Physical Principles of Defibrillators

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Defibrillation is the application of a preset electrical current across the myocardium to cause synchronous depolarization of the cardiac muscle with the aim of converting a dysrhythmia into normal sinus rhythm. Over 135,000 people die annually following acute myocardial infarction. The main cause of sudden death is ventricular fibrillation; the only effective treatment for which is early defibrillation. The defibrillator was invented in 1932 by Dr William Bennett Kouwenhoven.

Capacitors
The most important component of a defibrillator is a capacitor that stores a large amount of energy in the form of electrical charge, then releases it over a short period of time. A capacitor consists of a pair of conductors (e.g. metal plates) separated by an insulator (called a dielectric). Conductors lose and gain electrons easily, and therefore allow current to flow; whereas insulators do not lose their electrons, and hardly allow any current to flow. The maximum working voltage is the voltage that when exceeded causes the dielectric to break down and conduct, often with catastrophic results.

The unit of electric charge (Q) is the coulomb (C). 1 coulomb is the quantity of electricity transported in 1 s by a current of 1 ampere (A) and is equivalent to 6.24 x 10^18 electrons (Figure 1).

Capacitance (C) is the ability to store charge. A capacitor has 1 farad of capacitance if a potential difference of 1 volt is present across its plates, when a charge of 1 coulomb is held by them (i.e. C = Q/V). Capacitors typically have values of microfarads (µF = 10^-6 F), nanofarads (nF = 10^-9 F) or picofarads (pF = 10^-12 F). For a simple capacitor, the capacitance is proportional to the area over which the plates overlap (A), inversely proportional to their distance apart (D), and related to the dielectric constant (E₀). Thus C α A/D. E₀.
Figure 2 shows a defibrillator. When the switch is in position 1, direct current (DC) from the power supply is applied to the capacitor. Electrons flow from the upper plate to the positive terminal of the power supply and from the negative terminal of the power supply to the lower plate. Therefore current flows and a charge begins to build up on each electrode of the capacitor, with the lower plate becoming increasingly negatively charged, and the upper plate increasingly positively charged. As the charge builds up on the plates, it creates a potential difference across the plates (V), which opposes the electromagnetic force of the power supply (E). Initially when there is no charge on the plates, V is zero and it is easy to move electrons onto the plates. As V increases, however, it opposes further movement of electrons, and increasing work must be done to move more electrons onto the plates. The work done (W) to move charge (Q) through a potential difference V is: \( W = VQ \). Charging a capacitor is therefore an exponential process, with a time constant determined by the capacitance and the resistance of the circuit through which the current flows (Figure 3). When V equals E, the current ceases to flow and the capacitor is fully charged. In this example, the amount of charge stored \( Q = CV \) is 32 \( \mu \)F x 5000 V = 160 mC.

Work must be done against the field to store charge in the capacitor. The charged capacitor is therefore a store of potential energy, which may be released on discharge. Theoretically, the amount of energy stored in a capacitor is CV.

When the paddles are applied to the patient’s chest and the switch is moved to position 2, a circuit is completed. Electrons stored on the lower (negative) plate of the capacitor are able to pass through the patient and back to the upper plate. Thus, current flows, stored electrical energy is released, and the potential difference across the plates (V) falls to zero (i.e. the capacitor is discharged). The rate of discharge declines as the potential difference across the plates falls; it is an exponential process (Figure 4) with a time constant determined by the capacitance and the resistance of the circuit through which the current flows.

The energy delivered may be calculated from: Energy (J) = \( 1/2 \times \) stored charge \( \times \) Potential (V) (i.e. Energy = QV/2). Thus, 400 J = \( 1/2 \times 160 \text{ mC} \times 5000 \text{ V} \). The apparent loss of half of the stored charge on discharge is due to circuit resistance, radiation and arcing of switch contacts.

Inductors
For successful defibrillation, the current delivered must be maintained for several milliseconds. However, the current and charge delivered by a discharging capacitor decay rapidly and exponentially. Inductors are therefore used to prolong the duration of current flow. They are coils of wire that produce a magnetic field when current flows through them. When current passes through an inductor, it generates a flow of electricity in the opposite direction which opposes current flow as predicted by Faraday’s law of electromagnetic induction. This opposition to current flow is called inductance (L) and is measured in henries (H). Inductors typically have values of microhenries (\( \mu \)H).

Power supply
Step-up transformers are used to convert the mains voltage of 240 V AC to 5000 V AC. This is then converted to 5000 V DC by...
a rectifier. In practice, a variable voltage step-up transformer is used so that different amounts of charge may be selected by the clinician. The control switch is calibrated in energy delivered to the patient (J), because this determines the clinical effect. If a mains supply is unavailable, most defibrillators have internal rechargeable batteries. These supply DC, which is then converted to AC by means of an inverter, and then amplified to 5000 V DC by a step-up transformer and rectifier as above.

**Patient factors**

Successful defibrillation depends on delivery of the electrical charge to the myocardium. Only part of the total current delivered (about 35 A) flows through the heart. The rest is dissipated through the resistance of the skin and the rest of the body. The impedance of skin and thoracic wall act as resistances in series, and the impedance of other intrathoracic structures act as resistances in parallel with the myocardium. The total impedance is about 50–150 $\Omega$, however, repeated administration of shocks in quick succession reduces impedance.

**Safety**

**Patient**: before administering the charge, it is essential to make the correct diagnosis to avoid defibrillating a patient who is already in sinus rhythm. If a defibrillator monitor is being used, check that the leads are correctly connected, and whether the device is monitoring from the paddles or from chest electrodes.

The paddles should be placed across the long axis of the heart to facilitate effective defibrillation. The paddles should not be placed over transdermal patches, because they may block current delivery or if they contain an inflammable substance (e.g. glyceryl trinitrate) may result in burns or explosion. The paddles should not be placed near metal objects, either on the surface of the skin (e.g. ECG leads or electrodes, skin clips, jewellery), or subcutaneously (e.g. implanted pacemakers), because the current follows the path of least resistance through the metal, resulting in heating or burns. The paddle size should be appropriate for the patient (typically 13 cm diameter for adults): large enough to prevent burns but small enough to deliver an adequate current density.

Conductive gel pads and firm pressure (about 10 kg force) are used to improve electrical contact between the paddles and the patient’s chest. Liquid electrode gel should not be used, because excess may cause arcing across the surface of the chest wall or the operator’s hands.

All sources of oxygen must be removed from the patient during defibrillation, because it supports combustion if arcing occurs.

**Staff** should not touch the bed, patient or any equipment connected to the patient during defibrillation. Fluids may conduct electricity, therefore it is important to ensure that the immediate area is clean and dry. The defibrillator should not be charged until the paddles are applied to the patient’s chest, because accidental discharge from open paddles may cause injury or death. The operator must not touch any part of the paddle electrodes. Before administering the charge, the operator must shout “Stand clear!” and check that all staff have done so.

If the defibrillator is charged but a shock is no longer indicated, it should be discharged through the defibrillator internally by turning the control knob to zero before removing the paddles from the patient’s chest: charged paddles should never be returned to the defibrillator.

**Equipment** that does not have the ‘defibrillator protected’ symbol (Figure 5) should be disconnected from the patient before defibrillation to prevent damage, heating or arcing effects. The defibrillator should never be discharged with the paddles shorted together, as this may cause burning and damage to the electrical contacts.

**FURTHER READING**
