The Dependence of the Fibrillation Cycle Fraction on which the Defibrillation Pulse is Effective on the Pulse Energy

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Abstract — **Based on the data of modeling the response of a cardiomyocyte in a state of simulated fibrillation to rectangular defibrillation pulses, diagrams of the dependence on the energy of the defibrillation pulse of the fraction of the fibrillation cycle were constructed, on which the defibrillation pulse causes a long-term extension of the refractory period of cardiomyocytes (defibrillation completeness index). The constructed diagrams showed that the long-term extension of the refractory period of cardiomyocytes on a part of the fibrillation cycle is achieved at a pulse energy lower than the excitation energy. Presumably, such pulses provide safe low-energy defibrillation. The defibrillation completeness index of safe low-energy defibrillation pulses increases with increasing pulse duration. Guaranteed defibrillation is achieved when the defibrillation pulse causes the extension of the current refractory period of cardiomyocytes to a value of the pulse repetition period of fibrillation and more. The energetically optimal pulse duration of guaranteed defibrillation is approximately 2 times higher than the energetically optimal pulse duration of the excitation. The relative threshold energy of the pulses providing guaranteed defibrillation at pulse durations shorter than the optimum significantly exceeds the values corresponding to the Hoorweg–Weiss–Lapicque law.**

Keywords — defibrillation; cardiomyocyte model; fibrillation cycle; long-term extension of refractoriness; depolarizing pulse; hyperpolarizing pulse

I. Introduction

In previous studies performed on the ten Tusscher-Panfilov 2006 model of human heart ventricular myocytes [1] in the BeatBox simulation environment [2], it was found that defibrillation pulses cause a long-term lengthening of the refractory period of cardiomyocytes, which prevents the propagation of the fibrillation wave [3], [4]. Previously, this phenomenon was discovered in experimental studies [5] - [8]. In [3], the presence on the diagram of the energy / phase of the fibrillation cycle of the regions of the effectiveness of the depolarizing defibrillation pulse was found, in which a long-term lengthening of the refractory period of cardiomyocytes is achieved. In this work, according to the results of studies [3], [4], the dependences of the defibrillation completeness index on the energy of depolarizing and hyperpolarizing defibrillation pulses are obtained for the previously studied defibrillation pulse durations of 5, 10, 15, 30, 45, 60 ms.

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II. Materials and Methods

To construct the dependences of the defibrillation completeness index on the pulse energy coefficient, a freely distributed GNU Octave mathematical calculation system was used, using a high-level language compatible with MATLAB [9]. A script written for GNU Octave calculated the defibrillation completeness index at the energy coefficient levels listed in a text file. Levels from 10 to 10000000 $\mu A^2 \cdot ms/cm^4$ were set for the E48 series. The data of the lower and upper thresholds of the defibrillation efficiency areas were prepared in separate text files for each of the pulse durations. The calculation results are recorded in a separate file for each of the pulse durations. The results were calculated by linear interpolation from the values of the two nearest points of the source data.

To compare the results with the threshold excitation energy coefficients of the cardiomyocyte model in a continuous state of rest, we used the minimum threshold energy coefficient of 116.2$\mu A^2 \cdot ms/cm^4$ for the optimal rectangular excitation pulse of 15.6ms duration obtained in [10] (for a cardiomyocyte located under the influence of excitation impulses with a frequency of 240 min-1 simulating fibrillation, the minimum threshold energy coefficient is 126.2$\mu A^2 \cdot ms/cm^4$ with a pulse duration of 15.0ms). The threshold energy coefficients for the pulses were calculated in accordance with the Hoorweg–Weiss–Lapicque law [11] according to the formula:

$$E = Eopt \cdot (1 - Topt / T)^2 \cdot T / (4 \cdot Topt), \qquad (1)$$

where T – excitation impulse duration, E – threshold coefficient of excitation energy of excitation impulse with duration T, $Topt$ – excitation impulse duration with a minimum

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threshold coefficient of excitation energy (15.6ms), *Eopt* – threshold coefficient of excitation energy of a impulse with a duration of *Topt* (116.2μA^2·ms/cm^4).

All the materials and data in the article are presented in the online resource ResearchGate [12].

III. Results end Discussion

The results are presented in Fig. 1 for depolarizing pulses and in Fig. 2 for hyperpolarizing pulses. The defibrillation completeness index is the fraction of the fibrillation cycle in which the defibrillation pulse caused a long-term lengthening of the refractory period of cardiomyocytes. A depolarizing impulse, in contrast to a hyperpolarizing impulse, provides a long-term lengthening of the refractory period of cardiomyocytes over most of the fibrillation cycle. Long-term lengthening of the refractory period of cardiomyocytes on a part of the fibrillation cycle is achieved when the pulse energy is lower than the energy of the excitation pulses. Presumably, such pulses provide safe low-energy defibrillation [13], [14], since they cannot cause repeated fibrillation. The defibrillation completeness index for pulses of safe low-energy defibrillation increases with increasing duration. The dependence of the pulse defibrillation completeness index with a threshold coefficient of excitation energy of cardiomyocytes in a prolonged state of rest is shown in Fig. 3.

The threshold level of the energy coefficient of guaranteed defibrillation is the level of the energy coefficient of the depolarizing pulse, at which the current refractory period caused by the pulse has a duration equal to the duration of the period of the simulated fibrillation cycle (250ms). In this case, there are no conditions for the propagation of the fibrillation wave. In Fig. 1 the value of the defibrillation completeness index is less than 1 after the above threshold levels of the energy coefficient caused by continuing excitation pulses of the simulated fibrillation cycle, which in reality should be absent, since the entire field of propagation of the fibrillation wave was "cleaned".

The dependence of the relative threshold energy of guaranteed defibrillation on the duration of the depolarizing pulse is shown in Fig. 4. For comparison, the dependence corresponding to the law of Hoorweg–Weiss–Lapicque is presented. The optimal duration of the depolarizing pulse for the cardiomyocyte model was about 35.5 ms, which is approximately 2 times the optimal duration of the cardiomyocyte excitation pulse (15.6ms). The relative threshold energy of the pulses, providing guaranteed defibrillation at pulse durations shorter than the optimum, increases significantly more than according to the Hoorweg–Weiss–Lapicque law. With pulse durations longer than optimal, only small discrepancies between the curves are observed.

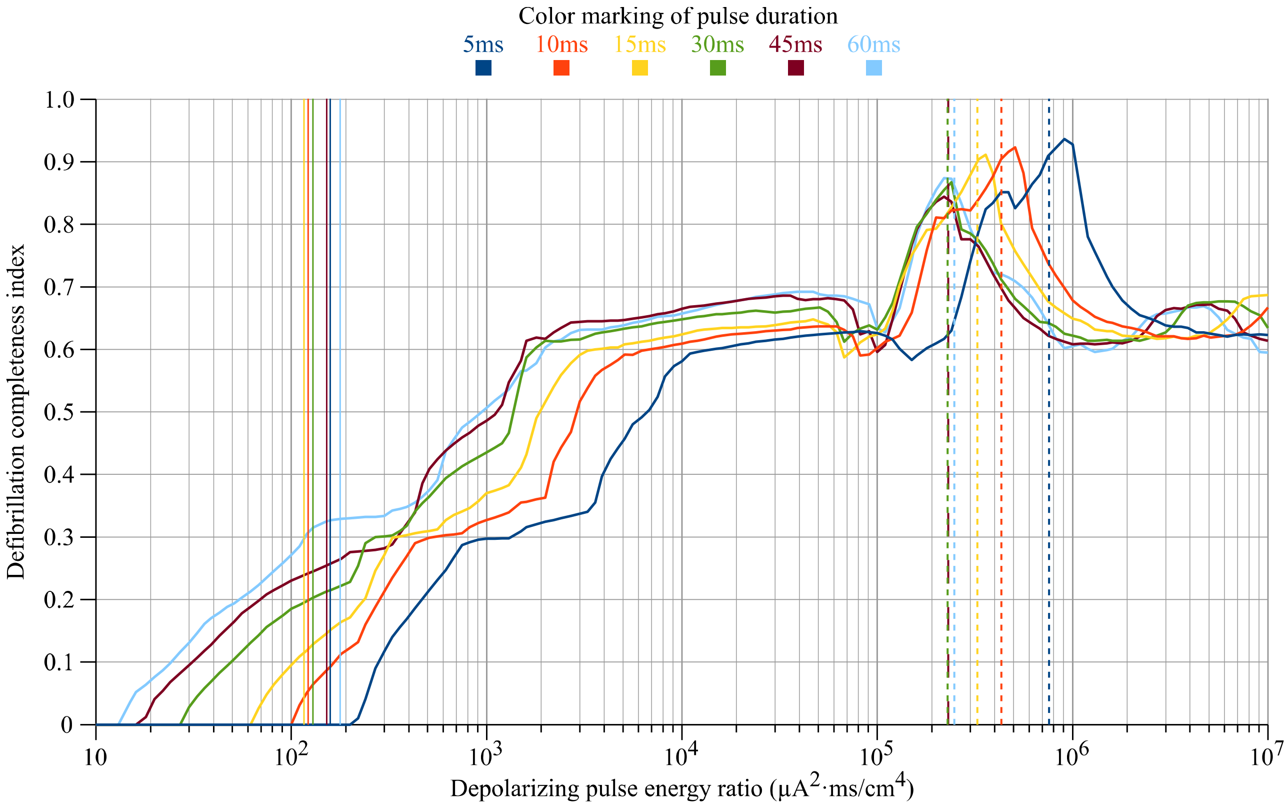

Fig. 1. Dependence of the defibrillation completeness index on the energy ratio for the depolarzing pulse. Solid vertical lines are the energy ratio thresholds of excitation of cardiomyocytes, which are in a prolonged resting state. Dashed vertical lines are energy ratio thresolds of guaranteed defibrillation.

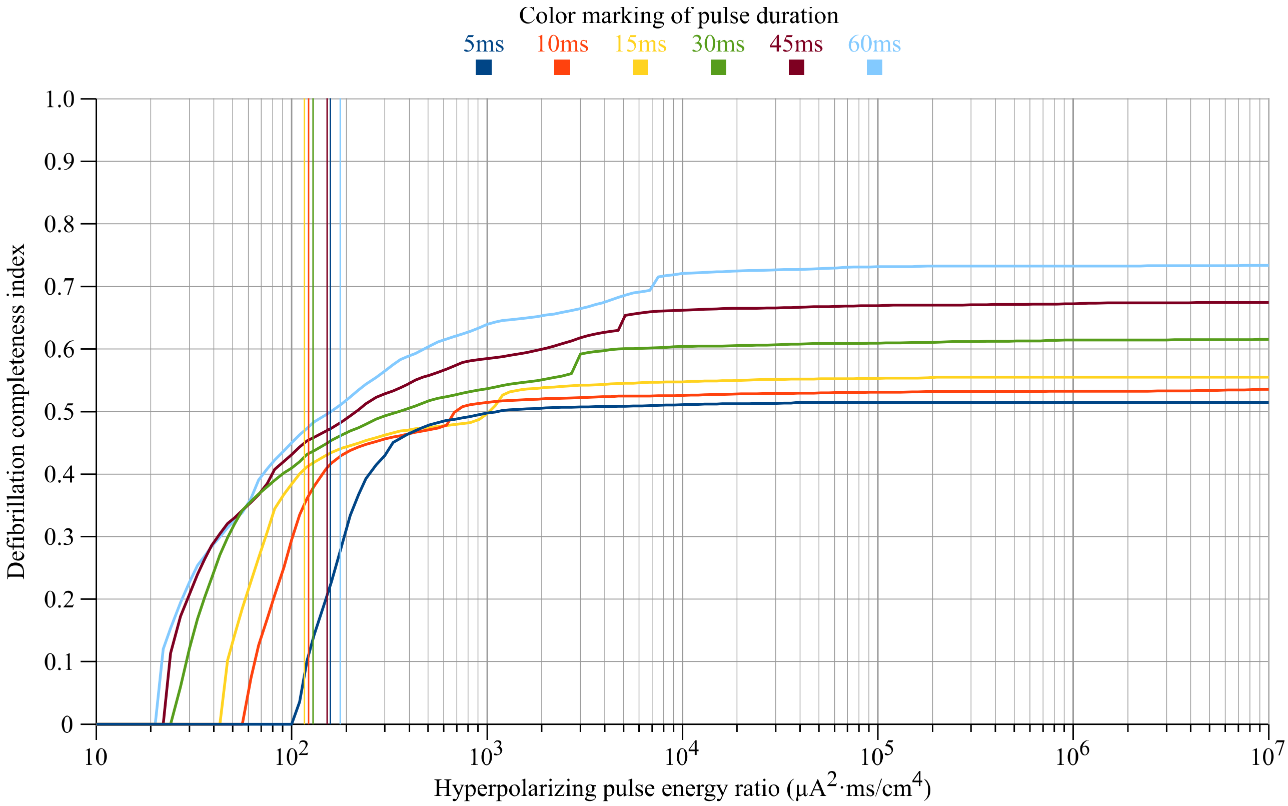

Fig. 2. Dependence of the defibrillation completeness index on the energy ratio for the hyperpolarzing pulse. Solid vertical lines are the energy ratio thresholds of excitation of cardiomyocytes, which are in a prolonged resting state.

IV. Conclusions

The data obtained on the cardiomyocyte model showed that pulses with lower energy than the excitation energy of cardiomyocytes can cause a long-term lengthening of the refractory period of cardiomyocytes, which prevents the propagation of fibrillation waves. Presumably, such pulses provide safe low-energy defibrillation. Since the defibrillation completeness index of safe low-energy defibrillation pulses increases with their duration, it can be assumed that the duration of safe low-energy defibrillation pulses should be longer than the duration of the energetically optimal classical defibrillation pulse.

The energetically optimal duration of the depolarizing pulse, which ensures the duration of the current refractory period of cardiomyocytes equal to the duration of the fibrillation cycle (guaranteed defibrillation), is approximately 2 times longer than the duration of the energetically optimal duration of excitation pulses.

The relative threshold energy of the pulses providing guaranteed defibrillation at pulse durations shorter than the optimum significantly exceeds the values corresponding to the Hoorweg–Weiss–Lapicque law.

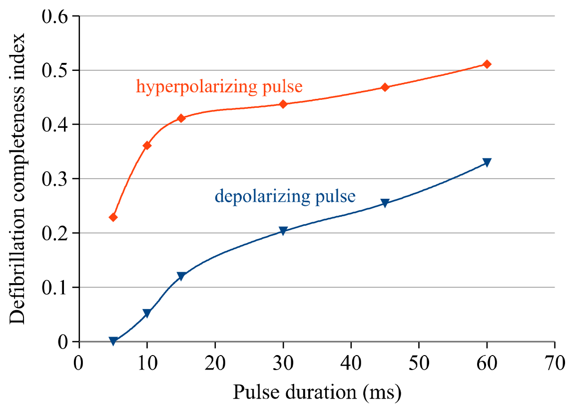

Fig. 3. Dependence of the defibrillation completeness index on the duration of the pulse with energy ratio thresholds of excitation of cardiomyocytes, which are in a prolonged resting state.

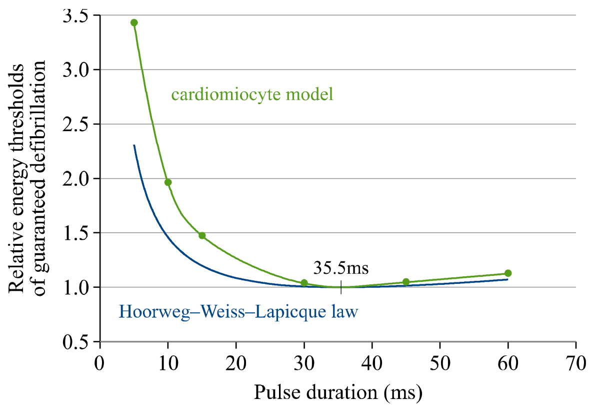

Fig. 4. Dependence of the relative energy thresholds of guaranteed defibrillation on the depolarizing pulse duration.

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