with the majority of human impedance levels,\(^{25–27}\) all AEDs were much below 30 A with the exception of the Fred Easy and Fred Easyport which had a peak current of 37.2 and 32.6 A respectively. Comparable trends were observed in the
### Table 2
Comparison of AED first and second phase duration in relationship to impedance.

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<th>Cardiac Science 5</th>
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<th>General Electric Responder</th>
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T1, first phase duration; T2, second phase duration; Tt, total duration of the shock (milliseconds).

The missing data refer to those AEDs that did not deliver the shock at the impedance values of 25 and 200 Ω. Standard deviation not reported because of negligible values.
average intensity although the differences among the AEDs were less pronounced.

Previous studies by Kerber stated that excessive current may cause morphologic and functional damage to myocardial cells. However, his study did not report whether it was a high peak or a high average current that caused these detrimental effects. Yet, his and other studies did not report if there was a critical threshold above which damage to the cells occurs. The effects of different levels of the defibrillating current in human fibrillating hearts, however are, as yet, largely unknown.

Shock duration is the other variable that makes defibrillation more or less effective. To achieve successful defibrillation, a theoretical model described by Kroll estimated that the ideal pulse duration for first phase of a biphasic shock should be comprised between 3.8 and 10.2 ms in a range of impedance from 40 to 100 ohm by using a capacitor of 100–150 microFarad (μF). A more precise duration of the first phase was demonstrated by Shan et al. in a guinea pig model of ventricular fibrillation. These authors demonstrated that the highest proportion of successfully defibrillated animals was achieved when the duration of the first phase was set at 5 ms.

The optimal duration of the first phase depends on the time constant of the myocardial cells. Since the cell membrane can be considered like a capacitor, the cell model consists in a RC (Resistance–Capacitance) electric circuit characterized by a time constant τ (tau) related to capacitance and to resistance. The membrane response depends on the cell time constant and, typically, for exponential waveforms, it reaches a maximum value and then it decreases. The phase duration is optimized when it is truncated at the time in which the membrane response reaches its maximum level. Shorter or longer phase duration determines a reduced wave effectiveness leading in turn to waste of current. Previous animal and human studies demonstrated that the time constant ranges between 2 and 5 ms.

The modern generation of AEDs adjusts defibrillation output by measuring the trans-thoracic impedance before the shock delivery. Our data indeed highlighted that the duration of the first and second phase of the two main types of waveforms, BTE and RLB, act differently by using two different methods of impedance compensation: time-based compensation and current-based compensation. The AEDs that use the first method act by increasing the shock duration according to the changes in impedance. In the second method the devices maintain a fixed shock duration at every impedance values.

Typically the BTE waveforms use the time-based compensation method. Our measurements showed a raise of first and second phase duration in relationship to the increases in impedance. On the other hand, all devices that use a RLB waveform showed an almost unchanged durations for both first and second phase at every impedance level.

In their respective studies Gliner and Feeser demonstrated that defibrillation is more effective when the first phase is equal to or longer than the second phase. However, Matula demonstrated that the defibrillation success decreases when the total duration of the wave increases above 16 ms. With respect to these findings, our data showed a large difference among the AEDs. At an
**Fig. 2.** Upper panel: variation of first phase average current in relationship to impedance increase; lower panel: variation of second phase average current in relation to impedance increase. Standard deviation not reported because of negligible values.

**Fig. 3.** FRx = AED Philips model FRx. AED Plus = AED Zoll model AED Plus. Upper row: variation of shock duration in relationship to impedance increase. Lower row: AEDs pattern which maintain the same shock duration at every impedance level.
impedance value equal to 100 Ω only two defibrillators showed a total shock duration greater than the “limit” indicated by Matula. At the same time, when the impedance value rose up to 200 Ω all devices using a BTE waveform showed a total shock duration greater than 16 ms.

Impedance that represents a critical issue to achieve a successful defibrillation. Kerber and Dalzell in their previous and independent studies reported that the range of the trans-thoracic human impedance did not exceed 160 Ω. However, more recent studies by Chen reported measurements of human trans-thoracic impedance much higher than 200 Ω. These findings are of paramount importance since AEDs should be able to detect impedance levels higher that 200 Ω in order to deliver a shock. Instead we identified some AED which was not able to detect the underlying rhythm when impedance was set at 200 Ω. In these instances these devices vocally prompted to connect the electrodes as they were not able to detect the ECG signal. A similar behavior was seen at an impedance value of 25 Ω. This, however, might be a less critical issue because the AEDs are usually equipped with the special pediatric paddles which support very low impedances.

A previous study by Achleiter and coworkers compared seventeen defibrillators the majority of which (14/17) were monophasic manual defibrillators and two were semi-automated monophasic defibrillators. However, the goal of their study was to compare the selected energy and the delivered energy in relationship to the impedance increase. There is no mention on the real current delivered. In their second study four biphasic defibrillators (two manual and two semi-automated) were tested by reporting the result values of energy, initial voltage, initial current, waveform duration and tilt. These results were obtained by using a mathematical software that analyzed the shock waveforms previously recorded. Accordingly, they did not measure directly those parameters, but they rather calculated them.

The present work has some limitations: firstly, the tests were made on the bench only, secondly, our evaluation did not consider every AED presently available in the world.

Another issue is the absence of the pads replaced by the plugs. The characteristics of the electrode pads and how they modify current and duration of waveforms vary among manufacturers and pads may not necessarily be made by the company that manufactured the defibrillator itself. Indeed, as previously reported, trans-thoracic impedance (TTI) relies on patient impedance and on the skin/pad contact. We reasoned that the total TTI value was more appropriated to ascertain the effective current delivered as it considers both TTI components. Nevertheless, this issue could be the subject of further investigations.

As we are not aware of previous studies on restoration of spontaneous cardiac function following defibrillation with different levels of current applied to a defibrillating heart, our data may prompt further investigations in animal models in order to ascertain the impact of the shocks on the success of defibrillation by using different current intensity and different time durations for both first and second phase. Our comparison could also be used by the manufacturers to improve the technical features of their devices owing to the potential advantage of a systematic unbiased assessment of a large number of AEDs worldwide marketed.

5. Conclusion

There are marked differences in energy, current delivered, first and second phase duration among the AEDs.

Several studies proposed that defibrillators should be current-based rather than energy-based. We fully support this concept. Beside the current the time duration represents the other variable to be taken into account in order to achieve the maximal defibrillation effectiveness. These variables should be separately considered such as to precisely quantify them. This should allow to deliver a high current within an appropriate time interval. Additional experimental and subsequent clinical data are warranted to apply our results in the experimental and subsequently in the clinical setting.

Conflict of interest statement

The authors state the absence of any conflict of interest.

References