The Investigation of Exponential and Rectangular Monophasic Defibrillation Pulses in the Langendorff-Perfused Rabbit Heart

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Summary

The pulse form for defibrillation of ventricular fibrillation is the subject of this study. There are a number of values that have an influence on the defibrillation threshold. These include the pulse duration and the capacitance of the capacitor used in the defibrillator. The experiments were performed on a rabbit heart perfused through Langendorff's method. The heart was set into fibrillation with a 50 Hz alternating current. After > 5 seconds of ongoing fibrillation, a defibrillation pulse was delivered. Different defibrillators were used in the experiments. The first defibrillator ($defib_{max}$) was equipped with a 1250 µF capacitor and could create almost ideal rectangular pulse forms. In comparison, a second defibrillator ($defib_{min}$) with a discharge capacitance 100 µF was used. The dependence of the defibrillation threshold on the pulse duration was determined on 5 heart preparations. Defibrillator $defib_{max}$: The graph of the dependence of the defibrillation threshold on the pulse duration shows a curve similar to the strength-duration curve known from pacing. The curve declines monotonically with increasing pulse duration, and can be mathematically described by a hyperbole. Defibrillator $defib_{min}$: In contrast to $defib_{max}$, the defibrillation threshold increases again for $defib_{min}$ starting at 10 ms pulse duration. This behavior is known from implantable defibrillators. Due to the low capacitance of the capacitors used in implantable devices, only a low voltage remains at the electrodes toward the end of the pulse duration. It is suspected that fibrillation is re-induced by this low voltage after an initially successful defibrillation pulse.

Key words

Defibrillation, rectangular pulse, strength duration curves

Introduction

The high efficiency of implantable defibrillators in the treatment of ventricular tachycardias and fibrillation has been extensively proven. The pulse form for defibrillation of ventricular fibrillation has been the subject of numerous studies [1,2,6,7,9]. In spite of this, the mechanism responsible for defibrillation is not yet completely understood. There are a number of values that influence the defibrillation threshold (DFT). These include the pulse duration and the capacitance of the capacitors used in the defibrillator. The strength-duration relation has always played a decisive role in the electrostimulation of the heart [5]. The threshold for pacing is defined as the smallest electrical pulse that can depolarize the heart after the end of the physiologic refractory period and is generally described by the pacing duration and the voltage delivered. The voltage varies according to its physical relation to the pulse width, and is described by the classical Lapicque curve [4,5]. Every point above that curve stimulates effectively, all points below the curve are ineffective.

In the past, it has been attempted to describe defibrillation of the heart according to the same principle as pacing [2,7]. But this description is limited by one characteristic of DFT. The DFT cannot be described by one

single curve, it is a wide area, in which the defibrillation can be effective or ineffective. Thus, DFT determines a threshold curve, below which defibrillation is improbable [8]. During defibrillation, capacitors discharge a defined value of high voltage. So, the potential applied to the electrodes decreases during the delivery of a defibrillation pulse. Therefore, the single values of the DFT are defined using the pulse duration and the voltage at the beginning of the defibrillation pulse.
It is observed that the DFT, expressed in terms of voltage, current, or energy, can increase for pulse durations longer than 10 ms [3,6]. Possibly, ventricular fibrillation is re-induced, if the defibrillation voltage drops to certain threshold [1]. This study examines the duration-voltage course for monophasic rectangular pulses in comparison to that for monophasic defibrillation pulses falling exponentially. The evaluation of these different pulse forms is of fundamental importance for the development of new implantable defibrillators [1].

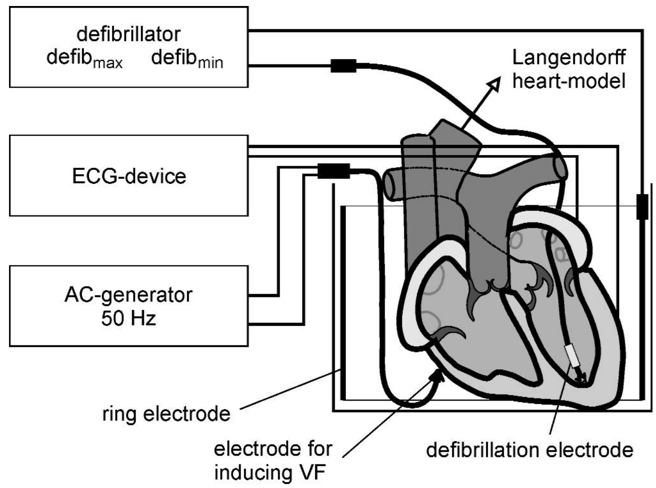

Figure 1. Experimental set-up for the determination of the defibrillation threshold in the Langendorff model.

Materials and Methods

The experiments were carried out using an isolated rabbit heart in a Langendorff heart model (Hugo Sachs™). We examined the hearts of five female, white, New Zealand rabbits with a mean body weight of 3.5 kg. Mean heart weight was 10 ± 1 g. The animals received subcutaneous pre-medication with ketamine. An ear vein was then punctured, and ketamine and disoprivane were administered intravenously. Heartbeat and breathing were continuously monitored. The heart was explanted using a combined transversal abdominal and parasternal approach. The pericardium was opened and, after cutting the larger vessels, the heart was immediately placed into the Langendorff model, where perfusion with the nutrition solution was started. Mean time between explantation and perfusion was 30 ± 5 seconds.
Two electrodes were applied to the perfused rabbit heart. One electrode (induction electrode) was screwed into the left ventricle epicardially, and the second electrode (defibrillation electrode) was screwed into the left ventricle endocardially. Sinus rhythm, continuing fibrillation, and the result of pulse delivery were monitored via a surface ECG. A third electrode (ring electrode) was placed around the heart preparation. Fibrillation was induced by applying a 50 Hz alternating voltage at the induction electrode. The delivery of the defibrillation pulse occurred between the defibrillation electrode in the left ventricle and the ring electrode.
Two different defibrillators were used in the experiments. The first defibrillator (defib$_{max}$) was equipped with an efficient capacitor. The capacitance of the capacitor was 1,250 µF, and monophasic pulses could be delivered with a duration from 0.1 ms to 32 ms. These pulses had almost an ideal rectangular pulse form. The second defibrillator (defib$_{min}$) was constructed identical to industry-standard implantable defibrillators, and the integrated capacitor had a capacity of 100 µF. For this device, the duration of the monophasic pulse was selectable from 1 to 30 ms.
The dependence of the DFT on the pulse duration was determined for 5 heart preparations. The series of tests were carried out with both defibrillators successively on the same hearts. First, the 50 Hz alternating current was applied for 3 seconds via the induction electrode. After the voltage was turned off, the ECG was used to check whether the heart was in fibrillation. If the fibrillation lasted 5 seconds, an appropriate defibrillation pulse was delivered. The pulse was defined by its duration and the charge voltage of the capacitor. The ECG then recorded the effect of the delivered pulse.

Results

The impedance in the pulse current path was 50 ± 2 Ω. The time constant was then τ = 63 ms for the defi-

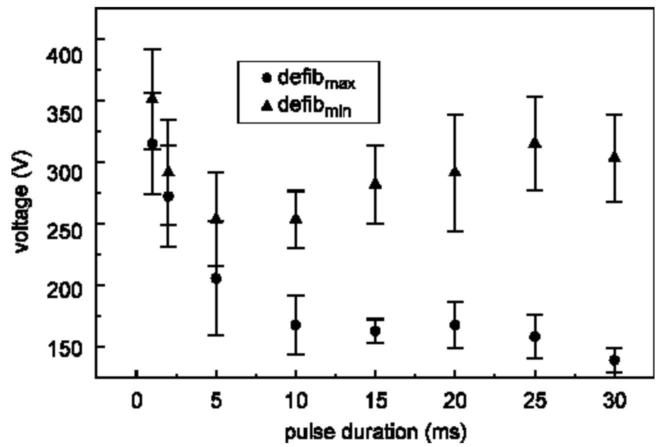

Figure 2. The defibrillation threshold as a function of pulse duration using the defibrillator defib$_{max}$ (t = 63 ms) and the defibrillator defib$_{min}$ (t = 5 ms)

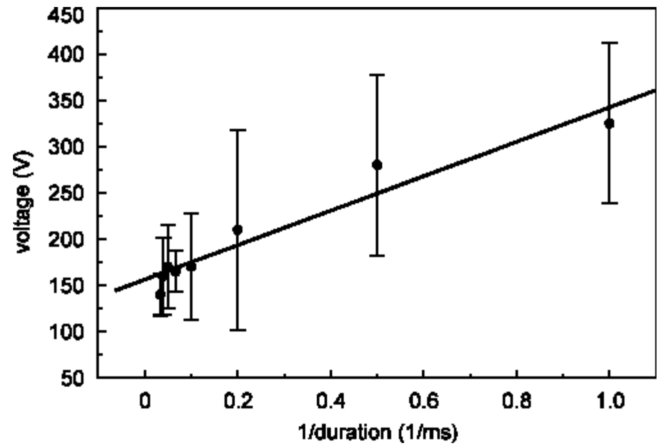

Figure 3. The defibrillation threshold as a function of inverse pulse duration using the defibrillator defib$_{max}$ (t = 63 ms). The solid line is the linear fit of the data (r = 0.96, p = 0.001).

brillator defibmax and τ = 5 ms for the defibrillator defib$_{min}$. Figure 2 shows the average voltage values over the pulse duration of both experimental series for the 5 hearts studied. The dependence of the voltage on the pulse duration showed a curve that was similar to the strength-duration curve of cardiac pacing. As to the short pulse duration ($t < 5$ ms), the necessary voltage decreased presto on both devices. Concerning the long pulse duration, there was a clear difference between the two defibrillators. Moreover, the graph of defib$_{max}$ falls monotonically with increasing pulse durations. In contrast, the DFT increases again for the defibrillator defib$_{min}$ starting at 10 ms.

The progression of the strength-duration curve for pacing is describable as a hyperbole. A simple mathematical function through the measurement points showed that the DFT curve for the defibrillator defib$_{max}$ can be described as a hyperbole with the general form:

$$U = \frac{a}{t} + b$$

where U is the charge voltage at the capacitors, t describes the pulse duration, and a and b are constants. If this relationship holds, then there must be a linear dependence between the charge voltage U and the inverse of the pulse width. These dependencies are portrayed in Figures 3 and 4.

Figure 3 shows the graphs for defib$_{max.}$ The result is a straight line with a correlation coefficient of $R_{max} = 0.96$ ($p < 0.001$). The results for defib$_{min}$ are portrayed in Figure 4. A correlation coefficient of $R_{min} = 0.62$ ($p = 0.10$) results for the linear correlation.

Discussion

The voltage required for ventricular fibrillation is very high for short pulse durations. However, the DFT for both of the defibrillators used decreases monotonically with increasing pulse durations up to 10 ms. For pulses longer than 10 ms, defib$_{max}$ and defib$_{min}$ differ sharply from each other. The DFT for defibmax

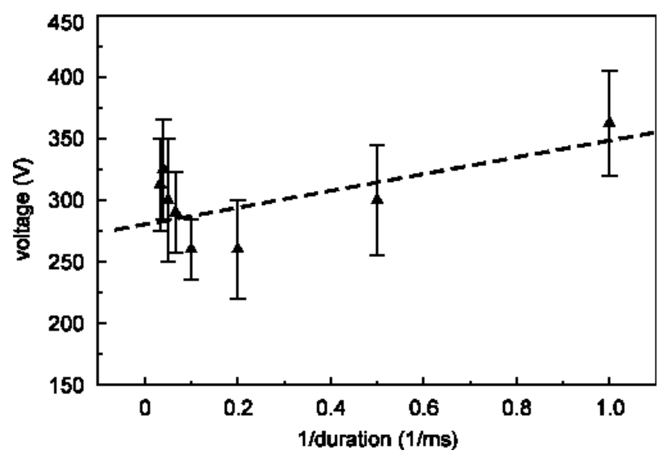

Figure 4. The defibrillation threshold as a function of inverse pulse duration using the defibrillator defibmin (t = 5 ms). The solid line is the linear fit of the data (r = 0.62, p = 0.10).

decreases further with increasing pulse duration (t > 10 ms). In contrast, the DFT from defibmin again begins to increase. This behavior is already known for implantable defibrillators [1,6]. Due to the low capacitance of the capacitors used in implantable devices, only a low voltage remains at the electrodes toward the end of the pulse. It is suspected that fibrillation is re-induced by this low voltage after an initially successful pulse [3]. The presented results show clearly, that the increase of the DFT concerning the values of a long pulse duration are not caused by the pulse duration [3,6]. The results support the notion that the increase in the defibrillation threshold for long-lasting pulses is due to a rest voltage that is too low.

However, it should be noted that the small number of cases studied, 5 hearts, means that the results are somewhat uncertain. Also, rabbit hearts are the smallest hearts that can be set into ongoing fibrillation. In order to obtain results that are more statistically significant, the results must be confirmed with larger hearts and larger numbers of cases.

The good correlation of the data of the $defib_{max}$ with the hyperbolic approximation ($r = 0.96$, $p < 0.001$) point out, that the defibrillation can be described by such a formula. Concerning this question, there was a large discussion in the past. But most of the authors neglected the influence of the voltage decrease regarding small capacitors [7]. According to our data, it seems that in the case of almost rectangular monophasic defibrillation pulses, the voltage-pulse duration curve can be described as a hyperbole. The clear divergence of the $defib_{min}$ data to the expected hyperbolic course of the DFT ($r = 0.62$, $p = 0.10$) shows that it is impossible to measure a classical Lapicque curve using normal implantable defibrillators (ICD).

It is now important to determine the real strength duration of the defibrillation using the presented process in a model, which resembles the conditions of the human organism. Then, the question of the optimal capacitor and energy consumption of implantable defibrillators has to be answered.

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