transesophageal atrial stimulation (TAS), current density, atrial pacing threshold, selective electrodes, omnidirectional electrodes

Fryderyk PROCHACZEK[1], Jerzy GALECKA[1], Miroslaw SIKORA[2], Jedrzej GLASEK[3]

EVALUATION OF CURRENT DENSITY ON THE SURFACE OF THE LEFT ATRIUM DURING TAS

Conditions for the indirect transesophageal atrial stimulation (TAS), useful for cardiac diagnosis and treatment, are optimized both by way of clinical experiment and a computer modelling. The paper demonstrates the results of comparison of electric current density, obtained on the surface of the left atrium during computer modelling, with the results of our own experiments. An evaluation was made with the use of spiral CT scanning of the distance between the esophagus and the posterior wall of the left atrium. The average distance in the tested group of 27 subjects was 4.7 $\pm\sigma = 1.1$ mm. During transesophageal stimulation, we have determined the average excitation threshold of the left atrium, obtaining the value 5.5 $\pm\sigma = 1.8$ mA in the examined group of 27 patients. The calculated average current density on the surface of left atrium for the selective electrode with point poles used in the experiment amounted to 39.6 μA/mm^2. Electric current densities obtained by other researchers by means of computer modelling for omnidirectional and selective ring electrodes turned out to be much lower after adjustment to similar conditions, which was the result of electrically active larger sizes surfaces of the poles of electrodes used in the modelling.

1. INTRODUCTION

Transesophageal cardiac stimulation has been used in cardiac treatment and diagnosis for over 50 years. However, the most rapid development of this method took place in the 1970s and 1980s with significant input from Polish researchers [12], [13], [9]. The left atrium of the heart is stimulated most frequently as it is close to the esophagus at a certain length in most of the subjects.

Several attempts have been made over the years to optimize this cardiac stimulation method for achieving the patient's positive tolerance of the examination [8] as well as its readable record [11], [10], as required by the physician. Attempts have also been made to model transesophageal cardiac stimulation with the use of a computer, based on the two- or three-dimensional finite elements method [4], [6], [5] in order to explain occurrences that are difficult to investigate in clinical conditions. Our own clinical experiments so far indicate lower values of atrial excitation thresholds and a better comfort of the examination if directional point electrodes are used to maximize electric current transmission towards the left atrium.

Arzbaecher and Jenkins assumed that the resistivity of the transesophageal and left atrium tissue is homogenous and proposed the use of simple and well-known relations which describe the electric phenomena quite well to calculate the density of the electric current on the surface during stimulation [1].

[1]Institute of Medical Technology and Equipment ITAM, Roosevelta 118 Street, 41-800 Zabrze.
[2]Department of Anesthesiology and Intensive Care, A. Mielecki Clinical Hospital, Medical University of Silesia, Katowice, Poland.
[3]Laboratory of Diagnostic Imaging, St. Leszczynski Hospital, Katowice, Poland.

The works conducted so far on the mathematical modelling of atrial stimulation are based on the anatomical documentation of the esophagus and left atrium, obtained on the basis of CT scans from the 1990s. An assumption was made in the works that the distance between the esophagus and the left atrium is 10 mm on average. Only the paper by Crawford et al., published in 1985 and based on CT scanning and MRI, evaluated the distance between the esophagus and the posterior wall of the left atrium in persons aged $1 \div 40$ years to be an average of 3.3 mm. In order to calculate electric current densities on the surface of the left atrium in a reliable way, we decided to check this distance again in adults by means of spiral CT scanning.

Our work is aimed at answering the question if the models used by researchers for scientific calculations describing transesophageal atrial pacing reflect the real conditions of transesophageal stimulation during the tests. To this end, with the use of spiral CT scanning, an evaluation was made of the average distance of the esophagus from the posterior wall of the left atrium, and the average excitation threshold of the left atrium was defined during transesophageal pacing. Based on the results, the average current density on the surface of the left atrium was calculated and then compared with the results obtained by other researchers by way of computer modelling.

2. METHODOLOGY

The topographic relations between the esophagus and the posterior wall of the left atrium were evaluated by means of CT scanning in subjects diagnosed for thoracic changes. The examination covered 27 patients (13F and 14M) at the average age of 61.2 years ($12 \div 81$, $\pm\sigma = 14$). The group under study included only those subjects in whom changes caused by illness and discovered via CT scanning did not affect the anatomy or topography of the heart, esophagus, trachea, main and lobar bronchi and the stomach. The spiral tomograph Elscint HeliCat II was used to evaluate the anatomic and topographic relations in the thorax. In order to visualize both the parenchymatous organs and lung tissue, the ”windows” C 500 jH, W 1500 jH, as well as C 35, W 370 were used. The tests were made with a layer of 6.5 and 13 mm, pitch 1 and 5.5 and 11 mm, pitch 1.5. Both images in a cross-section and oblique reconstructions (”oblique” 2D) were used for the measurements.

The anatomic and topographic relations in the thorax were evaluated off-line, from the material obtained from patients lying on their backs and breathing in deeply. For the needs of atrial pacing, the distance from the internal wall of the esophagus to the left atrium was evaluated. The distance was assumed to be the thickness of the esophagus at the point of adherence to the left atrium. If the lumen of the esophagus could not be seen, the thickness of the wall was assumed to be half the sagittal diameter. The length at which the esophagus is directly adjacent to the left atrium was also calculated.

The real thresholds of effective transesophageal atrial stimulation were evaluated in 27 patients (4F, 23M) of the II Department of Maxillofacial Surgery, Medical University of Silesia in Katowice, undergoing surgery in general anesthesia. The patients' average age was 39.8 years ($19 \div 70$, $\pm\sigma = 14,3$). The tests were approved by the Scientific Research Ethics Committee of the Medical University of Silesia, as well as subject to the individual written consent of each participant of the tests.

During the tests, there was used a prototypical transesophageal selective electrode with an ellipsoid cross section and a diameter of ca 9 mm (Hagmed, Poland, Fig. 1), and 2 carbon poles with a diameter of 5 mm, at a distance of 30 mm from each other. A specially formed (bent) drain made it possible to place the stimulating poles of the electrode to the left atrium.

Before joining the test group, the patient had a routine anesthesiological examination to qualify for planned general anesthesia. Persons with esophageal and swallowing disorders and pregnant women were excluded from the tests. Each patient was premedicated orally with midazolam, 7.5 or 15 mg, 40 minutes before anesthesia. Induction and conduction of general anesthesia were typical, by means of intravenous and inhalant substances in standard doses.

In general anesthesia subjects, before the surgery, the electrode was introduced to the esophagus through the mouth or nose (depending on clinical conditions), at a depth calculated from a modified Roth formula: through the mouth - ($height \times 0,2 - 2$) cm, through the nose - ($height \times 0,2 + 2$) cm

Fig. 1. A transesophageal selective electrode with carbon poles used in own research.

[8], [11], [10], using the markers.

After inserting the electrode, the atrial excitation threshold was defined for a rectangular impulse 10 ms wide, using the cardiac stimulator NAP-601 (ITAM Zabrze, Poland). The threshold was defined for stimulation rate 30 $^1/_{min.}$ higher than the recorded sinus rhythm.

3. RESULTS

Table 1 demonstrates the average distance between the location of the active pole in the esophagus and the excited heart structure, as well as the length at which the esophagus is adjacent to the left atrium. The distance R_{E-LA} of the esophagus to the posterior wall of the left atrium was $4.7 \pm \sigma = 1.1$ mm on average. The left atrium was adjacent to the esophagus at a length of $44.8 \pm \sigma = 11.4$ mm on average, while in one subject both the left atrium and the left ventricle were adjacent to the esophagus at a length of 80 mm.

Table 1. The average distance R between the internal wall of the esophagus (E) and the surface of the left atrium (LA) in the tested group of 27 subjects (13F, 14M).

	Age $[year]$	Distance R_{E-LA}) $[mm]$	Lenght of adjacent $[mm]$
Mean	61.2	4.7	44.8
$\pm\sigma$	14.3	1.1	11.4

Fatty tissue $1 \div 3$ mm thick was detected between the esophagus and the left atrium, however, precise measurement of its thickness turned out to be impossible for technical reasons. The CT scan failed to show a distinctive borderline between the external wall of the esophagus, fatty tissue and the external wall of the left atrium (Fig. 2).

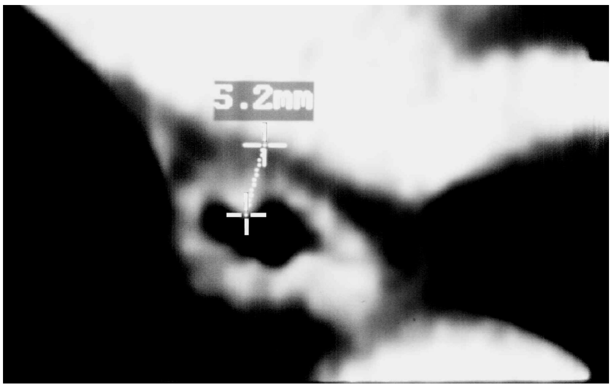

Fig. 2. An example of the cross-section of the esophagus with the marked distance 5.2 mm from the internal wall of the esophagus (E) to the left atrium (LA).

Table 2 demonstrates the average results of the atrial current excitation threshold (I) for the tested group of 27 patients including the values of the impulse voltage amplitude (U) and impedance (Z) for stimulation rate 30 $^{1}/_{min.}$ higher than the recorded heart beat of sinus origin.

Table 2. The average atrial stimulation threshold for a rectangular impulse 10 ms wide in the examined group of 27 patients (4F, 23M).

	Age $[year]$	Weight $[kg]$	Height $[cm]$	Electrode depth $[cm]$	I $[mA]$	U $[V]$	Z $[k\Omega]$
Min	19	48	164	33	4.0	6.0	1.3
Max	70	114	195	42	11.0	24.5	6.5
Mean	39.8	67.5	173	37.2	5.5	13.1	2.5
$\pm\sigma$	14.3	14.6	9.1	1.9	1.8	5.4	1.2

Fig. 3 shows the position of the bipolar directional point electrode as used in own research, in the esophagus against the atrium. As the distance between the poles of the electrode b=30 mm is several times higher than the value 1.4R = 6.6 mm, (theoretically) optimal for the bipolar electrode [1], it can be assumed that in this situation unipolar stimulation occurs from the pole located closer to the heart, against the other pole located at a greater distance. In order to calculate the current density of the impulse on the surface of the left atrium, it was assumed that the electrode was located in a homogeneous environment, while the impact area of the electrode takes up half of the surface of the sphere (equation 1).

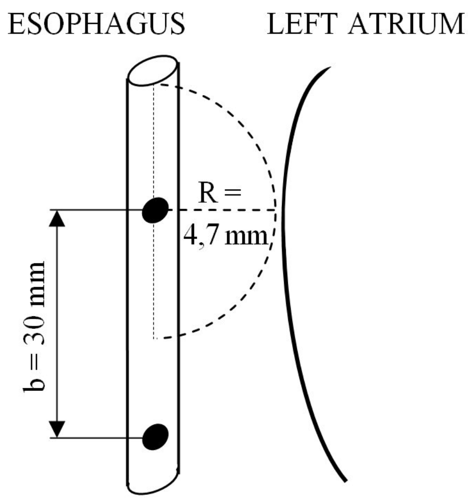

Fig. 3. Bipolar directional point electrode with a large distance between the poles (b), placed in the esophagus at a short distance (R) from the wall of the left atrium.

$$J = \frac{I}{2\pi R^2} \tag{1}$$

Table 3 shows the average current density, calculated from equation 1, on the surface of the posterior wall of the left atrium, based on topographic measurements (Table 1) and real thresholds of effective transesophageal stimulation in the examined groups of patients (Table 2).

Table 3. The average current density (J) on the surface of the posterior wall of the left atrium in examined group of patients.

I mean $[mA]$	R_{E-LA} $[mm]$	J $[\mu A/mm^2]$
5.5	4.7	39.6

4. DISCUSSION

Effective cardiac stimulation requires electric current density that is higher than the excitation threshold in the stimulated area. In the temporary endocavitary stimulation, when the stimulating pole of electrode with an area of approximately 50 mm^2 is directly adjacent to the heart muscle, the electric current threshold of effective atrial stimulation that is not felt by the patient is, according to paper [1], 1 mA. However, other available sources provide a higher value as a typical threshold of effective atrial stimulation, usually about 2 mA [3], which results in the current density of approximately 40 $\mu A/mm^2$. We have assumed this value to be our point of reference, for indirect cardiac stimulation (i.a. via the esophagus); the value is close to the result obtained in our experiments (Table 3).

In spite of performing several experimental and theoretical optimization works and achieving clear progress, transesophageal stimulation of the left atrium can still be felt by the subject. One of the ways to minimize the current necessary to achieve threshold electric current density in the stimulated tissue is to place the stimulating pole or poles in the esophagus, as close as possible to the posterior wall of the left atrium. The fact that we used a modified Roth formula, combining the position with the patient's height, in our research to determine the position of the stimulating poles in the esophagus, turned out to be a sufficiently effective method. In this way, we ensured low excitation thresholds of the left atrium at the level of 5.5 mA on average ($4 \div 11$, $\pm\sigma = 1.8$), while for 9 out of 27 patients the threshold was at a level of 4 mA. The results are similar to those presented in paper [7] where for a group of 49 males the average atrial excitation threshold of 5.1 $\pm\sigma = 0.4$ mA was obtained, while for a group of 51 females the average threshold was 4.4 $\pm\sigma = 0.4$ mA. However, the position of the stimulating poles of the electrode was optimized individually, based on the amplitude of the P wave recorded from the esophagus.

Given the distance of the internal wall of the esophagus from the back wall of the left atrium being 4.7 mm on average as indicated in spiral CT scanning, we can state that the distance in our tests is two times lower than can be inferred from anatomical atlases developed on the basis of CT scans from the 1990s. In the works on the modelling of electric current density during transesophageal atrial stimulation, the distance of 10 mm is usually assumed, which impacts the implications from the evaluation of test results, referring to the calculated electric current.

Attempts have been made in recent years to model the electric atrial stimulation by means of a computer, with an electrode placed in the esophagus. Bipolar [4], [6], [5] and unipolar stimulation was modelled against a surface electrode placed on the chest [4], from electrodes with ring poles, emitting electric current both omnidirectionally and selectively (a ring sector). The results were graphically visualized to demonstrate the distribution of electric current density in planes that are perpendicular to the electrode in the esophagus, in the plane intersecting the axis of the electrode and the atrium of the heart, as well as in the form of graphs depicting the change of current density along axes connecting the electrodes and the atrium of the heart. In the work by Lackovic et al. from 2005 [6], a computer simulation of transesophageal atrial stimulation confirmed a clear advantage of the selective (directional) electrode over the classic omnidirectional ring electrode; the advantage was mentioned in our research conducted already in the 1980s [8].

The results of our own experimental tests of the topographic relations between the esophagus and the posterior wall of the left atrium, as well as the outcome of the tests of the stimulation thresholds of the left atrium in general anesthesia patients have made it possible for us to refer to research results [4], [6], [5] obtained by way of computer modelling. We have made a comparison of electric current densities on the surface of the left atrium obtained by way of modelling, after a recalculation to meet the conditions of our own experimental research. The results of the comparison can be found in Table 4.

We are aware of the fact that electric current density calculated on the basis of our experimental tests relies on results obtained from 2 various patient groups. This solution was necessary because we failed to obtain the consent of patients after dental surgeries to perform a completely unnecessary CT scan of the chest or the consent of patients after a CT scan to perform diagnostic transesophageal stimulation, not necessary in their case. Similar to the work of the Roth one limitation of our study is that CT data are from a different population than that that studied in the operating room, so that extrapolation of anatomical findings may be somewhat imprecise [14].

Comparison of the results presented in Table 4 indicates significant differences between the electric current density calculated on the basis of the outcome of experimental tests with the use of our selective electrode with point poles and current densities obtained as a result of computer modelling for various electrode types and sizes.

Table 4. Electric current densities on the surface of the atrium wall, in the axis of the electrode pole adjusted to the current of the stimulating impulse, equal to 2 mA and at a distance of R_{E-LA} = 5 mm.

Current density J	A	B	C	D	E	F	G*
In the axis of the pole of the electrode [μA/mm^2]	40	6.4	1.2	3.0	1.3	3.3	1.9
In the axis between the poles of the electrodes [μA/mm^2]	40	–	0.8	1.4	0.3	0.6	–

*the paper does not define the assumed distance R_{E-LA} (esophagus – left atrium)

A – Reference current density based on endocavitary stimulation [1],
B – Bipolar selective electrode with point poles used in own research,
C – Bipolar electrode with cylindrical poles; ϕ = 6 mm, l = 8 mm and d = 20 mm [6],
D – Bipolar selective electrode; ϕ = 6 mm, l = 8 mm, $\varphi = 60^o$ and d = 20 mm [6],
E – Bipolar electrode with cylindrical poles; ϕ = 7 mm, l = 8 mm and d = 20 mm [5],
F – Bipolar selective electrode; ϕ = 7 mm, l = 8 mm, $\varphi = 60^o$ and d = 20 mm [5],
G – Bipolar electrode with cylindrical poles; ϕ = 7 mm, l = 8 mm and d = 20 mm [4],

The differences can be easily seen after the calculation of all results for the same conditions: stimulating current I = 2 mA and the distance of the atrium from the esophagus R_{E-LA} = 5 mm. Electric current densities in modelled conditions both in the axis of the electrode pole and in the axis of half of the distance between the poles are much lower, even for selective electrodes. As a result, the anticipated currents of effective stimulation are defined at an excessively high level (e.g. for selective electrode D: 40/3 = 13.3 mA). This is a consequence of the sizes of electrode poles as assumed in modelling, as well as of the resulting large, electrically active surfaces. As can be inferred from our previous research [8], the surfaces are not optimal for the minimization of the thresholds of transesophageal stimulation of the left atrium.

In existing mathematical modelling, the use of stimulating large-area poles was due to the fact that they were implemented early in clinical practice. Because it was believed that large areas of the electrode poles reduce the potential ability of damage to the tissue of the esophagus caused by electric current flow of pacing pulses. Currently, the ring electrodes of large dimensions are still useful for transesophageal electrical cardioversion of atrial fibrillation, but are no longer used for transesophageal stimulation, both diagnostic and therapeutic. The results of experimental research presented in Arzbacher work [1] leave large amplitude-safety margin for the esophagus, particularly in the case of low atrial pacing thresholds, obtained for the electrode with a small area poles of 50 mm^2 order.

5. CONCLUSIONS

Juxtaposition in our work of real distances between the esophagus and the left atrium with excitation threshold values of the left atrium obtained during the conducted research indicates that directional, small-area electrode allows for more than three-fold increase in current density on the surface of the left atrium. The resulting low thresholds of atrial excitation leave a large margin of safety for the esophagus site, ensuring the application safety of low-area directional electrodes.

Results of our examinations indicate the need of computer modelling of transesophageal stimulation of the left atrium for directional electrode having small surface poles and small, of 5 mm order, distance between stimulating poles and the atrium being excited. It would enable the optimization of indirect, transesophageal cardiac stimulation in circumstances close to present conditions of experimental examinations. This should help to eliminate discomfort connected with stimulation in 70 % of the patients treated.

New assumptions in mathematical modelling should turn out useful for clarification of phenomena being difficult to study in clinical conditions. They should contribute to improving the tolerance and stimulation effectiveness, particularly in conscious persons.

ACKNOWLEDGEMENT

This work was financed in part by the National Centre for Research and Development.

BIBLIOGRAPHY

[1] ARZBAECHER R., JENKINS J. M., A Review of the Theoretical and Experimental Bases of Transesophageal Atrial Pacing. Journal of Electrocardiology 2002, Vol. 35 Supplement, pp. 137-141.

[2] CRAWFORD TM, DICK M 2nd, BANK E, JENKINS JM., Transesophageal atrial pacing: importance of the atrial-esophageal relationship. Med Instrum. 1986, Jan-Feb; 20(1):40-44.

[3] FROMER M., SHENASA M., Ultrarapid Subthreshold Stimulation for Termination of Atrioventricular Node Reentrant Tachycardia. JACC 1992, Vol. 20, No. 4 October:879-83.

[4] KRASTEVA V., Finite Element Modeling Approach for Optimal Electrode Configuration in Atrial Pacing, Computers in Cardiology, 2003, 30:441-444.

[5] LACKOVIC I., MAGJAREVIC R., Analysis of Current Density Distribution during Transesophageal Pacing Using the Finite-Element Model. World Congress on Medical Physics and Biomedical Engineering 2006, IFMBE Proceedings 2007, Volume 14, Part 16, pp. 2673-2676.

[6] LACKOVIC I., MAGJAREVIC R., Computer Simulation Of Transesophageal Pacing With Conventional And Selective Leads Using 3-D Models. 3rd European Medical and Biological Engineering Conference EMBEC, 2005, IFMBE Proceedings 2005, Vol. 11, pp. 2864-2869.

[7] PATTISON C. Z., ATLEE J. L., MATHEWS E. L., BULJUBASIC N., ENTRESS J. J., Atrial pacing thresholds measured in anesthetized patients with the use of an esophageal stethoscope modified for pacing. Anesthesiology 1991, 74:854-859.

[8] PROCHACZEK F., GALECKA J., Transesophageal cardiac stimulation: properties of ring electrodes lead and point-direction electrodes one, Part I, Kard. Pol. 1988, 32:683-690 (in Polish).

[9] PROCHACZEK F., GALECKA J., STANEK K., STOPCZYK M., New diagnostic prospects for transesophageal pacing of the heart on the basis of an esophageal atrial electrogram received during stimulation, Stimucoeur. 1986, 14:159-165.

[10] PROCHACZEK F., GALECKA J., STOPCZYK M., A method of esophageal electrogram recording for diagnostic atrial and ventricular pacing, PACE 1990, 13:1136-1141.

[11] PROCHACZEK F., GALECKA J., STOPCZYK M., Cardiac transesophageal pacing: value of artifacts suppression circuit of pacing impulse for quality of ECG tracing recorded from pacing transesophageal electrode, Part III, Kard. Pol. 1989, 32:379-385 (in Polish).

[12] PROCHACZEK F., WODNIECKI J., Evaluation of oesophageal left atrial stimulation for the diagnosis of coronary artery disease, Wiad. Lek., 1977, Vol. 30, pp. 593–598 (in Polish).

[13] PROCHACZEK F., WODNIECKI J., MAZANEK-SZYMANSKA E., Transesophageal left atrial stimulation for revealing additional pathways of atrioventricular conduction, Pol. Tyg. Lek. 1979, 34:1073-1076 (in Polish).

[14] ROTH J. V., BRODY J. D., DENHAM E. J., Positioning the pacing esophageal stethoscope for transesophageal atrial pacing without P-wave recording: implications for transesophageal ventricular pacing. Anest Analg 1996, 83:48-54.