Determining a human cardiac pacemaker using fuzzy logic

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Abstract. The paper presents a possibility of estimating a human cardiac pacemaker using combined application of nonlinear integral transformation and fuzzy logic, which allows carrying out the analysis in the real-time mode. The system of fuzzy logical conclusion is proposed, membership functions and rules of fuzzy products are defined. It was shown that the ratio of the value of a truth degree of the winning rule condition to the value of a truth degree of any other rule condition is at least 3.

1. Introduction

One of the ways of informative evaluation of the human condition is the analysis of the heartbeat carried out on the basis of electrocardiosignal processing [1, 2]. In the course of such an analysis, it is necessary to diagnose different heart seizures including premature systoles [3]. In relation to the latter, the necessity of their disclosure is conditioned by the fact that it signalizes about psycho-emotional overexertion. What is more, it helps to exclude premature intervals from an array of cardio cycles durations to calculate the parameters of heart rate variability [4].

It is necessary to estimate cardiac pacemaker for disclosure of premature beats and other heart seizures. Such a task for purposes of human condition analysis must be carried out in the real-time mode.

Nowadays, automatized assessment of the cardiac pacemaker is carried out only for the sinus and ventricular heart rate in the real-time mode [5, 6]. Other forms of heart seizures are either not singled out or not singled out in the real-time mode.

The aim is to work out the way to estimate the human cardiac pacemaker using fuzzy logic in the real-time mode.

To define the type of the cardiac pacemaker, it is necessary to analyze relationships between atrial and ventricular activation in every cardiac cycle, in other words, it is necessary to define, which of the heart compartments is activated first.

Normally, the electrical pulse, appeared in the synoauricular node, is spread through atriums downwards. Positive waves P are recorded in the electrocardiosignal in deviation II. In this case, atrial activation always precedes ventricular activation. That is why, positive wave PII is recorded before each QRS-complex. In most cases, during each deviation they have the same form and they appear at regular intervals from the QRS-complex.

In case of absence of these attributes, different types of a non-sinus rhythm are diagnosed. They include an arterial rate, atrio-ventricular rhythm and a ventricular rate.

In those cases, when the cardiac pacemaker is in the lower arterial compartment (e.g. in the area of
coronary sinus), the electrical pulse is spread recursively (upward), and in the electrocardiosignal in deviation II negative wave P is recorded. They precede QRS-complexes. As the wave motion of activation through ventricles is not distressed, natural unchanged QRS-complexes are recorded.

If the cardiac pacemaker is located in the AV-connection, the activation of ventricles proceeds naturally – downwards, and arterial activation proceeds upwards. That is why, natural unchanged QRS-complexes and negative wave P are recorded by the electrocardiosignal. In this case, if an ectopic pulse reaches atria and ventricles simultaneously, wave P layers are upon the QRS-complex, and it is not recorded by the electrocardiosignal. If the ectopic pulse reaches ventricles before atria, negative wave P is located after the QRS-complex.

If the source of activation is a ventricular conduction system (stem and branches of the His bundle and Purkinje fibers), this refers to a ventricular rate. Activation is conducted through ventricles in an unusual manner: firstly, it overtakes the ventricle in which there is the ectopic cardiac pacemaker, and then it slowly reaches another ventricle. Consequently, QRS-complexes are exaggerated and deformed. Activation is not conducted to atrial myocardium. That is why, there is no constant obligate connection between QRS-complexes and waves P. Ventricles are activated in their slow rate, while atria are activated in their natural rate, the source of which is a still synoauricular node.

Table 1 shows marks of the cardiac pacemaker for the electrocardiosignal of deviation II.

| Cardiac pacemaker   | Waves P                                                                 | QRS-complexes                      |
|---------------------|-------------------------------------------------------------------------|------------------------------------|
| Synoauricular node  | Positive with the same constant form, precedes QRS-complexes            | Usual unchangeable                 |
| Atria               | Negative, precedes QRS-complexes                                        | Usual unchangeable                 |
| AV-connection       | There is no consistent connection in location with QRS-complexes        | Usual unchangeable                 |
| Ventricles          | There is no consistent connection in location with QRS-complexes        | Exaggerated and deformed           |

It is necessary to single out waves of the electrocardiosignal to determine the source of activation after it, it is possible to classify the cardiac pacemaker applying logical rules towards data points of the waves location. Logical rules can be presented in terms of neural circuitry.

However, there is no connection between presence and location of waves P and QRS-complexes due to presence of theventricular rate and the rate of the AV-connection. Thus, using logical rules can lead to mistakes in classifying in the real-time mode. In such cases, it is possible to use fuzzy logic.

2. Materials and methods
The analysis of the electrocardiosignal should be started with complementary processing of the signal. It includes elimination of high-pitched noise and deviation of the flatline. Then, for defining the cardiac pacemaker, it is necessary to distinguish elements of the electrocardiosignal and data points in each cardiac cycle. This problem can be solved using non-linear integral transformations [7, 8] that are to result in signals:

\[ y^{(P)} \] – signal of presence of positive wave P; \[ y^{(-P)} \] – signal of presence of negative wave P; \[ y^{(QRS)} \] – signal of presence of the natural QRS-complex; \[ y^{(QRS^*)} \] – signal of presence of the deformed QRS-complex.

These signals take the maximum value in the area of the corresponding element.

The data points in each cardiac cycle can be distinguished in the TP-segment [7, 8]. In this case, logic signal \( s_{TP} \) is formed; it assumes a value of 1 in the area of the TP-segment and 0 – in other cases.

The system of fuzzy logic (FLS) is offered for distinguishing the type of the cardiac pacemaker. It has a variety of advantages both against its actualization in the form of Boolean logic circuit, and it is
viewed according to the neutral network approach [9]. These advantages consist in the fact that FLS takes into account ambiguity of benchmark data considering handling with the fuzzy concept. In particular, it takes into account information about presence and location of waves. Authenticity of the classification is determined by the ratio of belonging of the linguistic variable (LV) to one or another linguistic utterance (LU) [10].

A previously obtained set of signs of types of the cardiac pacemaker is an initial data for FLS. It is based on the analysis of behavior of the output signals of presence of waves $y^{(-P)}$, $y^{(P)}$, $y^{(QRS)}$, $y^{(QRS^*)}$. Along with this, at the entry of FLS, the valuation of maxima of signals of wave presence $y^{(-P)}$, $y^{(P)}$, $y^{(QRS)}$, $y^{(QRS^*)}$ that were reached during a cardiac cycle at the moments, corresponding to the end of each cardiac cycle, in other words, at the moments when $s_{OT} = 1$, is considered. Also, they take into account the moments of signal maxima $y^{(-P)}$, $y^{(P)}$, $y^{(QRS)}$ relative to each other.

To specify the structures of FLS, it is necessary to define the input and the output of LV, membership functions (MF) for each LU as their valuations can be taken by LV; rules of fuzzy products.

The FLS under discussion possesses 6 inputs and 1 output LVs. The input LVs show a previously revealed evidence of the cardiac pacemaker. Thus, LV1 “Negative wave P”, LV2 “Positive wave P”, LV3 “QRS-complex”, LV4 “Deformed QRS-complex” can take the value of LU “No” and “Yes” according to their MF. Signals $y^{(-P)}$, $y^{(P)}$, $y^{(QRS)}$, $y^{(QRS^*)}$ are standardized at the stage of analysis, that is why, values of variables LV1 – LV4 change within the range of $[0, 1]$. The example of MF for LV2 is in Figure 2. The limits $[a, b]$ assume the intervals of uncertainty.

![Figure 2. The membership functions of linguistic utterances “Yes” and “No” for LV2](image)

In this case (Figure 2), z-shaped $\phi_1^{(P)}$ and s-shaped $\phi_2^{(P)}$ MFs are used:

$$\phi_1^{(P)}(x) = \begin{cases} 1, & \text{if } x \leq a_1; \\ \frac{b_2 - x}{b_1 - a_1}, & \text{if } a_1 < x \leq b_1; \\ 0, & \text{otherwise}. \end{cases}$$

$$\phi_2^{(P)}(x) = \begin{cases} 0, & \text{if } x \leq a_2; \\ \frac{x - a_2}{b_2 - a_2}, & \text{if } a_2 < x \leq b_2; \\ 1, & \text{otherwise}. \end{cases}$$

Two additional input LVs show the time of appearance of signal maxima $y^{(-P)}$, $y^{(P)}$ in ratio to the moment of appearance of signal maxima $y^{(QRS)}$. Thus, LV5 “Wave moment $-P$” and LV6 “Wave moment $P$” take the value of two LUs “The wave preceded the QRS-complex” and “The wave followed the QRS-complex”.

The output LV “Cardiac pacemaker” can take the value of 4 LVs: “Sinoatrial rate”, “Atrial rate”, “Rate from AV-connection” and “Ventricular rate”. As output LV, the value is taken, as it has the largest value of the membership degree. That is why, there is no necessity in the stage of defuzzification and defining MF for LU of output LV.

The rules of FLS fuzzy products for defining the type of the cardiac pacemaker are based on the data that are presented in a tabulated form (Table 1). In this case, the rules of FLS fuzzy products are presented in such a way:

**Rule 1:** If Positive wave $P$ = «Yes» AND (Negative wave $P$ = «No» OR Negative wave $P$ = «Yes» AND Wave moment $-P$ = Wave followed the QRS-complex) AND QRS-complex = «Yes» AND Deformed QRS-complex = «No» AND Wave moment $P$ = Wave preceded the QRX-complex, THEN Cardiac pacemaker = “Sinoatrial rate”.

Rule 2: If (Positive wave P = «No» OR Positive wave P = «Yes» AND Wave moment P = Wave followed the QRS-complex) AND Negative wave P = «Yes» AND QRS-complex = «Yes» AND Deformed QRS-complex = «No» AND Wave moment P = Wave preceded the QRS-complex, THEN Cardiac pacemaker = “Atrial rate”.

Rule 3: If (Positive wave P = «No» OR Positive wave P = «Yes» AND Wave moment P = Wave followed the QRS-complex) AND (Negative wave P = «No» OR Negative wave P = «Yes» AND Wave moment –P = Wave followed the QRS-complex) AND QRS-complex = «Yes» AND Deformed QRS-complex = «No», THEN Cardiac pacemaker = “AV-connection rate”.

Rule 4: If QRS-complex = «No» AND Deformed QRS-complex = «Yes», THEN Cardiac pacemaker = “Ventricular rate”.

In general view, the procedure of defining the cardiac pacemaker on the basis of the FLS consists of several steps:
1. Defining a clear value of input signals that are presented in the form of integral transformation of the electrocardiosignal.
2. Defining values of the membership degree of input LV with LU by means of calculating MFs $\phi_1^{(p)}$ and $\phi_2^{(p)}$ with corresponding parameters (Table 2).

Table 2. Parameters of membership functions of analyzed LVs

| Linguistic variable         | Linguistic utterances | Membership function | Function parameters |
|----------------------------|-----------------------|---------------------|---------------------|
| Negative wave P            | “Yes”                 | S-shaped            | 0.2 0.7             |
|                            | “No”                  | Z-shaped            | 0.2 0.7             |
| Positive wave P            | “Yes”                 | S-shaped            | 0.2 0.7             |
|                            | “No”                  | Z-shaped            | 0.2 0.7             |
| QRS-complex                | “Yes”                 | S-shaped            | 0.6 0.9             |
|                            | “No”                  | Z-shaped            | 0.6 0.9             |
| Deformed QRS-complex       | “Yes”                 | S-shaped            | 0.6 0.9             |
|                            | “No”                  | Z-shaped            | 0.6 0.9             |
| Wave moment P              | “Wave preceded QRS-complex” | Z-shaped   | -0.5 0.1           |
|                            | “Wave followed QRS-complex” | S-shaped     | -0.1 0.5           |
| Wave moment -P             | “Wave preceded QRS-complex” | Z-shaped   | -0.5 0.1           |
|                            | “Wave followed QRS-complex” | S-shaped     | -0.1 0.5           |

3. Calculating the degree of truth conditions of each rule of the fuzzy output. The sub-conditions are united according to the rule “AND” or the rule “OR”. Two obtained unions of sub-conditions can be presented respectively:

$$y = \min(x_1, x_2, \ldots) \text{ and } y = \max(x_1, x_2, \ldots)$$

where $x_1, x_2, \ldots$ – the list of input arguments, presented as values of the truth degree corresponding sub-conditions; $y$ – truth degree of the union of sub-conditions.

Calculating the truth degree of the condition of the fuzzy output rule is defined analogically.

4. Defining the rule with the maximal truth degree of the condition, which, in its turn, draws a conclusion about the cardiac pacemaker. Herewith the defined cardiac pacemaker is reliable, if the value of the truth degree of the winning rule condition is at least 3 times larger than the value of the truth degree of any other rule condition. Otherwise, the defining cardiac pacemaker can be single-valued.

3. Results and Discussion
In Figure 3, there is the example of the electrocardiosignal (Figure 3, a) and its transformation to
definite positive wave P (Figure 3, b), negative wave P (Figure 3, c), QRS-complex (Figure 3, d) and
deformed QRS-complex (Figure 3, e). After introduction of the norms, the numerical value of the
analyzed disposal variables for the cardiac cycle highlighted with a dotted line will have values shown
in Table 3. Fuzzy logic operations AND/OR are presented as functions min/max respectively.

**Table 3.** Values of the analyzed disposal values for the cardiac cycle under discussion (refer to
Figure 3)

| Linguistic variable          | Standardized values of transformation signals | Membership degree to an utterance “Yes” | Membership degree to an utterance “No” |
|------------------------------|-----------------------------------------------|----------------------------------------|----------------------------------------|
| Negative wave P              | 0.87                                          | 0.9                                    | 0.1                                    |
| Positive wave P              | 0.58                                          | 0.76                                   | 0.24                                   |
| QRS-complex                  | 0.87                                          | 0.9                                    | 0.1                                    |
| Deformed QRS-complex         | 0.035                                         | 0                                      | 1                                      |
| Wave moment P                | 0.25                                          | 0                                      | 0.58                                   |
| Wave moment -P               | -0.15                                         | 0.42                                   | 0                                      |
The truth values of the conditions are calculated, when values of the membership degree of LV refer to the following utterances:

Rule 1: \( \min(0.76; \max(0.1; \min(0.9; 1)); 0.9; 1; 0) = 0; \)
Rule 2: \( \min(\max(0.24; \min(0.76; 0.58)); 0.9; 0.9; 1; 0.42) = 0.42; \)
Rule 3: \( \min(\max(0.24; \min(0.76; 0.58)); \max(0.1; \min(0.9; 0)); 0.9; 1) = 0.1; \)
Rule 4: \( \min(0.1; 0) = 0. \)

Among the obtained values, the maximum is the truth condition of the 2nd rule, which outnumbers the truth value of other rules at least 4.2 times. Thus, it is possible to draw a conclusion that the cardiac pacemaker, the electrocardiosignal of which is presented in Figure 3,a, is atria.

4. Conclusion
The article shows a possibility of determining the human cardiac pacemaker in the real-time mode using a combined use of non-linear integral transformation and fuzzy logic. The suggested system of fuzzy logic uses Z-shaped and S-shaped functions of membership and 4 rules of fuzzy production. It is shown that the ratio of the value of the truth degree of the winning-rule condition to the value of the truth degree of a condition of any other rule is equal to at least 3.

The main advantage of using fuzzy logic is taking into account multiplicity of incoming output data, in particular, results of non-linear transformation and corresponding information about the presence and location of waves, especially in case of the AV-connection rate and the ventricular rate, when there is no regular connection between waves P and QRS-complexes.

Implementation of the analyzed method helps to determine forms of extrasystoles and other defects and incursions more precisely. By means of it, it is possible to analyze human stress and to react to changes in his or her medical condition.

References
[1] Sherbakova T F, Osipova O S 2015 Antenna Theory and Techniques (ICATT), 2015 International Conference on The analysis of an electrocardiosignal in a system of data transmission in control office 1-2
[2] Domingues D G, Miosso C J, Paredes A E, Rocha A F 2011 Pan American Health Care Exchanges Module for the acquisition and processing of biological signals related to the emotional state 237-238
[3] Bruggemann T, Andresen D, Weiss D, Rose J, Chorianopoulos A, Schroder R 1993 Computers in Cardiology 1993, Proceedings Heart rate variability: how to exclude extrasystoles from the analysis? 467-470
[4] Tripathi A, Ayub S 2015 International Conference on Computational Intelligence and Communication Networks (CICN) Heart Rate Variability Detection in Arrhythmia 357-362
[5] Chazal P 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) Detection of supraventricular and ventricular ectopic beats using a single lead ECG 45-48
[6] Mateo, Laguna P 2003 IEEE Transactions on Biomedical Engineering Analysis of heart rate variability in the presence of ectopic beats using the heart timing signal 50 (3) 334-343
[7] Varnavsky A N, Sinitisina N V 2015 5th Mediterranean Conference on Embedded Computing (MECO) Determination of driver's psycho-emotional state parameters 405-409
[8] Varnavsky A N, Melnik O V 2007 Biomedical Engineering An energy approach to detection of electrocardiosignal arrhythmias 41 6 271-273.
[9] Jan Bohaci J, Matiasko K, Benedikovic M 2015 Cybernetics (CybCONF), 2015 IEEE 2nd International Conference on Linguistic variable elimination for a heart failure dataset 196-200
[10] Keller J M, Liu D, Fogel D B 2016 Fundamentals of Computational Intelligence: Neural
Networks, Fuzzy Systems, and Evolutionary Computation 400