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Influence of the shape of the pacing pulse on ventricular excitation threshold and the function of skeletal muscles in the operating field during non-invasive transcutaneous cardiac pacing under general anaesthesia

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Abstract

Background: *Transcutaneous cardiac pacing (TCP) in patients under general anesthesia does not pose a problem of pain threshold for high amplitudes of pacing pulses, but their application causes contractions of skeletal muscles, which is a problem during surgery. Evaluation of the influence of various shapes of the pacing pulse on the ventricular excitation threshold, the electric energy transmitted to the system of electrodes and the movement of the operating field during TCP performed under general anesthesia.*

Methods: *The study included 58 patients operated under general anesthesia with TCP performed subsequently by means of rectangular pulses, square of the sinus and root of the sinus shaped pulses with identical pulse base width of 40 ms.*

Results: *With incomplete muscle relaxation, for the amplitudes of up to 120 mA, the pacing was the most efficient (94%), ventricular excitation thresholds (VET) were the lowest, i.e. 70.5 ± ± 18.3 mA on average, and the operating field was the most stable when rectangular pulse was applied. The lowest electrical energy, i.e. 44.0 ± 13.8 mJ on average, was provided to the system of electrodes by the pulse shaped like the square of the sinus. The rectangular pulse caused the earliest excitation of skeletal muscles at 40.5 ± 15.6 mA on the average. However, in the conditions of complete muscle relaxation, the skeletal muscle excitation thresholds doubled, which greatly reduced the movement of the operating field.*

Conclusions: *The rectangular pacing pulse ensured the lowest VET, the least movement of the operating field and the most efficient pacing during TCP under general anesthesia. The square of the sinus shaped pulse allowed for the lowest electrical energy applied to the*

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heart. Owing to full skeletal muscle relaxation, the surgeon operated in a stable operating field. (Cardiol J 2007; 14: 137–142)

Key words: transcutaneous electrode, ventricular pacing, general anaesthesia

Introduction

In each operated patient, there is a not easily quantifiable risk that bradycardia will occur, leading to hypotension. Therefore, apart from medication which accelerates the heart rate, an anaesthesiologist needs a non-invasive electric pacing technique which can easily be used not requiring a cardiologist. Transcutaneous cardiac pacing (TCP) meets the current criteria for non-invasiveness because it does not interfere either in body tissues or orifices [1, 2]. During transcutaneous cardiac pacing only ventricles are excited directly; the atria are excited indirectly, after the excitation reverses through the AV node. This practically leads to the loss of the transportation function of the atria [3, 4]. Transcutaneous cardiac pacing may be initiated by the anesthesiologist within a few dozen seconds. Initiation of TCP during surgery is indicated in each case of bradycardia leading to hemodynamic instability [5–7].

General anaesthesia eliminates the problem of unpleasant sensations related to skeletal muscle excitation occurring in conscious patients during TCP [6, 7]. General anaesthesia enables the application of high amplitude pulses, what greatly increases the effectiveness of TCP. Yet, high amplitude pulses at the same time cause skeletal muscle excitation, which leads to the movements of the operating field, thus making it difficult or impossible to perform planned surgery [1, 4–6].

Hence, there was a need to search for solutions to eliminate or minimize the movements of the operating field which accompany TCP.

As the extent of movements of the operating field depends not only on the amplitude of the pulse but also on its shape [8], it was necessary to determine which pulse shape makes it possible to achieve the lowest ventricular excitation thresholds and causes the smallest movement of the operating field. Such steps taken to optimize the conditions for TCP are aimed to explain that there is no need to be concerned about potential ineffectiveness of TCP, movements of the operating field or the possible damage to the heart.

The objective of the paper was to evaluate the influence of the pacing pulse shape on the ventricular excitation threshold, the value of the energy of the pacing pulses, as well as the extent of the movement of the operating field during TCP carried out under general anesthesia.

Methods

66 consecutive patients (54 women and 12 men) aged 30–78 (52 years old on average) of the 1st Clinic of General, Vascular and Transplantation Surgery of the Silesian Medical Academy in Katowice were included in the study. The tests were carried out with the approval of the Research Ethics Committee of the Silesian Medical Academy (no. NN–013–22/01).

The exclusion criteria were chronic atrial fibrillation or flutter and dermatopathy close to the spots where the pacing electrodes were placed. The pacing was performed in a three-electrode system, with the use of the cardiac stimulator NAP-601 and disposable electrodes EX-130S of 50 cm^2 in area (ITAM Zabrze) [4]. The active electrode was placed on the front of the chest, in the area of absolute cardiac dullness, which most frequently corresponded to the electrocardiographic point C3. The passive electrodes were placed symmetrically, on both sides of the backbone, in the sacral area (Fig. 1).

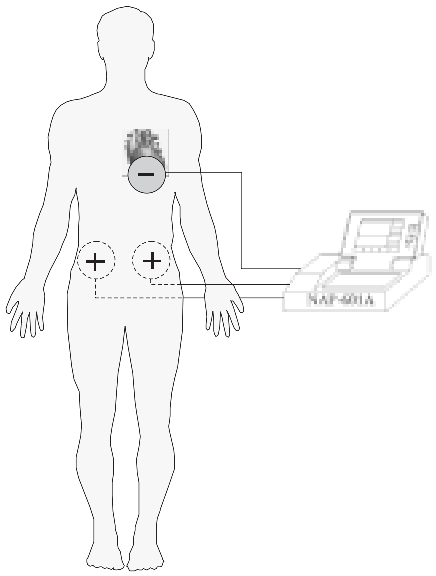

Figure 1. The placement of the active electrode (–) and passive electrodes (+) on the chest during transcutaneous cardiac pacing in an operating room.

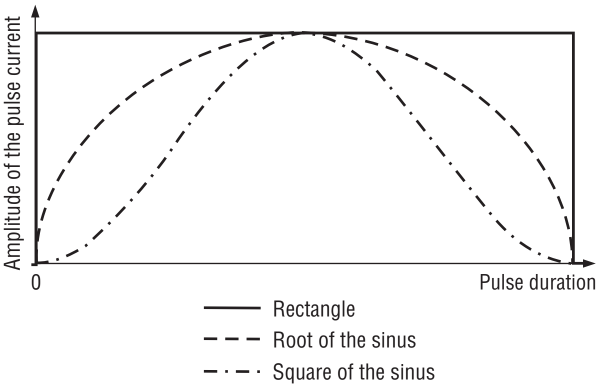

Figure 2. Shapes of the tested pacing pulses.

The width at the base of the three tested pacing pulses (rectangle, square of the sinus and root of the sinus) was identical and amounted to 40 ms (Fig. 2).

45 min before general anaesthesia, each patient received oral premedication, midazolam. The choice of anaesthetic drugs during induction and conduction depended on the general condition of the patient and the type of surgery. Since effective TCP with rectangular pulses,as well as square of the sinus and root of the sinus shaped pulses were achieved in 58 patients, this group was further analyzed and compared. Cardiac pacing was performed in the final stage of the surgery because the examination is time-consuming and artifacts caused by electrocoagulation are observed in the ECG recording during TCP. Such timing of the examination met the criteria of painless cardiac pacing, yet, it did not answer the question how the operating field would move in conditions of complete muscle relaxation. Therefore, the patients were divided into two groups. Group I (N = 58) consisted of subjects who underwent cardiac pacing at the end of surgery, in conditions of incomplete relaxation. Group II consisted of 10 patients from group I who were subject to an additional examination protocol exclusively for the rectangular pulse immediately after the induction of general anaesthesia (with complete muscle relaxation).

Each subject was stimulated with a rate higher by $30^{1}/_{min}$. than their own previously recorded heart rate. The pacing was started with rectangular pulses with an amplitude of 10 mA which was next gradually increased by leaps of 5 mA until effective pacing of ventricles was achieved. As soon as effective pacing was achieved, it was interrupted and restarted with the pulse amplitude reduced by 5 mA. From then on, the pacing pulse amplitude was increased by leaps of 1 mA. VET was assumed to be the lowest amplitude value for the pacing pulse current assuring effective pacing of ventricles for more than a dozen breathing cycles of the patient. The electric and haemodynamic effectiveness of pacing was monitored on the screen of the noninvasive cardiac stimulator NAP-601 (ECG and the plethysmographic curve). Afterwards, the same procedure was repeated for the next two tested shapes of pacing pulses.

Skeletal muscle excitation thresholds (MET) were marked for all tested shapes of pacing pulses based on the assumption that the threshold was the lowest pulse current amplitude at which the first movement of the operating field (chest and/or abdominal cavity) was noticed by the surgeon or anaesthesiologist. The extent of skeletal muscle movement at the level of VET was evaluated in each subject with the use of the three-grade movement evaluation scale. The first grade was lack of movement of the operating field, the second grade was slight movement of the operating field which did not interfere with tissue preparation and the third grade was equivalent to significant movement of the operating field preventing precise tissue preparation.

The impedance of the pacing system in which the pulse current flows between the cathode (electrode in point V3) and anode represented by two electrodes in the sacral area was determined both for the skeletal muscle excitation threshold and ventricular excitation threshold (VET). The electric energy of the pulse for VET was calculated according to the following formula: $E = B \times I^2 \times T_{imp} \times Z_{pacj}$, where I — current values in [mA], T — pulse duration in [s], Z — impedance of the patient in [Ω], B — coefficient depending on the shape of the pacing pulse.

The statistical tests used the Shapiro-Wilk test with normal distribution and the one-factor analysis of variance ANOVA for a model with repeated measurements [9].

Results

Effectiveness of pacing for the rectangular pulse amounted to 94%, for the pulse shaped like the root of the sinus: 92% and for the pulse shaped like the square of the sinus: 88%. VET for the rectangular pulse was 70.5 ± 18.3 mA on average and was lower than the threshold for the pulse shaped like the square of the sinus 79.9 ± 17.7 mA and the threshold for the pulse shaped like the root of the sinus 74.9 ± 18.4 mA. The differences were

Table 1. Values of VET, MET, electric energy of the pulse and the extent of movement of the operating field for subjects in groups I and II.

Type of pulse	VET [mA]	p	MET [mA]	p	Difference VET–MET [mA]	Energy value [mJ]	p	Movement evaluation scale value
Group I								
Rectangular pulse	70.5 ± 18.3	< 0.05	40.5 ± 15.6	< 0.05	30.0	99.7 ± 34.9	< 0.05	1–3
Pulse root of the sinus	74.9 ± 18.4		47.8 ± 16.4		27.1	65.2 ± 21.8		1–3
Pulse square of the sinus	79.9 ± 17.7		45.8 ± 16.7		34.1	44.0 ± 13.8		1–3
Group II								
Rectangular pulse	67.5 ± 17.7		82.5 ± 16.7		–15	86.0 ± 25.0		1–2

statistically significant for the significance level $p < 0.05$ (Table 1).

The pulse shaped like the square of the sinus delivered the lowest electric energy amounting to 44.0 ± 13.8 mJ on average to the system of electrodes during pacing with threshold amplitude. For the pulse shaped like the root of the sinus, the energy amounted to 65.2 ± 21.8 mJ and for the rectangular shape: 99.7 ± 34.9 mJ. The differences were statistically significant for the significance level $p < 0.05$ (Table 1).

The lowest MET was achieved for the rectangular pulse and amounted to 40.5 ± 15.6 mA. For the pulse shaped like the square of the sinus, the threshold was 45.8 ± 16.7 mA and for the pulse shaped like the root of the sinus: 47.8 ± 16.4 mA. The differences were statistically significant, as well (Table 1).

The average value of VET for the rectangular pulse obtained in group II, in subjects in a state of complete relaxation amounted to 67.5 mA ± 17.7 mA and was similar to the value of VET obtained in group I, i.e. in patients in a state of incomplete relaxation (Table 1). The values of the current for MET in group II amounted to 82.5 ± 16.7 mA on average and were twice as high as in group I (Table 1).

The most intensive movement of the operating field, i.e. movement of the third degree, was most frequently observed during effective TCP for the pulses shaped like the square of the sinus. On the other hand, movement of the first and second degree occurred with similar frequency for pulses shaped like a rectangle and the root of the sinus. Movement of the third degree was not recorded in any examination in patients in group II (Table 2).

The movement of skeletal muscles during effective pacing of ventricles could not be noticed by the surgeon or anaesthesiologist when the difference between the values of VET and MET equalled zero or had a negative value (Table 1).

Table 2. Extent of movement of the operating field in SOR scale achieved in group II in patients in a state of complete relaxation.

Type of pulse	Points in movement evaluation scale		
	1	2	3
Movement of skeletal muscles in the chest			
Rectangular pulse	8	2	0
Movement of skeletal muscles in the abdominal cavity			
Rectangular pulse	8	2	0

Discussion

The effectiveness of TCP for the rectangular pulse achieved in our tests equalled 94% and was the highest among the three tested shapes of pacing pulses. The effectiveness of pacing was slightly lower in tests conducted by Zoll, Falk, Kaplan and their teams in conscious subjects and, depending on the type of stimulator, ranged from 80% to 94% for the rectangular pulse [1, 10, 11]. On the other hand, the teams: Berline, by means of a stimulator with the maximum pulse amplitude of 200 mA and Kelly and Amara — 140 mA, achieved 100% effectiveness under general anesthesia [5–7].

Until now, only Jędrszczak et al. [8, 13] have tested the effectiveness of pacing of ventricles under general anesthesia by means of the pulse shaped like the square of the sinus. He achieved effectiveness of 97%, i.e. 5% higher than in our study. The difference may be caused by the use of the amplitude of the current up to 125 mA compared with 120 mA applied in our tests.

The results that we have obtained show the statistically significant influence of the shape of the pacing pulse with a base of 40 ms in width on VET, MET, the amount of energy delivered to the system of electrodes, as well as on the extent of the movements of the operating field. No paper containing a similar comparison has been published so far. Therefore, we can only refer our results to the results of tests carried out with the use of the rectangular pulse. In the study carried out by Berliner et al. [5] the average value of VET for the rectangular pulse in anaesthesia was very high and amounted to 143 mA and in the study conducted by Amar et al. [7] 86.9 mA (right-sided thoracotomy) and 106.7 mA (left-sided thoracotomy), respectively. Very high values of VET in these studies were probably obtained because shorter pacing pulses (20 ms) were used and various factors making TCP difficult were present, such as open chest surgery, intraoperative mediastinal movement, ventilation of one lung, atypical placement of electrodes or a lateral position of the patient.

The conditions for the tests or the method of general anaesthesia in our patients were similar, it can thus be assumed that they did not have a significant impact on the obtained results. Among the tested pulses, the lowest average VET value 70.5 ± ± 18.3 mA and the highest effectiveness of pacing were achieved for the rectangular pulse. It should be underlined that the degree of relaxation did not seem to have any influence on the value of VET for the rectangular pulse. Our results indicate that in the case of the pulse shaped like the square of the sinus, the lowest electric energy is transmitted to the system of electrodes. Thus, this shape has theoretically the lowest damaging potential.

Jawor [12] (transesophageal pacing with a rectangular pulse) and Jędrszczak et al. [8, 13] (transcutaneous pacing with a pulse shaped like the square of the sinus) also conducted research into the amount of electric energy delivered to the system of electrodes in a pacing pulse (to a large extent transmitted to the heart) and the safety of ventricular pacing in patients under general anesthesia. After 10-min pacing resulting in the delivery of 75 J (Jawor) and 90 J (Jędrszczak) in total in pacing pulses, the authors did not state any increase in the marker of myocardial necrosis, such as troponin I. Although these tests were based on a short, 10-minute pacing period and did not disclose any heart damage, some studies indirectly indicate the need to reduce the electric energy affecting the heart muscle not only during pacing [1, 14]. In view of the above, the pulse shaped like the square of the sinus produced the best results in our tests with energy of 44 mJ on average, i.e. half the energy delivered by the rectangular pulse. This definitely implies that a pulse shaped like the square of the sinus should be used in case of longer TCP.

Excitation of regional structures occurs during TCP, such as the phrenic nerve, diaphragm, skeletal muscles of the chest or abdominal integument. Muscular contractions accompanying the ventricular pacing were observed by most researchers specializing in TCP [1, 13, 15]. In many cases, they represented the main obstacle preventing successful TCP in conscious subjects. The first attempts to classify the patients' sensations caused by contractions of transverse striated muscles were made by Zoll et al. [1] and continued by Prochaczek et al. [4, 15]. Although the patients were under general anaesthesia during our tests and therefore did not suffer any discomfort from pacing (due to anesthetics), the movement of the operating field caused by pacing still remains a serious problem during surgery. The literature does not discuss the problem of the movements of the operating field during TCP. There is information though that all factors enabling the reduction of VET also result in less movement of the skeletal muscles accompanying TCP. Our results are in line with these findings because when comparing numeral distributions of the movement of the first, second and third degree, it can be seen that most of the cases of third-degree movement (the most troublesome for the operator) occurred during pacing with the pulse shaped like the square of the sinus for which the biggest value of VET was obtained, amounting to 79.9 ± 17.7 mA (Table 1).

The test results also indicate a relation of the movements of the operating field not only to the ventricular excitation threshold (VET), but also to the difference between the ventricular excitation threshold (VET) and skeletal muscle excitation threshold (MET). The smallest differences between VET and MET amounting to 27.1 mA and 30.0 mA occurred in the group with incomplete muscle relaxation for the pulse shaped like the root of the sinus and for the rectangular pulse. Also, the largest number of cases of first- and second degree movements of the skeletal muscles of the chest and abdominal integument in the operating field was observed during TCP for these pulse shapes. Comparing these two pacing pulse shapes, one can see that most of the cases of first-degree movements occur in the case of the rectangular shape. Similar conclusions were presented in the study carried out by Prochaczek et al. [4]. The bigger the difference between MET and VET, the bigger the movement of the operating field and the smaller the difference — the smaller the movement of the operating field according to our grading scale.

The influence of muscle relaxation drugs on the behaviour of skeletal muscles during TCP has not been investigated so far. Our research definitely indicates that the skeletal muscle excitation threshold increases twofold in a state of complete relaxation of transverse striated muscles. Having analyzed the difference between the values of VET and MET, we found out that for the patients in group II in a state of complete muscle relaxation it had a negative value. As a result, the third-degree movement of the operating field was not observed in any of the 10 subjects from group II in a state of complete relaxation, stimulated with rectangular pulse (Table 2), which ensured appropriate stability of the operating field.

The results of our study imply the need to equip the non-invasive transcutaneous cardiac stimulator applied in anaesthesiology with a rectangular pulse and a pulse shaped like the square of the sinus. The use of the rectangular pulse assures the highest probability that effective cardiac pacing will be achieved with the lowest ventricular excitation threshold and with the least movement of skeletal muscles. On the other hand, the use of the pulse shaped like the square of the sinus protects the heart from excessive accumulated electric energy in TCP lasting longer.

From the operator's point of view, TCP performed by the anaesthesiologist requires that the patient should be in a state of complete muscle relaxation.

Analysis of the above results indicates the need to continue research on the optimization of the parameters of the pulse shaped like the square of the sinus. Given much lower energy of this type of pacing pulse compared with the rectangular pulse needed for effective pacing of the ventricles and higher pacing thresholds, a wider base should be used when choosing this pulse type. This would enable the maintenance of significant energy gain identified during tests while at the same time lower thresholds of effective pacing and less movement of the operating field are anticipated.

Conclusions

1. Under general anaesthesia, TCP performed with rectangular pulses assures the lowest ventricular excitation thresholds, the least movement of the operating field and the highest effectiveness (94%) within the range up to 120 mA.
2. Relaxation of skeletal muscles under general anaesthesia assures less movement of the operating field during TCP by means of rectangular pulses, which is important for the operator.
3. Among the tested pulses, the pulse shaped like the square of the sinus transmits the lowest electric energy to the system of electrodes during TCP.

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