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Experimental paper

The effects of second and third phase duration on defibrillation efficacy of triphasic rectangle waveforms☆

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ABSTRACT

Background: Biphasic waveforms are superior to monophasic waveforms for the termination of ventricular fibrillation (VF). However, whether triphasic waveforms are more effective than biphasic ones is still controversial. In the present study, we investigated the effects of second and third phase duration of triphasic rectangle waveform on defibrillation efficacy in a rabbit model of VF.
Methods: VF was electrically induced and untreated for 30 s in 20 New Zealand rabbits. A defibrillatory shock was applied with one of the 7 waveforms: 6 triphasic rectangle waveforms and a biphasic rectangle waveform. The triphasic waveforms had identical first duration but with different second and third phase durations. A 5 step up-and-down protocol was utilized for determining the defibrillation threshold (DFT). After a 5 min interval, the procedure was repeated. A total of 35 cardiac arrest events and defibrillations were investigated for each animal.
Results: Two triphasic waveforms with identical first and second phase duration but shorter third phase duration had significantly lower DFT energy than biphasic waveform (0.57 ± 0.18 J vs. 0.80 ± 0.28 J, $p = 0.001$; 0.60 ± 0.18 J vs. 0.80 ± 0.28 J, $p = 0.003$). However, no statistical difference in DFT energy was observed between the two triaphsic waveforms that had identical phase duration but different voltages (0.57 ± 0.18 J vs. 0.60 ± 0.18 J, $p = 0.638$).
Conclusions: Phase durations played a main role on defibrillation success for triphasic rectangle waveforms. The optimal triphasic rectangle waveforms that composed of identical second and first phase durations but with shorter third pulse were superior to biphasic rectangle waveform for ventricular defibrillation.

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Introduction

With an incidence ranging from 35 to 125 cases per 100,000 people, out-of-hospital cardiac arrest (OHCA) remains a major public health problem all over the world.[1] The percentage of ventricular fibrillation (VF) decreased over the past 20 years, while the incidences and the average survival to discharge did not change demonstrably.[1] Electrical defibrillation, which consists of delivering of a therapeutic dose of electrical current to the fibrillating heart with the aid of a device known as defibrillator, is still the only effective way to treat this life-threatening arrhythmia.[2]

Since characteristics of defibrillation waveform are associated with defibrillation efficacy and affect the cardiac damage caused by a shock, multiple waveforms have been designed for clinical application.[3] For decades, external defibrillators have used monophasic waveforms. Although monophasic defibrillation was recognized to be highly effective for the termination of VF, but risk of post-shock complications such as myocardial dysfunction and skin burns was high.[4]

Compared with monophasic waveforms, biphasic waveforms that consisting of two phases of opposite polarity significantly decreased the shock strength needed for defibrillation and caused less myocardial dysfunction.[5] The second phase of the biphasic shock is believed to neutralize virtual electrodes and tissue polarization residual from the first phase.[6] The biphasic waveforms are more effective than monophasic waveforms due to a lesser tendency to re-initiate VF from regions of residual charge left on the myocardium.

Even though biphasic defibrillation is more efficient than monophasic defibrillation, researches for more efficient low energy defibrillation are continuing. Triphasic waveforms, which composed of three pulses with the polarity of the second pulse reversed

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have been evaluated but with controversial results: some studies demonstrated that triphasic waveform was more effective for ventricular defibrillation than biphasic ones,[7–10] whereas other studies reported that adding an additional phase to a biphasic waveform did not necessarily improve defibrillation efficacy.[11–15] The inconsistency might resulted from the difference in the waveform design since earlier studies explored that defibrillation efficacy was influenced by the duration, tilt, amplitude, and polarity of each phase of biphasic shocks.[16–26] The optimal parameters of triphasic waveforms, however, have not been identified.

In the present study, we evaluated the effects of second and third phase duration of triphasic rectangle waveform on defibrillation efficacy in a rabbit model of VF. We hypothesized that triphasic rectangle waveforms with optimal phase durations are more effective than biphasic waveform for ventricular defibrillation.

Methods

Study design and institution review

This prospective, randomized animal study was designed to evaluate the effects of second and third phase duration of triphasic rectangle waveform on efficacy of transthoracic defibrillation, in which each animal served as its own control. This study was approved by the animal investigation committee of Third Military Medical University. All animals received humane care in compliance with the Principles of Laboratory Animal Care and Guide for the Care and Use of Laboratory Animals.

Animal preparation

Twenty New Zealand rabbits of both sexes, weighing between 1.7 and 2.5 kg, were utilized for the proposed study. This model was used because earlier studies demonstrated that the rabbit ventricular action potentials resembled the human and this model was suitable for assessing electrical fibrillation and defibrillation mechanisms.[27,28] The experimental animal was fasted overnight except for free access to water. Anesthesia was initiated by ear vein injection of sodium pentobarbital at a dose of 30 mg kg^{-1}. After placing on a surgical board in the supine position, the tracheas of the animals were intubated through a tracheotomy with a 11-gauge cannula and mechanically ventilated with a tidal volume of 0.60 mL/100 g at a FiO_2 of 0.21 (ALC-V8, Alcott Biotech Co. Ltd, Shanghai, China). A side steam infrared CO_2 analyzer (Model: C300, National Medical co. ltd, Beijing, China) was used to monitor End-tidal P_{CO_2} $\left(P_{etCO_2}\right)$. Respiratory frequency was adjusted to maintain P_{etCO_2} between 36 mmHg and 42 mmHg before inducing cardiac arrest and when mechanical ventilation was resumed after resuscitation. A PE-160 catheter was inserted into the surgically exposed right femoral artery for measurement of arterial pressure. For induction of VF, a 5-French pacing catheter was advanced from the right external jugular vein into the right ventricle. Electrocardiogram (ECG) signal was obtained using three adhesive electrodes applied to the shaved skin of the right upper, left upper, and lower limbs. Arterial pressure and conventional lead II ECG was continuously measured by a multiparameter monitor (Model 90369, Spacelabs, Snoqualmie, WA, USA). Rectal temperature was monitored by a thermocouple probe (TH-212, Bjhocy science and technology Co. Ltd., Beijing, China) that was placed into the rectum and maintained between 37.5 °C and 38.0 °C by a heating lamp.

Defibrillation system and electrodes placement

A custom-built defibrillation system, which was capable of delivering biphasic or triphasic rectangle waveform shocks with adjustable polarity, pulse duration, and phasic voltage, was used for this experiment. As shown in Fig. 1, the desired waveform was generated by the MCU-based (Model: MSP430F149, Texas Instruments. Inc, Dallas, TX, USA) arbitrary waveform generator and then amplified through a high voltage power amplifier (MCF10000, Yutian electrical technology, Zhengzhou, China). Another commercially available defibrillator (Zoll M series CCT, Zoll Medical corporation, Chelmsford, MA, USA) placed in parallel with the custom-built defibrillation system through a defibrillation source switch, was used to deliver rescuer shock if the custom-built defibrillation system failed to terminate VF. A break-out box with a built-in high voltage probe and current probe was connected to the defibrillation system and the animal. The defibrillation voltage and current waveforms delivered to the animal were simultaneously recorded with a high speed USB data acquisition system (Model: DI-730-USB, Dataq instruments, Akron, OH, USA).

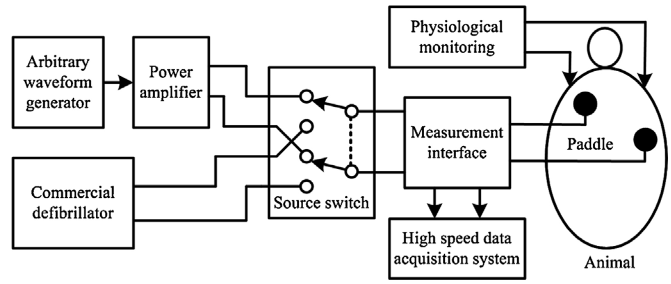

Fig. 1. Schematic illustration of the experimental setup.

A pair of external defibrillation pads (Ø = 40 mm) was attached on the right and left side of chest, with the positive electrode placed at the right side and the negative electrode placed at the left side so that the heart was directly interposed between the two electrodes. An electrically conductive adhesive gel (SIGNA GEL, Parker Laboratories Inc, Fairfield, NJ, USA) was then interposed between the pads and the skin.

Defibrillation waveforms

In order to select the potential triphasic waveforms that may superior to biphasic waveform, a preliminary experiment was performed in 17 rabbits with 4 biphasic and 36 triphasic waveforms. After a lengthy investigation, we retrospectively selected 7 defibrillation waveforms, which included 6 triphasic rectangle waveforms of different durations and shapes and a biphasic rectangle waveform (Fig. 2). These waveforms differed from the traditional truncated exponential waveforms by having rectangle pulses since earlier studies demonstrated that rectangle waveform was more efficient than the exponential ones.[29–31] The triphasic rectangle waveforms had identical first phase duration, but with different second and third phase durations and shapes. The three phase voltage ratio was 1:0.6:0.4 for triphasic A1 (4 ms/4 ms/2 ms), A2 (4 ms/4 ms/4 ms), and A3 (4 ms/6 ms/4 ms). For triphasic B1 (4 ms/4 ms/2 ms), B2 (4 ms/4 ms/4 ms) and B3 (4 ms/6 ms/4 ms), the three phase voltage ratio was 0.5:1:0.5. A biphasic rectangle waveform with a first phase duration of 6 ms and a second phase duration of 4 ms (phase voltage ratio 1:0.5), which was demonstrated to be efficient for transthoracic defibrillation in study, served as control.[31]

Experiment procedures

After measurement of baseline hemodynamics and P_{etCO_2}, VF was induced by delivering a 50 Hz AC current of 2–5 mA into the right ventricular endocardium and was confirmed by the sudden decrease of arterial pressure and absence of pulse. After 30 s of untreated VF, a test shock was delivered from the custom-built

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