International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

The Historical Development, Functions and Design Features of Defibrillators: A Comprehensive Analysis

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DOI: https://doi.org/10.55248/gengpi.4.723.49027

ABSTRACT:

Defibrillators as critical tools in the field of emergency medicine are significantly improving the chances of survival for individuals experiencing cardiac arrest by restoring normal heart rhythm have played a pivotal role in saving countless lives by restoring normal heart rhythms in cases of cardiac arrest. This paper aims to provide a comprehensive analysis of the history, development, functions, and design features of defibrillators. It explores the evolution of defibrillation technology, from early manual devices to modern automated systems, and delves into their intricate mechanisms and capabilities.

Keywords: defibrillator, history, development, functions, design features, biphasic waveforms, automated external defibrillator, cardioversion, synchronized cardioversion, usability, safety features.

1. Introduction

Defibrillators are a critical tool in the field of emergency medicine, as they are significantly improving the chances of survival for individuals experiencing cardiac arrest by restoring normal heart rhythm promptly. Their widespread availability and proper utilization are vital for effective cardiac emergency care. As a medical device, they are used to deliver an electric shock to the heart in order to restore normal heart rhythm in cases of life-threatening cardiac arrhythmias, particularly ventricular fibrillation and ventricular tachycardia. These abnormal rhythms can lead to cardiac arrest, a condition where the heart stops pumping blood effectively. Millions of people suffers from cardiac arrest leading to lost of lives (Liping et al., 2022). They work by delivering a controlled electric shock to the heart, either externally or internally, to interrupt the abnormal rhythm and allow the heart to reestablish its normal beating pattern. The electric shock depolarizes the heart muscle, temporarily stopping all electrical activity, and then allows the heart's natural pacemaker to resume its normal rhythm. Defibrillation is a critical step in the treatment of cardiac arrest as it can be the only way to restore a normal heart rhythm and save the life of the individual (Naser 2023).

The history of cardiac defibrillation therapy is long and fascinating, spanning several centuries, many countries and continents.

1.2 Types of Defibrillation Devices

There are different kinds of defibrillators in use today. They include the manual external defibrillator, manual internal defibrillator, automated external defibrillator (AED), implantable cardioverter-defibrillator (ICD), and wearable cardiac defibrillator.

1.2.1 Manual External Defibrillator

These defibrillators require more experience and training to effectively handle them. Hence, they are only common in hospitals and a few ambulances where capable hands are present. In conjunction with an ECG, the trained provider determines the cardiac rhythm and then manually determines the voltage and timing of the shock—through external paddles—to the patient’s chest.

1.2.2 Implantable Cardioverter Defibrillator

Another name for this is automatic internal cardiac defibrillator (AICD). They constantly monitor the patient’s heart, similar to a pacemaker, and can detect ventricular fibrillation, ventricular tachycardia, supraventricular tachycardia, and atrial fibrillation. When an abnormal rhythm is detected, the device automatically determines the voltage of the shock to restore cardiac function.

1.2.3 Manual Internal Defibrillator

The manual internal defibrillators use internal paddles to send the electric shock directly to the heart. They are used on open chests, so they are only common in the operating room. It was invented after 1959.

1.2.4 Automated External Defibrillator (AED)

These are defibrillators that use computer technology, thereby making it easy to analyze the heart's rhythm and effectively determine if the rhythm is shockable. They can be found in medical facilities, government offices, airports, hotels, sports stadiums, and schools.

1.2.5 Wearable Cardiac Defibrillator

Further research was done on the AICD to bring forth the wearable cardiac defibrillator, which is a portable external defibrillator generally indicated for patients who are not in an immediate need for an AICD. This device is capable of monitoring the patient 24-hours-a-day. It is only functional when it is worn and sends a shock to the heart whenever it is needed. However, it is scarce.

1.3 Defibrillators (AC and DC Defibrillators)

There are several different kinds of defibrillation devices as mentioned above, but the two major are (Roggers 2023). The automated external defibrillators (AEDs) are applied in emergency situations involving cardiac arrest. They are portable and often can be found in places where large numbers of people circulate, such as airports. Immediate emergency response that enables early defibrillation is central to the successful restoration of heart rhythm during cardiac arrest. Another major type of defibrillator is the automatic implantable cardioverter defibrillators (ICDs) used in patients at high risk of sustained or recurrent arrhythmia that has the potential to impair heart function. The ICD consists of a shock generator and wires with electrodes on both ends. The generator is implanted under the skin in the chest or abdomen and is connected to the wires, which are fed through a major vein to reach the atria or ventricles of the heart (Roggers 2023). Figure 1 is ICD while figure 2 is the AED. Implantable cardioverter defibrillators (ICDs) are electronic intricately designed with the purpose of detecting as well as terminating cardiac arrhythmias (Ammannaya, 2020)

Figure 1. Implantable Cardioverter Defibrillator

(https://www.britannica.com/science/defibrillation#ref1118177)

Figure 2. AED (Roggerw 2023)

2. Historical Development of Defibrillator

The history and evolution of the defibrillator is date back to the evolution of electricity which the death Queen Victoria died in 1901 as reported (Christine and Featherstone 2019). Industrial electricity was still in its infancy and the medical world was only on the cusp of understanding its potential risks and benefits.

Commercially electricity first became available in the 1870s (Christine and Featherstone 2019). The use of electricity, both direct current (DC) and alternating current (AC), resulted in many accidental deaths, particularly among power company employees, but the mechanism of death remained elusive. There were many theories - from a loss of magnetic properties in arterial blood to suffocation and heart failure - but insufficient evidence to support any of them (Christine and Featherstone 2019). The answered finally came in 1899, when independent research by Italian physiologists Jean Louis Prevost and Frederic Battelli, and RH Cunningham of Columbia University, demonstrated that strong electric shocks stopped the hearts of experimental animals. Prevost and Battelli discovered that some of the animals with ventricular fibrillation were restored to sinus rhythm by applying further current through electrodes in the mouth and small intestine. According to this, defibrillators were first demonstrated in 1899 by Jean-Louis Prévost and Frédéric Batelli, two physiologists from University of Geneva, Switzerland. They discovered that small electrical shocks could induce ventricular fibrillation in dogs, and that larger charges would reverse the condition (Naser 2023), several accounts on the historical development of defibrillator later ensues with other schallars contributing;

Augustus Desiré Waller made the first publication which accountsed for electro- cardiograph in 1887 (Beck et al. 1947) that paved way for Willem Einthoven to develop into a practical clinical tool (Zoll et al, 1956). Around the 1920s, arrhythmias was described and, the physiology of the heart became much clearer (Naser 2023). In 1940, Carl Wiggers and René Wégria conclusively demonstrated and established a brief electric shock 'induces fibrillation only when the shocks fall during the vulnerable period of late systole (Lown et al., 1962.).

Louise Robinovitch pioneered the use of medical electricity, noting that is possible to resuscitate (Einthoven 1912).

By the 1920s, alternating current had become the standard power and the few remaining DC generators were shut down. William Kouwenhoven and colleagues at Johns Hopkins University. conducted years of research into the effects of electricity on the heart, publishing several articles in the Journal of Physiology in the early 1930s. In 1933, acknowledging the earlier work of Prevost and Battelli, they definitively established that electrically induced ventricular fibrillation could be reversed with an appropriate counter-shock. (Naser 2023)

2.1 The First Defibrillation in Humans 1947-1950

Claude Beck an American cardiac surgeon prove the viability of defibrillating human beings. Claude Beck, Professor of Surgery at Case Western University, Cleveland, closely followed the work of Kouwenhoven and of Wiggers, developed an alternating current defibrillator for internal defibrillation (Naser 2023). (Lown et al. 1962) and (Zoll et al, 1956).

2.2 The First Portable External Defibrillator

Kouwenhoven in 1951, explored the AC power as a means of sustaining a portable defibrillator. By 1957, he concluded work on one of the original closed-chest defibrillators for human use. The device used AC electricity to deliver 480-volt shocks safely to the adult heart. The limitation was that it weighed over 250 pounds (120 kg), which made it completely impractical as a portable device. Kouwenhoven among his team, developed the first truly portable defibrillator in 1961 weighing about 45 pounds and was capable of fitting into a small suitcase (Naser 2023) figure 3 iilustrates the external defibrillator.

Figure 3 External Defibrillator (Mary Williams 2021)

Paul Zoll a Harvard cardiologist (Zoll et al. 1956). 1n 1956, Zoll reported four successes of patients reversed from ventricular fibrillation to sinus rhythm. Overall, 11 shocks were administered (Naser 2023). Naser (2023) availed that Bernard Lown and colleagues brought all the earlier research together in 1962 when they reported the use of DC current from a synchronised capacitor for the treatment of cardiac arrhythmias. They noted the work of Prevost and Battelli with DC current and Kouwenhoven and Zoll with AC defibrillators (Hana Akselrod et al. 2014), as well as important work by Czech and Russian researchers with DC square wave capacitor discharges (Einthoven 1912). The brief pulse wave generated by these capacitors allowed synchronization with any given part of the cardiac cycle. Lown's work allowed for synchronised shocks and the subsequent development of small portable defibrillators, a standard feature of modern resuscitation. It is now recognized that early defibrillation 'provides the best chance of survival in victims with VF or pulseless VT. (Gurvich 1952)

In early 1961, Bernard Lown of the Peter Bent Brigham Hospital in Boston, Mass, fortunately, and quite accidentally, met a brilliant young electrical engineer, Baruch Berkovits, who was helping Lown's laboratory with instruments for research projects unrelated to the problem of cardioversion and defibrillation. In April 1961, Lown formally asked Berkovits to study his DC defibrillator in canines and for possible clinical application. A series of intense experiments followed that involved testing the efficacy of multiple waveforms and evaluating the safety of DC shock in a very large number of canines. During these experiments, the Lown-Berkovits investigation group, aware of the importance of avoiding the vulnerable period, introduced for the first time the novel concept of synchronizing delivery of the shock with the QRS complex sensed from the ECG. It was fortunate that Barough Berkovits bridged the gap between East and the West by making the DC transthoracic cardioverter/defibrillator available to Dr Bernard Lown, an interested and dedicated clinician. Bernard Lown is credited in the Western world with initiating the modern era of cardioversion. He was the first in the West to combine defibrillation and cardioversion with portability and safety. In 1959, in a patient with recurrent bouts of ventricular tachycardia (VT), Lown was the first to transthoracically apply AC shock using the Zoll defibrillator to successfully terminate an arrhythmia other than VF. ((Zoll et al. 1956)

However, In the west the development of the portable defibrillator is accredited to Prof. Frank Pantridge in Belfast, who in the early 1960s developed the first truly portable device, weighing over 70Kg and needing its own vehicle to transport it! Today, portable defibrillators are among the many very important tools carried by ambulances and also used in public settings by lay-persons. They are the only provable way to resuscitate a person who has suffered a cardiac arrest unwitnessed by Emergency Medical Service (EMS) who are still in persistent ventricular fibrillation or ventricular tachycardia prior to the arrival of an ambulance. By 1968, Pantridge developed an improved portable defibrillator that weighed less than 7 pounds and was powered by a miniature capacitor designed by NASA. This small, lightweight device is often considered the first true portable AED on account of its size and power. Starting as early as the late 1960s, Pentridge's innovative designs were adopted in hospitals and ambulances throughout the world. Surprisingly, though, the technology caught fire internationally before it became a mainstay of his own homeland. Defibrillators wouldn't become standard in all UK ambulances until 1990. (Cakulev et al. 2009)

2.3 The Modern History of AEDs - 1978 to the Present

There were understandable concerns about entrusting untrained laypersons with equipment capable of emitting hundreds of volts of electrical shock to the heart. The solution would come from a group of colleagues in Portland, Oregon, in 1978. Physicians Arch Diack and W. Stanley Welborn collaborated with engineer Robert Rullman with the goal of developing a fool proof portable defibrillator that bystanders could safely use in an emergency, and so they developed the Heart-Aid, the first commercially available AED designed for minimally trained lay-providers. The device contained a specially designed sensor that an operator could insert into the patient's airway. The sensor could detect if a patient was breathing (and therefore not in cardiac arrest) and would then cease operations. A computer chip could also detect heart rate activity from the electrode and determine if a shockable rhythm was present. And so they developed Heart-Aid, the first commercially available AED designed for minimally trained lay-providers. The device contained a specially designed sensor that an operator could insert into the patient's airway. The sensor could detect if a patient was breathing (and therefore not in cardiac arrest) and would then cease operations. A computer chip could also detect heart rate activity from the electrode and determine if a shockable rhythm was present. An adhesive electrode pad made the device safe for untrained users, as it allowed the user to take a hands-off approach and avoid the kind of accidental shock that could result from improperly operating a paddle. Finally, the device was equipped with real-time voice coaching, so an untrained user could listen along and deliver emergency treatment. (Cakulev et al. 2009)

The 'father' of the modern AED, Professor James Francis (1916- 2004) was a physician and cardiologist from Northern Ireland who transformed emergency medicine and paramedic services with the invention of the portable defibrillator. The history of AEDs is still unfolding. Today, most devices weigh around 3 pounds-a far cry from the 250-pound "portable" defibrillator developed by William Kouwenhoven. Many deliver automatic shocks, and most are available for home use. Today's automated external defibrillators can assess heart rhythms, coaching users in real time, and administering automatic or semi-automatic shocks. (Ettl et al. 2023) The physiological basis of defibrillation involves the restoration of normal heart rhythm by delivering an electric shock to the heart. Defibrillation aims to terminate life-threatening cardiac arrhythmias, particularly ventricular fibrillation and ventricular tachycardia, which can lead to cardiac arrest if left untreated.

When the heart is in a normal rhythm, electrical signals travel through specialized pathways, causing the heart muscle to contract and pump blood effectively. However, in certain conditions, such as during arrhythmias, these electrical signals become chaotic, causing the heart muscle to quiver or beat rapidly and irregularly.

During ventricular fibrillation, the electrical signals in the heart become disorganized, resulting in a rapid and irregular quivering of the ventricles, the heart's main pumping chambers. This chaotic rhythm prevents the heart from effectively pumping blood to vital organs and tissues, leading to a lack of oxygen and potential organ damage.

Defibrillation works by delivering a controlled electric shock to the heart muscle, momentarily depolarizing the cells and stopping all electrical activity. The purpose of this brief electrical reset is to allow the heart's natural pacemaker, the sinoatrial (SA) node, to regain control and reestablish a normal sinus rhythm.

When the electric shock is applied, it depolarizes the cells of the heart muscle simultaneously, causing all the cells to reach a reset state. This reset interrupts the chaotic electrical activity, allowing the SA node to resume its role as the primary pacemaker.

The SA node initiates an electrical impulse, which then spreads through the heart's conduction system, coordinating the contraction of the atria (upper chambers) and subsequently the ventricles. This organized and synchronized contraction restores the heart's effective pumping action, ensuring the proper circulation of oxygenated blood to the body's organs and tissues.

It is important to note that defibrillation is most effective when applied promptly after the onset of ventricular fibrillation or ventricular tachycardia. The sooner defibrillation is performed, the higher the chance of successfully restoring a normal heart rhythm and improving the patient's outcomes.

In summary, defibrillation works by delivering an electric shock to the heart muscle, temporarily interrupting chaotic electrical activity, and allowing the heart's natural pacemaker to regain control and restore normal sinus rhythm. This process enables the heart to resume its coordinated pumping action and supply oxygenated blood to the body's vital organs, thus increasing the chances of survival in cases of life-threatening arrhythmias(Naser 2023).

2.4 The Uses and Functions of a Defibrillator are:

A defibrillator as a medical device that delivers an electric shock to the heart to restore its normal rhythm during cardiac arrest. It is a crucial tool used in emergency situations where a person's heart suddenly stops beating or starts beating abnormally below are the uses/functions of the defibrillator;

1. Treating cardiac arrest: The defibrillator is used to treat life-threatening cardiac arrest caused by abnormal heart rhythms such as ventricular fibrillation, ventricular tachycardia, and pulseless ventricular tachycardia.

2. Monitoring heart rhythms: The defibrillator can also be used to monitor the heart rhythm of a patient, especially those with a history of heart disease or certain medical conditions.

3. Assessing responses to medications: During a cardiac emergency, medications may be administered to help restore the heart's normal rhythm. A defibrillator can be used to assess the effectiveness of these medications.

4. Providing CPR assistance: Some defibrillators have built-in CPR assistance features that guide rescuers through chest compressions and breathing until medical personnel arrive.

5. Automated external defibrillator (AED): AEDs are portable defibrillators that are commonly found in public places such as airports, malls, and sports stadiums. They are designed for use by non-medical personnel in emergency situations.

3.0 The Working Principles of Defibrillator

The heart is able to perform the important function of blood pumping only through the synchronized of the heart muscle fibers if lost (Sreejith 2018). The technique of returning the fibers to its normal synchronized working is called defibrillation which consists of delivering a therapeutic dose of electric energy to the affected heart with a device called defibrillator (Sreejith 2018). Defibrillators can be external, transvenous or implanted based on the nature of device used. Depending on this fibrillation that is classified into atrial fibrillation of atrial muscles and the fibrillation of ventricles called ventricular fibrillation

The earlier mechanical methods such as heart massages for achieving synchronism of heart muscles were used. But the most successful method of defibrillation was proved to be an application of electrical shock to the area of the heart, if sufficient current was applied to stimulate all musculatures of the heart for a brief period of time fibrillation can be prevented. The early defibrillators used the alternating current which was transformed from normal line voltage up to 300-1000 volts from a power socket to the exposed heart by way of paddle type electrodes. This application of an electrical shock to resynchronize, the heart is called counter shock. If the patient does not respond, the technique was repeated until defibrillation occurs. This method of defibrillation was called AC defibrillation. Nowadays this type of defibrillation is not used because it has some disadvantages. This technique was often unsuccessful and showed harm to the cells of heart muscle post mortem. The nature of the AC machine with a large transformer also made these units very hard to move and they tended to be very large units. So DC defibrillators are commonly used now.

Bernard Lown, a scientist used an alternating technique which involved the charging of bank capacitors to approximately 1000 Volts and then delivering the charge through an inductance such as to produce a heavily damped sinusoidal wave of finite duration. The waveform was called Lown waveform (Figure 6) and is the standard for defibrillation. In the DC defibrillation technique, a capacitor was charged to a high dc voltage and then allowed to discharge rapidly. The defibrillator is designed in such a way that the capacitor is rapidly discharged through electrodes across the chest of the patient. The AC fibrillators cannot be used to correct atrial fibrillation effectively. But DC defibrillator can correct both atrial and ventricular defibrillation. This is an important advantage of DC defibrillators over the AC defibrillators (Abhilash and Narayanan 2014). The DC method requires fewer repetitions and most importantly, it is less likely to harm the patient. The circuit representation of a DC defibrillator is shown below (Figure 4)

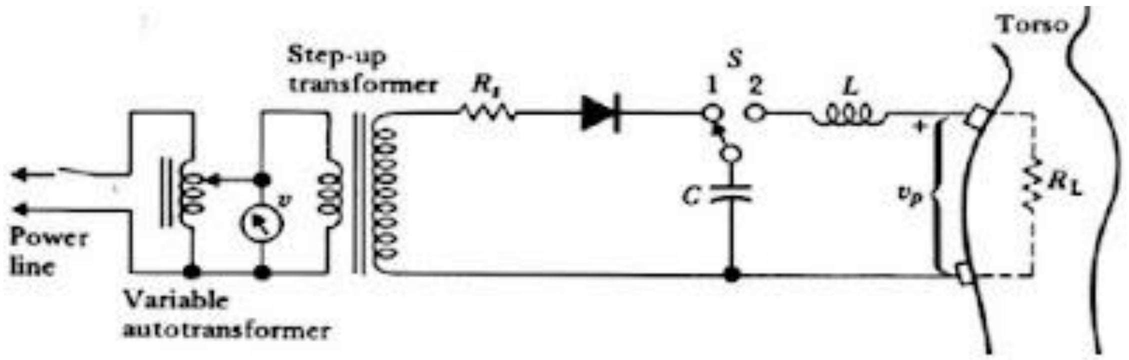

Figure 4: DC Defibrillator (Sreejith 2018).

3.1 DC Defibrillators Analysis

The secondary winding of the defibrillator in figure 5. They are connected to the electrodes that delivers electric shock to the heart of the patient. Voltage value ranging between 250 V to 750 V is applied for DC defibrillator does not produce side effects and produces normal heartbeat. Ventricular fibrillation is avoided when high-energy shock is passed through discharging capacitor that is exposed to heart or chest of the patient. The DC defibrillator consists of auto transformer T1 that acts as primary of the high voltage transformer T2.

A diode rectifier rectifies the output voltage from T2. It is connected to vacuum type-high voltage over switch. At position A, switch is connected to one end of the capacitor. When connected in this position capacitor charges to a voltage. A foot switch present on the handle of the electrode is used to deliver shock to the patient. Now the high voltage switch changes it position to B that makes the capacitor to discharge to the heart through electrodes. To slow down the discharge from the capacitor an inductor L is placed in one of the electrode lead. This L induces a counter voltage that reduces the capacitor discharge value.

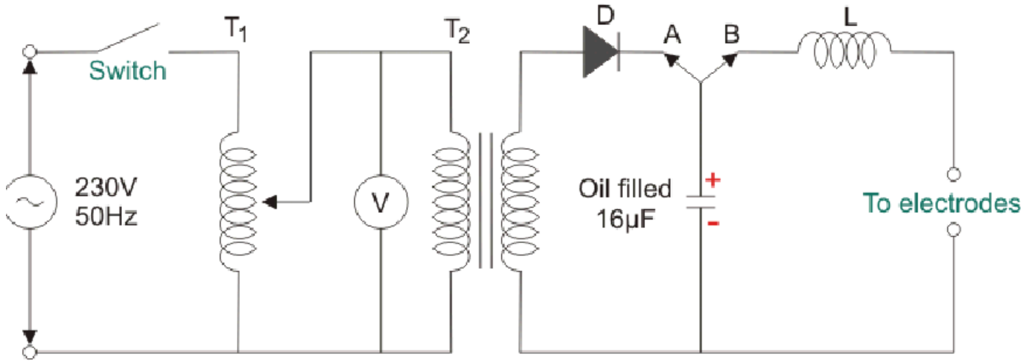

Figure 5 DC Defribillator

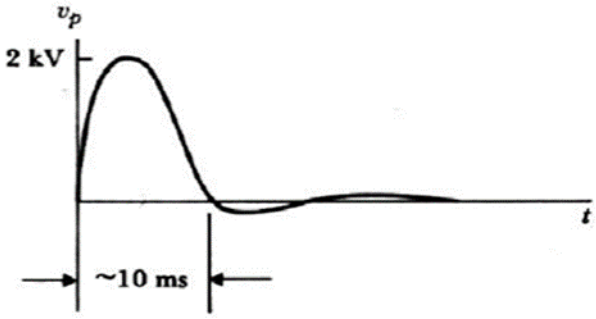

Figure 6: Lown waveform (Sreejith 2018).

The electrodes are the components through which the defibrillator used for delivers energy to the patient's heart. Many types of electrodes such as hand-held paddles, internal paddles, pre-gelled disposable electrodes etc. Disposable electrodes are used in emergency conditions because they have the advantages such as increasing the speed of shock and improving defibrillation technique. Larger paddles create a lower resistance and allows more current to reach the heart, so larger paddles are desirable.

Figure 6 shows a circuit diagram showing the simplest defibrillator desire depending on the inductor damping producing Lown waveform. In a defibrillator, the amount of electrical energy discharged by the capacitor may range from 100-400 Joules. The duration of discharge is 3-5 milliseconds, From the DC defibrillator discharge waveform (Sreejith 2018).

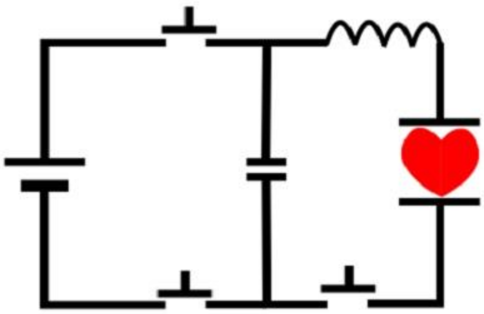

Figure 7 Simplest defibrillator (Sreejith 2018).

Several research studies showed that a biphasic truncated waveform (BTE) was equally effective when requiring lower levels of energy to produce defibrillation. Biphasic defibrillation was originally developed and is used for implantable defibrillators. When applied to external defibrillators, the biphasic defibrillation decreases the energy level necessary for successful defibrillation. So this dual peak waveform of longer duration is having less risk of damaging the myocardium. Biphasic waveforms deliver current that first flows in a positive direction for a specified duration. ln the second phase the device reverses the direction of current. The biphasic shocks appear to achieve the same defibrillation success rates as monophasic waveforms but at a significantly lower energy levels. The waveform is shown in figure. Another DC defibrillator wave is the tapered delay wave (figure). It has lower amplitude of around 700-800 Volts and much longer duration than the other two types of waveform. Here the energy delivered to the patient by the defibrillator is proportional to the area under the square of the curve.

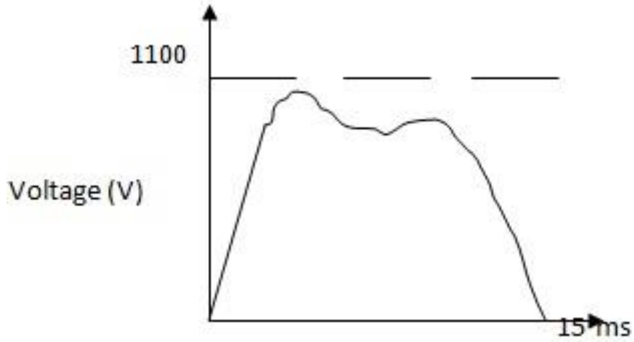

Figure 8 Biphasic truncated waveform (Sreejith 2018).

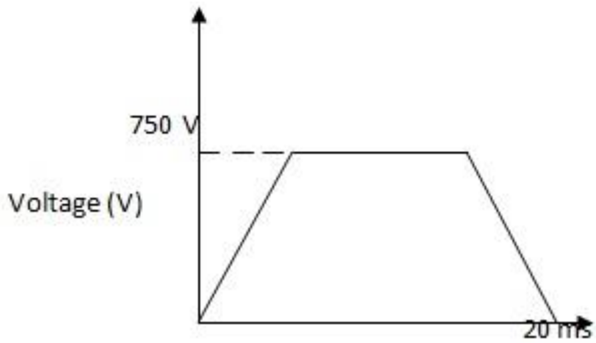

Figure 9 Tapered delay wave (Sreejith 2018).

4. Conclusion

Defibrillators as critical tools in the field of emergency medicine are significantly improving the chances of survival for individuals experiencing cardiac arrest by restoring normal heart rhythm have played a pivotal role in saving countless lives by restoring normal heart rhythms in cases of cardiac arrest. Defibrillators are critical resuscitation devices. The use of reliable defibrillators has led to more effective treatments and improved patient safety through better control and management of complications during Cardiopulmonary Resuscitation (CPR). We take for granted how intuitive these devices are, but it's been a long and complicated journey from experiment on animals to defibrillation-on-demand. The complete history of AEDs is complex and compelling. They're low-maintenance, easy to operate, and constantly improving as new technologies emerge. Different types of defibrillators work in different ways. Automated external defibrillators (AEDs), which are now found in many public spaces, are used to save the lives of people experiencing cardiac arrest. Even untrained bystanders can use these devices in an emergency. As lifesaving devices used to restore the normal rhythm of the heart during a cardiac emergency. They are crucial tools in ambulance services, hospitals, emergency rooms, and public places to manage sudden cardiac arrests. This paper provide a comprehensive analysis of the history, development, functions, and design features of defibrillators. It explores the evolution of defibrillation technology, from early manual devices to modern automated systems, and delves into their intricate mechanisms and capabilities.

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