Modified alternating current defibrillation: a new defibrillation technique

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Aims
Defibrillation is the only clinically effective treatment for ventricular fibrillation (VF). Early defibrillation improves the outcome and increases the chance of survival with full recovery. Immediate availability of a home-based defibrillator using mains-derived alternating current (AC) current will drastically improve the outcome. The aim was to develop a defibrillator based on the modulated AC, resembling biphasic configuration, and compare its efficacy, in a pig model, with a standard direct current (DC) defibrillator.

Methods and results
A computer controlled, modulated AC defibrillation system was developed using a high-voltage switch and a high-voltage transformer. The efficacy and safety was evaluated in five pigs (30–40 kg), under general anaesthesia with ketamine and isoflurane. A single quadripolar-pacing catheter was inserted percutaneously. Ventricular fibrillation was induced with rapid ventricular burst pacing, and stable VF was defibrillated after 15 s. Defibrillation threshold (DFT) was determined in each animal with AC and standard DC shock using the step-down protocol. A biphasic-like shock was used with a short isoelectric stage between the phases. The DFT with AC was 70.83 ± 24.81 J and with DC was 65.83 ± 12.41 J (P = 0.49). No macroscopic damage was observed after AC or DC defibrillation.

Conclusion
Modulated AC defibrillation is safe and effective as the commercially available DC defibrillation. The defibrillator is built from an inexpensive high-voltage transformer, without the need for capacitor, batteries, or routine maintenance, delivers repeated shock without any delay, and provides pacing as well. It may be an ideal platform for automatic home defibrillator.

Keywords
Defibrillation • Experimental study • Automatic external defibrillator • Home defibrillation

Introduction
Cardiac defibrillation is the standard treatment of sudden cardiac death, usually caused by malignant ventricular arrhythmias, both ventricular fibrillation (VF) and haemodynamically unstable ventricular tachycardia. Although this therapy is unanimously accepted and is still the only clinically relevant way to terminate these arrhythmias, its history is merely half-a-decade old. During 50 years, the first human defibrillation used alternating current (AC) shock and it was rapidly implemented in clinical practice. Soon, this defibrillation method was replaced with the monophasic direct current (DC) shock, then with the biphasic shock for both external and internal defibrillation. The DC shock requires charging of capacitors than a sudden discharge delivers a truncated shock. Therefore, it has become clear that only very early defibrillation may save life and may prevent irreversible anoxic brain damage. For more efficient therapy of sudden cardiac death, automatic defibrillators were located in public areas. However, most of the sudden cardiac death occurs at home. A logical extension of public access defibrillation is the home defibrillation and ideally an automatic defibrillator has to be placed in each house. A low-cost, but effective defibrillator is a prerequisite for such a vast location of defibrillation devices. Our aim was to develop a new defibrillation shock based on the modified alternating current (MAC) mimicking the routinely used DC defibrillation shocks and to evaluate, in a pig model, the efficacy of this modulated AC shock by comparing it with the best available DC shocks.

Methods
The Animal Ethics Committee at Hadassah Hebrew University Medical School approved the study.
General anaesthesia was achieved with ketamin and isofluran in five small pigs, 30 ± 5 kg each, and the animals were ventilated through a tracheal tube using a standard ventilator. High level of anaesthesia was ensured and a high level of arterial blood oxygenation was maintained during the whole experience.

The right femoral vein or the right internal jugular vein was cannulated with a 6 Fr quadripolar pacing-recording electrophysiology catheter with a 5 mm inter-pole distance, which was inserted in the right ventricular apex. This catheter was used to induce VF with rapid burst pacing (50 Hz pacing) and backup pacing if needed. The blood pressure was monitored through a 4 Fr catheter in the right femoral artery. Capillary oxygen saturation and end expiratory CO₂ were also monitored.

Heart rhythm, blood pressure, and the defibrillator activity were recorded using LabChart 5 software on PowerLab recording system (ADInstruments, Colorado Springs, Co, USA). The number of animals was limited to five as the results were repetitive and to avoid unnecessary animal sacrifice.

Modulated alternating current defibrillator

Figure 1A shows the simplified diagram of the modulated AC defibrillator. The power source is the regular home electrical current and the current is conducted, under automatic or manual, to a computerized high-voltage switch and current control and subsequently to the high-voltage transformer. From there, the modulated current is delivered to the pads for external defibrillation. The high-voltage switch and current controller performs the current modulation and monophasic-like, simple biphasic-like, and advanced biphasic-like shocks could be delivered (Figure 1B). Monophasic-like shock was obtained by using only half of the cycle and only in one direction. The simple biphasic-like shock was built on the whole cycle in both directions without an iso-electric interval between the two phases. The advanced biphasic-like shock had in addition a short biphasic interval between the two phases. The shocks can be delivered without any delay. There is no capacitor to be charged. Monophasic-like shock was not used in this study.

Ventricular fibrillation induction and defibrillation

Ventricular fibrillation was induced with rapid burst pacing, 50 Hz pacing, using a costume-made fibrillator. After 15–20 s of fibrillation, a defibrillation shock was delivered. The defibrillation threshold (DFT) with MAC and DC shocks were determined. A step-down method was used to determine the DFT. The threshold was confirmed with an additional defibrillation attempt at the same energy level and shock waveform. In each animal, if the first tested shock was the MAC, the second was the DC, and if the first was DC, the second was MAC. In the second subject, two separate tests were completed before the animal was sacrificed. Three tests were started with MAC defibrillation and three tests with DC defibrillation.

Statistical methods

The DFTs were compared using Student’s t-test. A P < 0.05 was considered significant. Prizm 4 for Macintosh (GraphPad Software Inc, San Diego, CA, USA) and SPSS 13 for Macintosh (SPSS Inc., Chicago, IL, USA) were used for statistical work-up.

**Table 1** Defibrillation Threshold with MAC and DC defibrillation

<table>
<thead>
<tr>
<th>Subject</th>
<th>MAC DFT</th>
<th>DC DFT</th>
<th>Type of MAC shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>113</td>
<td>75</td>
<td>Simple biphasic</td>
</tr>
<tr>
<td>2a</td>
<td>75</td>
<td>75</td>
<td>Advanced biphasic</td>
</tr>
<tr>
<td>2b</td>
<td>75</td>
<td>75</td>
<td>Advanced biphasic</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>50</td>
<td>Advanced biphasic</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
<td>50</td>
<td>Advanced biphasic</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>70</td>
<td>Advanced biphasic</td>
</tr>
<tr>
<td>Mean</td>
<td>70.8 ± 24.8*</td>
<td>65.8 ± 12.4</td>
<td>MAC DFT, modified alternating current defibrillation threshold; DC DFT, direct current defibrillation threshold.</td>
</tr>
</tbody>
</table>

*P = NS (MAC DFT vs. DC DFT).
Results

The mean DFT was 70.83 ± 24.81 J with MAC defibrillation and 65.83 ± 12.42 J with DC defibrillation (P = 0.743). The minimal, but non-significant, difference was because of a different wavefront used in the first animal, the classical biphasic vs. the advanced biphasic in the rest of the experiment (Table 1).

Figure 2 (A) Successful modified alternating current defibrillation and (B) failed modified alternating current defibrillation with rescue modified alternating current shock.
A total of 49 MAC defibrillation attempts and 25 DC defibrillation attempts were performed, during six evaluations in five pigs. The MAC defibrillator prototype has delivered all the shocks as expected. The device was tested before the study with more than 1000 shocks delivered in vitro.

Figure 2 shows a typical successful (Figure 2A) and failed (Figure 2B) MAC defibrillation. Figure 3 shows a typical classical biphasic and advanced biphasic shocks (Figure 3A and B). The delivered voltage, current, and energy, and the dynamics of the impedance of the advanced biphasic shock are also shown (Figure 3C–E). The voltage and the current had the same configuration (Figure 3B and C) and the energy was cumulative (Figure 3E), which shows the accuracy of the delivered energy of 100 J. The impedance is dynamic (Figure 3D), starting

**Figure 3** Real-time shocks characteristics: (A) classical biphasic (current); (B) advanced biphasic (current), a short isoelectric phase is added between the phases; (C) advanced biphasic (voltage); (D) impedance during advanced biphasic shock; and (E) cumulative 100 J shock.
at high impedance and decreasing logarithmically during both phases.

Any configuration could be achieved within the limits of the sinusoidal waveform. After the modulation, the high-voltage transformer amplified the shocks. The delivered energy confirmed the accuracy of the amplification (Figure 3E).

At the end of the tests, no skin burns were observed and the heart functioned normally, with immediate recovery of the blood pressure (Figure 2).

Discussion
The main finding of this study was that the MAC defibrillation mimicking biphasic DC defibrillation was not inferior to the best available biphasic DC defibrillation, and both defibrillation methods had similar DFT. The defibrillator delivered reliable MAC shocks repeatedly for unlimited times, without the need for charging time as in the conventional DC defibrillation.

Alternating current and direct current defibrillation
The first energy used for experimental and thereafter clinical defibrillation was the AC shock.3–6 The effectiveness of this AC shock was dependent on the amplitude and duration of the applied current. High-amplitude current did not induce fibrillation and low-amplitude current did not terminate the fibrillation, suggesting the lower and upper limit of vulnerability.3–6 A second observation in this early study was that the delivery of the current has to be sudden and not a gradual increase from low amplitude to high amplitude.5 Despite this elegant animal study, the first human defibrillation was performed much later and a general clinical acceptance of this method was even later.5–7 However, the AC shock was replaced with a much more efficient DC shock, which is achieved by a sudden discharge of a capacitor.5–9 The duration and the strength of the DC shock are dependent on the capacitor properties. The time for the repeated shock is prolonged because of the need for capacitor recharging.

Although the energy used in our defibrillator was the AC, the delivered waveform mimicked the most advanced biphasic DC shock. Our device incorporated the advantage of AC shock and those of the biphasic DC shocks. The MAC shock does not require a capacitor charging that delays the shock delivery, and it is not dependent on the capacitor properties. The biphasic DC shock is the most efficient shock waveform used today. When the waveform was adjusted to the advanced biphasic waveform, the DFT was identical to that of the regular biphasic DC shock. This type of defibrillator is based on DC defibrillation mechanisms27 and not on to the suggested AC defibrillations mechanisms.28–29

Because the plasticity of the waveform generated by our device, other wave combinations are also feasible in the limits of the AC cycle and further research is needed to evaluate their efficacy. Bradycardia pacing may also be implemented in this device, without compromising the battery longevity. Although a recent study failed to demonstrate the benefit of home defibrillation in a particular group of patients,30 a long-term impact of defibrillator in every house was still not evaluated. The hardware of our defibrillator is build on low-cost components and for this reason it may be considered as appropriate for home defibrillators.

Limitations
The number of test animals was limited to five. As the results were repetitive after implementation of the advanced biphasic type shock, further animals could not change the result without changing the waveform in the MAC defibrillation. Increasing the number of tested animals would cause unnecessary animal sacrifice without significant additional information. The second limitation at this time is that the device can be used only with direct connection to the electrical network. A future variant will be supplied by other electricity sources too. The third limitation is that the hearts were evaluated only macroscopically. As each animal received multiple MAC and DC shocks, the microscopic changes may not be relevant. However, for final prove of safety with this MAC shocks, the microscopic effect on the heart muscle will be evaluated.

Conclusions
In our pig model, AC defibrillations using a modulated AC shock, mimicking the biphasic DC shock, are as effective as the most advanced biphasic DC defibrillation. The simplicity of its use, the possibility of immediate shock delivery, and the low cost of the components make this type of defibrillation ideal for automatic external home defibrillation. Because the flexibility of the waveform generation, further improving of the defibrillation efficacy is foreseen, making this device even more suitable in the service of reducing the vast amount of sudden cardiac death worldwide.

Conflict of interest: none declared.

References