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# Principles of External Defibrillators

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Hugo Delgado, Jorge Toquero, Cristina Mitroi,  
Victor Castro and Ignacio Fernández Lozano

Additional information is available at the end of the chapter

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## 1. Introduction

Electrical defibrillation is the only effective therapy for cardiac arrest caused by ventricular fibrillation (VF) [1, 2] or pulseless ventricular tachycardia (VT). Scientific evidence to support early defibrillation is overwhelming [3-5], being delay from collapse to delivery of the first shock the single most important determinant of survival [6, 7]. If defibrillation is delivered promptly, survival rates as high as 75% have been reported [8, 9]. The chance of a favourable outcome decline at a rate of about 10% for each minute cardiac defibrillation is delayed [3, 10].

The guidelines on cardiopulmonary resuscitation of the European Resuscitation Council and American Heart Association (AHA) strongly recommend attempting defibrillation with minimal delay in victims of VF/VT cardiac arrest. As this event occurs most often in the victim's private home or in public spaces away from healthcare facilities, the need for early defibrillation has led to the development of automatic, portable defibrillators (Automated External Defibrillator - AED).

The purpose of this chapter is to review the mechanisms of external defibrillation, the available types of AEDs including the wearable cardioverter-defibrillator, its uses and limitations.

## 2. Cardiac external defibrillation – Basic science

### 2.1. History

In Switzerland, 1899, Prevost and Batelli discovered that small electric shocks could induce ventricular fibrillation in dogs and that larger charges would reverse the condition. Howev-

er it was not until 1956 when alternating current was first used for transthoracic defibrillation to treat ventricular fibrillation in humans [11]. Following this breakthrough, direct current defibrillators were introduced into clinical practice around 1962 [12] when it was demonstrated that electrical countershock or cardioversion across the closed chest could abolish other cardiac arrhythmias in addition to ventricular fibrillation [13]. Later on, Diack et al. [14] described the first clinical experience with an AED. Subsequently, further studies provided solid evidence on the potential role of these devices in the early defibrillation and survival.

## 2.2. Types of defibrillators

- Most defibrillators are energy-based, meaning that the device charges a capacitor to a selected voltage and then delivers a prespecified amount of energy in joules. The amount of energy which arrives at the myocardium is dependent on the selected voltage and the transthoracic impedance (which varies by patient).

Most current AEDs are energy-based but there are two other types of defibrillators less frequently used in clinical practice.

- **Impedance-based defibrillators** allow selection of the current applied based upon the transthoracic impedance (TTI). TTI is assessed initially with a test pulse and subsequently the capacitor charges to the appropriate voltage. In patients with high TTI there was a significant improvement in shock success rate using this approach when compared to the energy-adjusting defibrillators [15].
- **Current-based defibrillators** deliver a fixed dose of current which results in defibrillation thresholds that are independent of TTI [16]. The optimal current for ventricular defibrillation appears to be 30 to 40 amperes independently of both TTI and body weight thus achieving defibrillation with considerably less energy than the conventional energy-based method [17-19]. Current-based defibrillation was proved superior to energy-based defibrillation with monophasic waveforms in one clinical study [20] but this concept merits further exploration in the light of biphasic waveforms now available.

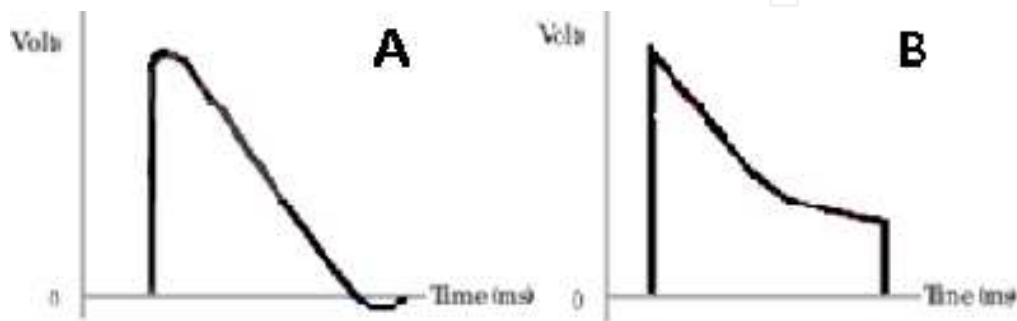
## 2.3. Waveforms and its importance

Energy-based defibrillators can deliver energy in a variety of waveforms, broadly characterized as monophasic, biphasic or triphasic.

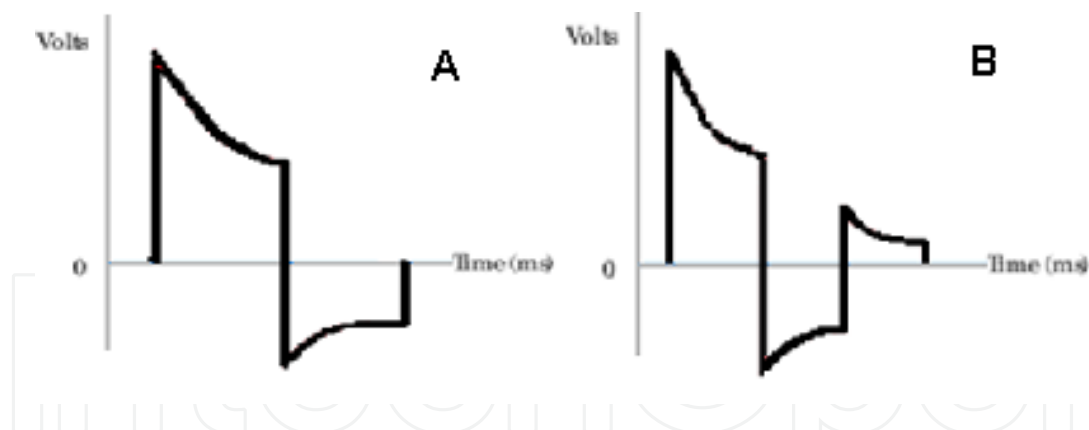
- **Monophasic waveform.** Defibrillators with this type of waveform deliver current in one polarity and were the first to be introduced. They can be further categorized by the rate at which the current pulse decreases to zero. If the monophasic waveform falls to zero gradually, the term damped sinusoidal is used. If the waveform falls instantaneously, the term truncated exponential is used (*figure 1*). The damped sinusoidal monophasic waveforms have been the mainstay of external defibrillation for over three decades
- **Biphasic waveform.** This type of waveform was developed later. The delivered current flows in a positive direction for a specified time and then reverses and flows in a negative

direction for the remaining duration of the electrical discharge (*figure 2A*). With biphasic waveforms there is a lower defibrillation threshold (DFT) that allows reductions of the energy levels administered and may cause less myocardial damage [21-24]. The use of biphasic waveforms permits a reduction in the size and weight of AEDs.

- **Triphasic waveform.** There are no human studies to support the use of multiphasic waveforms over biphasic. Investigation in animals suggests that the benefits of biphasic waveform could be harnessed through the use of a triphasic waveform in which the second phase has the larger strength to lower the DFT and the third phase the lower strength, to minimize damage [25] (*figure 2B*).



**Figure 1.** Monophasic waveforms. A. Damped sinusoidal wave (A) and truncated exponential (B).



**Figure 2.** A. Biphasic waveform. B. Triphasic waveform.

## 2.4. Cardioversion and defibrillation

Cardioversion is one of the possible treatments for arrhythmias that imply a re-entrant circuit. By delivering a synchronized electric shock all excitable tissue of the circuit is simultaneously depolarised making the tissue refractory and the circuit no longer able to sustain re-entry. As a result, cardioversion terminates arrhythmias resulting from a single reentrant circuit, such as atrial flutter, atrioventricular nodal reentrant tachycardia or monomorphic ventricular tachycardia. This term is also applied when using an electrical shock to termi-

nate atrial fibrillation although this arrhythmia involves multiple, micro-reentrant circuits. The term cardioversion implies to synchronize the delivery of the shock with the QRS complex of the patient.

Defibrillation is used to describe the utilization of an electric shock to terminate ventricular fibrillation (VF). VF is known to be a very persistent arrhythmia, and total elimination of the fibrillatory activity is obtained only with a relatively high energy shock that uniformly depolarizes the entire myocardium.

Current European Society of Cardiology and AHA guidelines suggest the following initial energy selection for specific arrhythmias [26-28]:

- For atrial fibrillation, 120 to 200 joules for biphasic devices and 200 joules for monophasic devices.
- For atrial flutter, 50 to 100 joules for biphasic devices and 100 joules for monophasic devices.
- For ventricular tachycardia with a pulse, 100 joules for biphasic devices and 200 joules for monophasic devices.
- For ventricular fibrillation or pulseless ventricular tachycardia, at least 150 joules for biphasic devices and 360 joules for monophasic devices.

Cardioversion is most commonly used for the treatment of atrial fibrillation and the development of biphasic defibrillators proved to be very useful. At least 2 randomized trials illustrated the benefit of the biphasic waveform when compared to escalating monophasic shocks [29, 30]. First shock efficacy was greater with a biphasic waveform (68 versus 21 percent), delivered energy was 50 percent less, and the overall cardioversion rate was higher (94 versus 79 percent) [29]. There were fewer total shocks (1.7 versus 2.8), less energy delivered (217 versus 548 joules), and a lower frequency of dermal injury (17 versus 41 percent) [30].

Similar findings were reported for patients with atrial flutter, in whom cardioversion was successful more frequently and at lower energy levels when using biphasic waveforms [31].

### **3. Automatic external defibrillators**

#### **3.1. Definition and basic AED components**

The term refers to a portable and lightweight computerized device that incorporates rhythm analysis and defibrillation systems and uses voice and/or visual prompts to guide lay rescuers and healthcare providers to safely defibrillate victims of cardiac arrest due to VF or pulseless VT.

There are two types of AED: the semi-automatic that indicates the need for defibrillation but requires that the operator deliver the shock by pushing a button and the fully automatic

AED which is capable of administering a shock without the need for outside interventions. See Table 1.

	Semi-automatic AEDs	Fully automatic AED
<b>Definition</b>	Indicates the need for defibrillation but requires an operator to deliver the shock by pushing a button	Capable of administering a shock without the need for outside interventions
<b>Advantages</b>	<ul style="list-style-type: none"> <li>• Recommended by current resuscitation guidelines</li> <li>• Widely used</li> <li>• Allows healthcare professionals to override the device and deliver a shock manually, independently of prompts.</li> <li>• Safer, no risk of inappropriate shocks to the rescuer</li> </ul>	<ul style="list-style-type: none"> <li>• Easier to use and more appropriate for lay-rescuers</li> <li>• Better compliance with resuscitation protocols</li> </ul>
<b>Disadvantages</b>	<ul style="list-style-type: none"> <li>• More complex to use for the untrained responders</li> <li>• More difficult to synchronize with CPR maneuvers for lay rescuers</li> </ul>	<ul style="list-style-type: none"> <li>• Longer times until shock delivery</li> <li>• Risk of electrocution for the rescuer if inappropriately used</li> <li>• No possibility to override the device</li> <li>• Not recommended by current guidelines except for special situations</li> </ul>

**Table 1.** Definition, main advantages and disadvantages for the different types of AED available.

Basically these devices consist of a battery, a capacitor, electrodes and an electrical circuit designed to analyze the rhythm and send an electric shock if is needed.

- **Batteries.** Essentially they are containers of chemical reactions and one of the most important parts of the AED system. Initially lead batteries and nickel-cadmium were used but lately non-rechargeable lithium batteries, smaller in size and with longer duration without maintenance (up to 5 years), are rapidly replacing them. Since extreme temperatures negatively affect the batteries, defibrillators must be stored in controlled environments. Also it is important to dispose of the batteries using designated containers as they contain corrosive and highly toxic substances.
- **Capacitor.** The electrical shock delivered to the patient is generated by high voltage circuits from energy stored in a capacitor which can hold up to 7 kV of electricity. The energy delivered by this system can be anywhere from 30 to 400 joules.
- **Electrodes** are the components through which the defibrillator collects information for rhythm analysis and delivers energy to the patient's heart. Many types of electrodes are available including hand-held paddles, internal paddles, and self-adhesive disposable electrodes. In general, disposable electrodes are preferred in emergency settings because they increase the speed of shock and improve defibrillation technique.



- **Electrical circuit.** AEDs are highly sophisticated, microprocessor-based devices that analyze multiple features of the surface ECG signal including frequency, amplitude, slope and wave morphology. It contains various filters for QRS signals, radio transmission and other interferences, as well as for loose electrodes and poor contact. Some devices are programmed to detect patient movement.
- **Controls.** The typical controls on an AED include a power button, a display screen on which trained rescuers can check the heart rhythm and a discharge button. Defibrillators that can be operated manually have also an energy select control and a charge button. Certain defibrillators have special controls for internal paddles or disposable electrodes.



**Figure 3.** Appearance of a common AED with pads attached

### 3.2. Defibrillation success

Defibrillation is considered successful when it terminates VF for at least 5 seconds following the shock [32]. DFT is the lowest effective energy needed to restore the cardiac rhythm. Defibrillation basically depends on successful energy selection and TTI.

#### 3.2.1. Energy levels

Modern AEDs are energy-based devices that can deliver the electrical shock in a monophasic or biphasic waveform. Although monophasic AEDs are not currently manufactured anymore they are still relatively easy to find in clinical practice. Energy levels vary by the type of device and the optimal energy level for defibrillation has not been determined yet.

Studies comparing biphasic shocks to a more traditional approach with 3 monophasic escalating shocks [33,34] have shown that defibrillation with relatively low energy ( $\leq 200$  J bi-

phasic) is safe and has equivalent or higher efficacy for termination of VF than monophasic waveform shocks of equivalent or higher energy [35-41]. However optimal energy for this first shock has not been determined so that for biphasic defibrillators, one should use the manufacturer's recommended energy dose (120 to 200 J). If the manufacturer's recommended dose is not known, defibrillation at maximal dose may be considered.

Commercially available biphasic AEDs provide either fixed or escalating energy levels. Human studies have not demonstrated evidence of harm from any biphasic waveform defibrillation energy up to 360 J [40, 41]. Based on available evidence, the second and subsequent shocks should be at an energy level equivalent or higher than the first one if possible.

In the absence of biphasic defibrillators, monophasic ones are acceptable. A recommendation for higher initial energy when using a monophasic waveform was weighed by expert consensus taking in consideration the potential negative effects of a high-energy first shock versus the negative effects of prolonged VF [42]. The consensus recommends that rescuers using monophasic AED should give an initial shock of 360 J. This single dose for monophasic shocks is designed to simplify instructions to rescuers but is not a mandate to recall monophasic AEDs for reprogramming. If the monophasic AED being used is programmed to deliver a different first or subsequent dose, that dose is acceptable.

### 3.2.2. *Transthoracic impedance*

It refers to the dissipation of energy in the lungs, thoracic cage and the other anatomic structures of the chest. In an animal study, only 4% of the energy supplied reached the heart [43]. The average adult human TTI is  $\approx 70-80 \Omega$  and is determined by multiple factors including energy level, electrode size, interelectrode distance, interface skin-electrode, electrode pressure, phase of ventilation, myocardial tissue and blood conductive properties [44].

When TTI is too high, a low-energy shock will not generate sufficient current to achieve defibrillation [44, 45]. To reduce TTI, the defibrillator operator should use conductive materials. This is accomplished with the use of gel pads or electrode paste [46] with paddles or through the use of self-adhesive pads.

### 3.2.3. *Others factors affecting defibrillation success*

There are several electrode characteristics that can affect defibrillation outcome. These include electrode position, pad size and hand-held versus patch electrodes. About electrode position, data demonstrates that 4 pad positions (antero-lateral, antero-posterior, anterior-left infrascapular and anterior-right-infrascapular) are equally effective [47]. For ease of placement and education, antero-lateral is a reasonable default electrode placement. Electrode pad size is an important determinant of transthoracic current flow during external shock. Larger paddles create a lower resistance and allow more current to reach the heart [48, 49] and may cause less myocardial necrosis [50]. Thus, larger paddles are more desirable. Most manufacturers offer adult paddles, which are between 8 to 13 cm in diameter, and pediatric paddles, which are smaller [51].



Hand-held paddle electrodes may be more effective than self-adhesive patch electrodes because if applied with pressure they may improve electrode-to-skin contact and reduce TTI [52]. Nevertheless they are never used for AEDs because of the need for training.

### 3.3. Automated rhythm analysis

One of the most important features of an ideal AED is the accuracy of rhythm diagnosis. As demonstrated in both in vitro and clinical studies, accuracy in terms of sensitivity and specificity is high, surpassing 90% [53, 54]. The rare errors noted in trials occurred when the device failed to recognize certain varieties of VF or when operators failed to follow recommended instructions [54, 55]. In order to diagnose VF the device must identify an ECG waveform with amplitude of at least 0.8mV faster than a preprogrammed rate while for VT the criteria are: frequency of at least 120 beats/minute, QRS duration of more than 160 ms and absence of P wave. ECG analysis is done in consecutive segments of 2.7 seconds and the diagnosis must coincide in 2 out of 3 segments in order to give a decision.

Although AEDs are not designed to deliver synchronized shocks (such as cardioversion for VT with pulse), these devices will recommend a nonsynchronized shock for monomorphic or polymorphic VT if the rate and R-wave morphology exceed preset values. This is why AEDs should be placed in the analysis mode only when full cardiac arrest has been confirmed (patient unconscious) and all movement has ceased.

There is evidence that VF waveform analysis can predict defibrillation success rate. Several animal and model studies suggest that this analysis may help to identify the optimal timing or waveform for each patient [56, 57]. However this feature is not yet sufficiently accurate to be implemented in clinical practice.

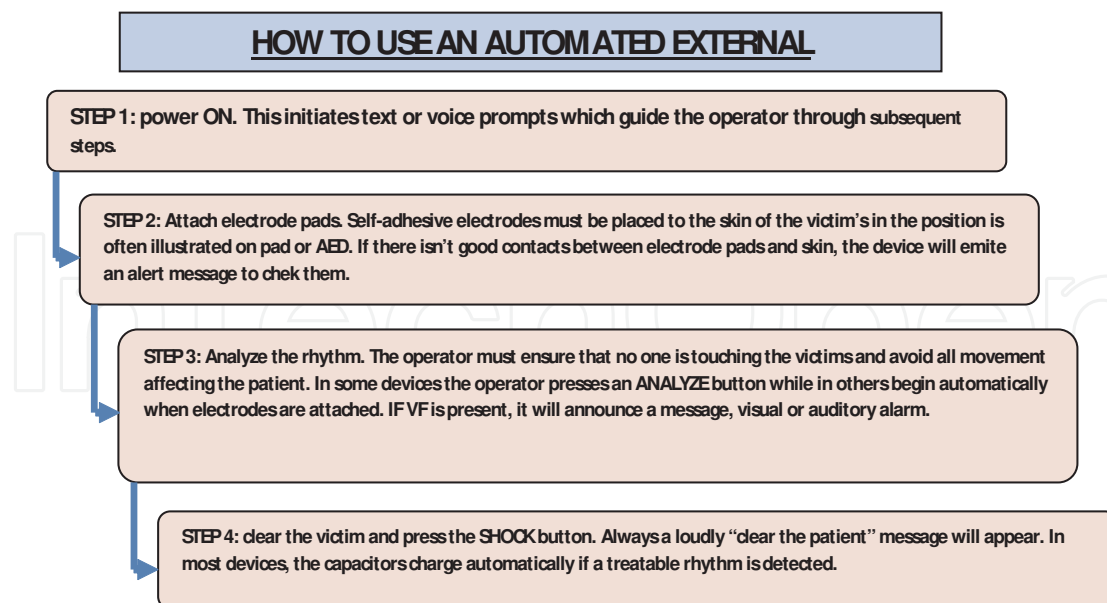
### 3.4. Device maintenance and quality assurance

Appropriate maintenance of the AED is vital for proper operation. AED manufacturers provide specific recommendations for maintenance and readiness, which should be followed carefully. Failure to properly maintain the defibrillator or power supply is responsible for the majority of reported malfunctions. Newer AED models require almost no maintenance. These devices conduct a self-check of operation and indicate “readiness to use”.

## 3.5. How to use an AED

### 3.5.1. Basic steps

AEDs are designed to be used by laypersons who ideally should have received AED training at some point in the past. Generally these devices are very intuitive and user-friendly so that even untrained bystanders can perfectly employ them to deliver an electric shock to a VF victim [58]. The basic steps common to all trademarks that need to be taken to deliver a shock are indicated in figure 4. In contrast, the more sophisticated manual and semi-automatic defibrillators used by health professionals can perform other functions but require a skilled operator able to interpret electrocardiograms.



**Figure 4.** How to use an AED. Basic steps.

The location of a public access AED should be displayed to large groups of people, regardless of age or activity. In order to make them highly visible, public access AEDs are often brightly colored, and are mounted in protective cases near the entrance of a building. In September 2008, the International Liaison Committee on Resuscitation issued a 'universal AED sign' to be adopted throughout the world to indicate the presence of an AED (figure 5).



**Figure 5.** Universal AED sign

### 3.5.2. Integration of AED use with basic life support measure

When arriving at the scene of a suspected cardiac arrest, rescuers must rapidly integrate cardiopulmonary resuscitation (CPR) with the use of the available AED. In general 3 actions must occur simultaneously: (1) activation of the Emergency System, (2) CPR and (3) operation of the AED (figure 6).

Latest European Resuscitation Council Guidelines [59] emphasize a number of changes compared to the 2005 version:

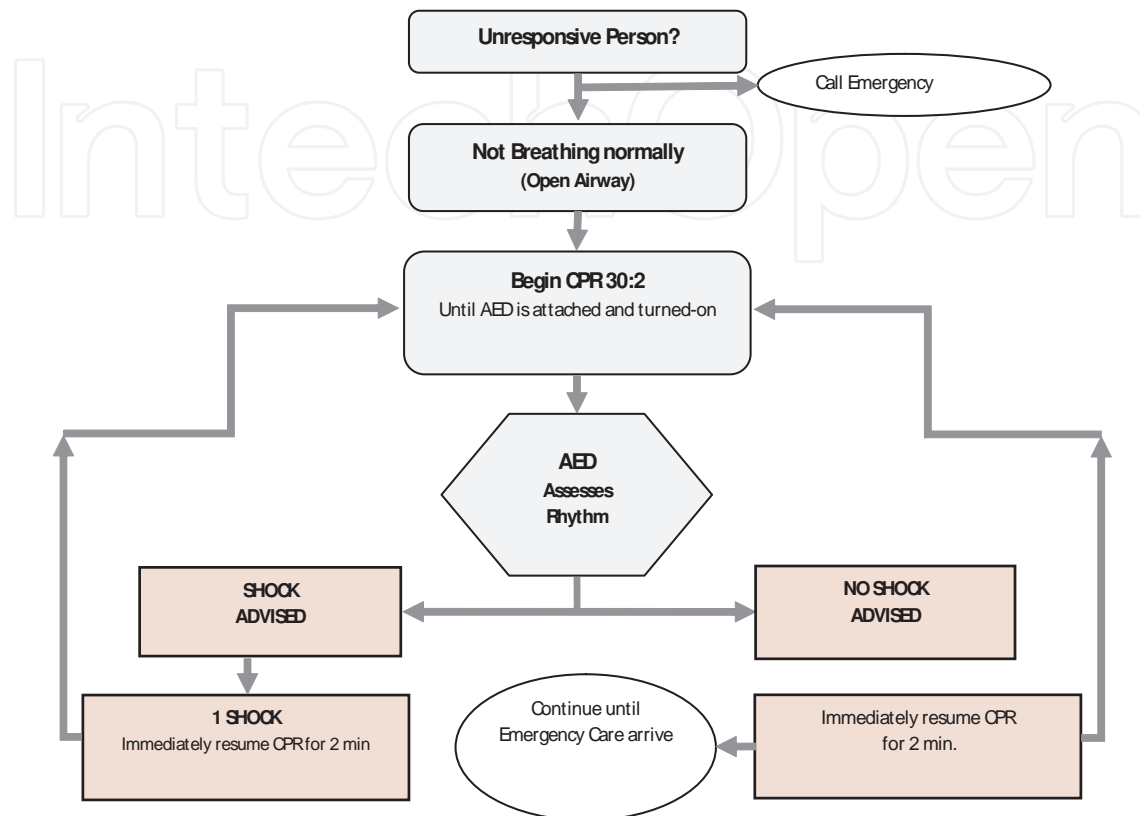
- Chest compression should be initiated as soon as possible and should be continued while the adhesive pads of the AED are being attached and during defibrillator charging. If only one rescuer is present, he should initially attach the pads and start afterwards chest compressions. With a sole rescuer present, it is recommended to do only chest compressions with no ventilation. If 2 or more rescuers are present chest compression and ventilation should be done in the classical 30:2 sequence.
- Minimize interruptions in CPR. The importance of early, uninterrupted chest compression is emphasized in all guidelines. Interrupt CPR only when it is necessary to analyze the rhythm and deliver a shock. The delivery of defibrillation should be achievable with an interruption in chest compressions of no more than 5 seconds. After an electrical shock it is recommended to start CPR immediately for the next 2 minutes and only after that stop to reanalyze the cardiac rhythm
- In the previous version of guidelines, CPR was recommended for 2-3 minutes before analyzing a rhythm. Now this recommendation was withdrawn for lack of benefit.
- The previous recommendation for three-stacked shocks is also withdrawn for the out-of-hospital VF. This strategy should be employed only with witnessed VF in the hospital setting such as in the cath-lab or for patients with recent heart surgery. All cardiac arrests in out-of-hospital setting should be treated with an initial shock if found in VF followed by 2 minutes CPR and subsequent rhythm reanalysis.
- Electrode pastes and gels can spread between the two paddles, creating the potential for a spark and should not be used.

Modified prototype AEDs record information about frequency and depth of chest compressions during CPR. These devices are now commercially available and can prompt rescuers to improve CPR performance.

### 3.5.3. AED use in pediatric and adolescent population

Cardiac arrest is less common in children than adults. In pediatric population cardiac arrest causes are more diverse with only 5% to 15% of all cases being attributed to VF [60]. The lowest-energy dose for effective defibrillation and upper limit for safe defibrillation in infants and children are not known, but doses  $> 4$  J/kg have effectively defibrillated children [61] and pediatric animal models [62]. Biphasic shocks appear to be at least as effective as monophasic shocks and less harmful, initial doses of 2 J/kg may be considered. Some AEDs

are equipped with pediatric attenuator systems to reduce the delivered energy to a dose suitable for children [63]. It seems that most AEDs can accurately detect VF in children with a high degree of sensitivity and specificity, but more studies are needed.



**Figure 6.** AED and CPR algorithm.

European and AHA guidelines recommend the using conventional, adults AEDs in children > 8 years old (approximately 25 kg body weight) with the same energy recommendation as in adult population. In children < 8 years it is reasonable to use a pediatric dose-attenuator system but if none is available the rescuer should use a standard AED. Infants should be treated with manual or dose-attenuating defibrillators although there are isolated cases of adult AED use in infants with good outcomes and without apparent myocardial damage [64].

### 3.6. AED for the masses

#### 3.6.1. AED use training

The design of AEDs is centered on being easy to use even for the untrained lay rescuers. A variety of studies have demonstrated that it is feasible especially when the rescuers receive instructions via telephone from emergency dispatchers [65, 66]. However, in order to improve outcomes in out-of-hospital cardiac arrests, the 'ideal' rescuer should have minimal

training on AED use and basic CPR. Multiple approaches for AED training and maintenance of learned skills have been employed (face-to-face, video or web-based training) with various degrees of success [67, 68].

### 3.6.2. *Public access defibrillation*

This concept includes all those strategies or programs to implement early defibrillation in the community. It has emerged from the recognition that AEDs and training lay people to use it are promising methods to achieve rapid defibrillation and survival in out-of-hospital cardiac arrest.

Resuscitation guidelines recommend early defibrillation (within 5 minutes of collapse) in order to increase survival from out-of-hospital cardiac arrest. The only way to achieve this goal is by generalizing of AEDs in the community. It is now accepted that an AED should be available for immediate use by trained laypersons wherever large numbers of people congregate [69, 70] such as airports, convention centers, sports stadiums and arenas, large industrial buildings, high-rise offices, large health fitness facilities. Furthermore AED should be provided also to the traditional emergency medical services (EMS), to non-medical emergency responders (police officers and firefighters), as well as placed in hospitals and in the private homes of high-risk individuals.

- **AED use by EMS.** In the USA initial large scale implementation of AED was with EMS and took place in the 1980s and 1990s. This strategy allowed EMS first responders, many of them who were emergency medical technicians without training in rhythm interpretation, to provide early defibrillation to cardiac arrest victims. Meta-analyses found that EMS AED programs resulted in a significant, overall 9 percent increase in survival [71, 72] although not all of the individual reports showed survival advantage [73]. One plausible explanation for this discrepancy is that the resuscitation algorithms originally used for AED rhythm analysis required considerable interruptions in CPR [74], and that the increase in "hands-off" time reduced the chances of successful resuscitation [75]. More recent AED algorithms and guideline recommendations for minimally interrupted cardiac resuscitation have demonstrated improved outcomes for out-of-hospital cardiac arrest victims [76, 77].
- **AED use by police officers and firefighters** was implemented in various USA states. Policemen were provided with AED and trained how to use them. Several studies demonstrated that this approach was able to significantly increase survival to hospital discharge and without neurological deficits [78, 79]. However this advantage was evident only in those states where police officers were able to get to the victim before EMS emphasizing one more time the importance of early defibrillation.
- **AED use in private homes** is a strategy that seems useful since three-quarters of sudden cardiac arrests occur in the victim's home. This approach was investigated by a randomized trial that included 7001 patients with previous anterior wall myocardial infarction who were not candidates for an implantable cardioverter-defibrillator [80]. There was no survival benefit for AED and CPR group versus CPR only. The negative result may be ex-

plained by a lower than expected cardiac arrest rate with only 50% of the events being witnessed and by a low usage of AED (only in 32 victims out of 117). In deciding whether AEDs are appropriate for home use, cost and the increasing role of implantable cardioverter-defibrillators in high risk individuals must be taken into consideration.

- **AED use in hospitals** was studied because of data suggesting that delayed defibrillation is common during in-hospital arrest even though medical personnel are often trained in rhythm interpretation and manual defibrillation. A delay of more than 2 minutes between collapse and defibrillation was associated with a lower probability of survival [81]. While small studies with AED allocated to specific clinical and non-clinical areas of the hospital suggested improved survival [82, 83], large registry data showed discrepant results [84]. Patients with in-hospital cardiac arrest by VF/pulseless VT reanimated using an AED had the same survival rate as those who were not treated with these devices. The patients with cardiac arrest without a shockable rhythm (asystole or pulseless electrical activity) had significantly worse survival when an AED was used, probably because of delays/interruptions in CPR needed for AED rhythm analysis. The optimal strategy of AED distribution and its ultimate benefit may depend upon a particular hospital's staffing, geography, and patient profile.
- **Survival benefit and cost efficiency in public access defibrillation**
- Several clinical, randomized, prospective studies confirmed a robust survival benefit when victims of cardiac arrest in public places where reanimated by lay rescuers who did CPR and used an AED versus CPR only. The survival rate to discharge was 23.4% when an AED was used versus 14% with CPR only in PAD trial [85] and 38% versus 9% in the largest cohort of patients that included 13,000 individuals [86]. Cost efficiency analysis showed a cost of \$35,000 to \$57,000 per quality adjusted life-year [87, 88], which is comparable to other widely-accepted medical interventions such as bone marrow transplant (\$52,000 per quality adjusted life-year) and heart transplant (\$59,000 per quality adjusted life-year). So convincing was the evidence of AED benefit that USA authorities established rules to implement AED programs in schools and many other federal locations [89].

### 3.7. Wearable cardioverter-defibrillator

#### 3.7.1. Definition and indications

The wearable cardioverter-defibrillator (WCD) (LifeVest®, ZOLL) is an external device capable of automatic detection and defibrillation of VT and VF. Its main indication is in situations where implantable cardioverter-defibrillator (ICD) may be initially deferred or may become unnecessary if the arrhythmic substrate is temporary or if the risk of ICD implantation is too high. While the WCD can be worn for years, typically the device is used for several months as temporary protection against cardiac arrest. The main indications where a WCD may be used are as follows:

- Recent myocardial infarction or coronary revascularization with severely reduced left ventricular ejection fraction



- Newly diagnosed nonischemic cardiomyopathy with severely reduced left ventricular ejection fraction
- Severe cardiomyopathy as a bridge to heart transplantation or in patients with ventricular assist devices
- Need for interruption of ICD therapy or the temporary inability to implant an ICD (e.g. infection)
- Syncope and a high risk of ventricular tachyarrhythmias
- Ambulatory event monitoring, often performed for several weeks in an effort to determine an arrhythmic etiology for syncope

### 3.7.2. How a WCD works

This device is composed of four non adhesive monitoring electrodes, three defibrillation electrodes incorporated into a chest strap assembly and positioned for apex-posterior defibrillation and a defibrillation unit carried on a waist belt. The monitoring electrodes must be placed circumferentially around the chest and held in place with an elastic belt. They provide 2 surface ECG leads. It is essential that the vest be properly fitted in order to have adequate skin contact and avoid noise and frequent alarms. See figure 7.



**Figure 7.** LifeVest®, ZOLL: main components and how it should be worn.

Arrhythmia detection by the WCD is programmed using rate criteria. When an arrhythmia is detected, the WCD emits audible and vibration alarms. The patients are trained to hold response buttons during these alarms in order to avoid a shock while awake. If an electric shock will be delivered a voice cautions the patient and bystanders to the impending shock. A patient's response serves as a test of consciousness; if no response occurs, the device charges, extrudes gel from the defibrillation electrodes, and delivers up to five biphasic shocks at preprogrammed energy levels with a maximum output of 150 joules.

The tachycardia detection rate is programmable for VF between 120 and 250 beats/minute and the VF shock delay can be programmed from 25 to 55 seconds. The VT detection rate is programmable between 120 bpm to the VF setting with a VT shock delay of 60 to 180 seconds. Additional shock delays (up to 30 seconds) may optionally be allowed during sleep. VT signals can allow synchronized shock delivery on the R wave, but if the R wave cannot be identified, unsynchronized shocks will be delivered. The shock energy is biphasic and can be programmed from 75 to 150 joules, with up to five shocks delivered per event.

The WCD has also the capability to store data regarding arrhythmias or asystole, patient's compliance with the device, noise and interference. All this information is stored and later transmitted via modem to the manufacturer network where it is available for clinician review. Of note is that WCD cannot deliver either antitachycardia pacing or pacing for bradycardia or asystole. (cannot + either/or vs. can + neither/nor)

### *3.7.3. Efficacy of WCD and other aspects*

In the USA postmarket study of 3569 patients, there were 80 sustained VT/VF events that occurred and the success of the first shock in terminating VT/VF in the unconscious patients was 100% with a survival rate of 86%. Death after a successful first shock occurred because recurrent VT/VF, bystander preventing therapy in one case, electrocardiogram signal disruption from a fall, and to inhibition of detection due to the pacing stimulus artifact from a unipolar pacemaker (one case). This study also reported that long-term survival was similar in WCD patients compared to a cohort of ICD patients [90]. Nevertheless, WCD does not offer pacemaker functions and in this study 23 out of 3569 patients (0.6%) experienced asystole with an associated mortality of 74%

Although the WCD is a very efficient device, cardiac arrest still can develop in some circumstances: patient does not wear the device, WCD is improperly positioned, or bystander interference. These results highlight the importance of patient education and compliance while using the WCD.

Some of the shocks that a WCD delivers may be inappropriate due to electronic noise, malfunction of the device or supraventricular tachycardia. The rate of inappropriate shocks by a WCD is comparable to the ICD rate [90, 91]. However WCD inappropriate shocks can be potentially reduced due to the ability to abort shock by pressing response buttons if the patient is awake. Also, when ECG noise occurs, the device emits an alarm prompting the patient to try to eliminate the electronic noise by changing body position or tightening of the electrode belt.

In spite of being an extremely efficient device, WCD has some important limitations that need to be acknowledged. It does not provide pacemaker functions and it requires patient interaction and compliance. The device must be removed for bathing and during this time periods a caregiver should be present. In one German study [91], mean daily use of WCD was 21.3 hours/day. The primary complaints associated with the WCD were the weight of the device, problems sleeping, particularly when noise alarms occurred and skin rash or itching.

### 3.8. Legal issues concerning AED

In the past use of AEDs was limited partly because of the concern for subsidiary responsibility of those who are not health personnel. The fact that defibrillation is a medical act represents a legal obstacle in many countries. In 2000 the U.S. Congress approved the Act of survival in cardiac arrest, which extended the protection of the Good Samaritan to the users of an AED. Lay rescuers are protected from lawsuits if they act voluntarily to try to help a person who is having a medical emergency. The rescuer should act with good faith and make an effort help another person. The rescuer's efforts must be reasonable and with common sense. This has been an important step in the diffusion and generalization of these devices.

### 3.9. Challenges and future development for AED

While these devices are very effective when treating ventricular arrhythmias, they still need the presence of a bystander capable of applying and operating it. Also, it must be taken into account, that only a half of the cardiac arrests are witnessed so for a large number of patients this therapy cannot be available.

The main drawback that was observed when using an AED is that it requires interruptions in CPR in order to analyze the rhythm and to deliver the electric shock. Ongoing efforts are aimed at minimizing this time, and technical advances may eventually enable accurate rhythm interpretation even while CPR is ongoing [92, 93]. Recent resuscitation guidelines emphasize strongly the need to reduce 'hands-off' time in order to obtain a favorable result.

It was advocated that AED should be included in the category of compulsory safety equipment such as smoke alarms or fire extinguishers. However this approach has not demonstrated survival benefit and at the moment is cost prohibitive.

One of the future directions of research is AED analysis of shape and pattern of VF waveform recorded by ECG. It promises help in guiding the rescuers for the best course of treatment with CPR, defibrillation and medication. See section 3.3

## 4. Conclusions

Sudden cardiac arrest, frequently due to VF or pulseless VT, is traditionally associated with poor survival rates. Saving the lives of these patients depends on early cardiac defibrillation which, with manual defibrillators, is limited only to qualified rescuers who can interpret ECGs. AEDs solve this problem since they are able to analyze rhythm and inform the rescuers whether a shock is indicated. This approach allows lay rescuers to provide effective early defibrillation which has been shown to significantly improve survival and survival with intact neurologic function after out-of-hospital cardiac arrest. One limitation is that AED use requires interruptions in CPR which was proved to be deleterious especially in patients with non-shockable rhythms. Special efforts are being made in order to improve rhythm analysis and 'hands-off' time during CPR.

## Author details

Hugo Delgado, Jorge Toquero\*, Cristina Mitroi, Victor Castro and Ignacio Fernández Lozano

\*Address all correspondence to: [jorgetoquero@secardiologia.es](mailto:jorgetoquero@secardiologia.es)

Hospital Puerta de Hierro Majadahonda, Madrid, Spain

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