Prediction of Local Abnormal Ventricular Myocardial Electrical Activation on Surface ECG in Patients with Structural Heart Disease

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Keywords: Endo- and Epicardial Electrograms, Surface ECG, Synchronous Registration, Signal Processing and Analysis, Ventricular Late Potentials, Correlation, Life-threatening Heart Disorders.

Abstract: The problems of processing and analysis synchronous records endo- and epicardial electrograms and surface ECG signals, detection of ventricular late potentials of patients with ventricular tachyarrhythmia and coronary heart disease by using spatial and temporal signal accumulation algorithms, correlation of temporal and spectral characteristics of late potentials with the dynamics and localization of dangerous heart disorders are considered.

1 INTRODUCTION

The surface ECG signal is the result of the spatio-temporal summation of the electric potential, which is formed as a result of the excitation of myocardial fibres by the action potential when it spreads along the conduction pathways of the heart and the contractile myocardium. Normally, the action potential is first generated by the sinoatrial node and sets the heart rate. A cardiac electrogram is an electrical signal recorded by a pair of electrodes of a special catheter when the action potential passes by this pair of electrodes. The temporal characteristics and form of intracardiac electrograms on paired catheter electrodes represent the nature of the propagation of the action potential along the myocardium. There is a relation between the characteristics of intracardiac electrograms and the waves and segments of the surface ECG signal. Endo- and epicardial electrogram registration is of paramount importance in diagnosis and treatment of heart rhythm disorders, since they allow establishing the localization and mechanism of tachyarrhythmias and conduction abnormalities. Ventricular late potentials and fragmented QRS complexes have significant diagnostic value. A large number of publications that have become classics of clinical cardiology (Breithardt, Borggrefe, Martinez-Rubio, et al, 1988; Simson, Euter, Michelson et al, 1981; Simson, 1983; Breithardt, Cain, El-Sherif et al., 1991) show that these potentials are reliable predictors of a number of life-threatening heart disorders and sudden death. However, the registration and analysis of endo- and epicardial electrograms is carried out only for certain indications, in contrast to the registration and analysis of the surface ECG signal, the identification and evaluation of the characteristics of ventricular late potentials and fragmented potentials is difficult due to their short duration (less than 180 ms), low amplitude (less than 40 μV), significant frequency variability (up to 700 Hz), amplitude and duration. Since in the majority cases ventricular fragmented and late potentials are not detected on surface ECG using simle analysis, special methods and algorithms

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Yuldashev, Z., Nemirko, A., Mikhaylov, E., Lebedev, D., Anisimov, A., Skorobogatova, A. and Ripka, D.
Prediction of Local Abnormal Ventricular Myocardial Electrical Activation on Surface ECG in Patients with Structural Heart Disease.
DOI: 10.5220/0009374103950401
In *Proceedings of the 13th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2020) - Volume 1: BIODEVICES*, pages 395-401
ISBN: 978-989-758-398-8; ISSN: 2184-4305

for processing and analyzing multi-channel recordings of a surface ECG signal are required.

In patients with structural heart diseases inhomogeneous and delayed electrical activation is associated with re-entrant and triggered life-threatening ventricular tachyarrhythmias, as it had been shown in many scientific researches (Kreiner, Gottlieb, Furukawa et al., 1992; Wong and Windle, 1994; Teptin, Latfullin, Konturov, Mamedova, 2004; Ohisa, Ohira, Mizonobe et al., 2002). Usually, local abnormal electrical activation of ventricular myocardium can be recorded invasively only, when a mapping catheter is placed at endocardial or epicardial surface in close proximity to the diseased area. In clinical practice, invasive mapping of ventricular tachycardia substrate is aimed at detection of areas with low amplitude and abnormal local activity. Although the presence and location of abnormal activity can be predicted according to patient clinical characteristics (for instance, in patients with known localization of post-myocardial infarction scar), there is a need in prediction models of the presence and extent of abnormal activity areas in patients with other cardiac diseases. Pre-procedure knowledge of localization of the target area for mapping and further catheter ablation (in order to terminate and render VTs non-inducibleis of paramount importance, since it helps to plan the required access and needed extent of tissue ablation.

The purpose of this study is to develop a processing algorithm for detecting ventricular late potentials and fragmented signals from synchronous recordings of surface ECG and invasively registered signals, and to improve the accuracy of estimation the presence of local abnormal electrograms and their spectral characteristics using the analysis of surface ECG.

To achieve this goal, we have solved the following research tasks:

1. Formation of a database of synchronous recordings of endo- and epicardial electrograms and 12-channel surface ECG signals reflecting the presence and absence ventricular late potentials and fragmented electrograms for various heart rhythm disorders.
2. Detection, analysis and classification of ventricular late potentials and fragmented QRS complexes using algorithms for synchronous accumulation and spatial averaging over surface ECG signals, comparison of the accuracy of detection of ventricular late and fragmented potentials and assessment of their characteristics taking into account synchronous recordings of intracardiac electrograms.
3. Formation of a complex of indicators of surface ECG signals correlating with intracardiac ventricular fragmented and late potentials.
4. Development of an algorithm for identifying late and fragmented ventricular potentials and evaluating their temporal, spectral and dynamic characteristics.
5. Formation of a complex of indicators of fragmented QRS complexes and ventricular late potentials, reflecting dangerous heart rhythm disorders.

2 METHODS

2.1 Patient Population

Patients with known structural heart disease and documented ventricular tachycardia (VT) were referred for electrophysiological study and catheter ablation of VT substrate. Inclusion criteria were the following: the presence of structural myocardial disease diagnosed using transthoracic echocardiography, magnetic resonance tomography, and/or endomyocardial biopsy; VT detected on surface ECG or by interrogation of an existent cardiac implantable electronic device (mainly, implantable cardioverter-defibrillator); signed informed consent to undergo an invasive electrophysiological study. Exclusion criteria were the following: the presence of a reversible VT cause, acute systemic inflammatory disease, intracardiac thrombosis, the need for coronary revascularization according to the clinical and angiographic evaluation.

2.2 Electrophysiological Study

The electrophysiological procedure was performed in an electrophysiological laboratory; patients were evaluated in a fasting state under general anesthesia with propofol, fentanyl and arduan. A femoral access was performed via the common femoral vein (a transseptal 8F Multipurpose sheath (Cordis, Johnson and Johnson, USA) and a 6F vascular sheath (Avanti, Cordis, Johnson and Johnson, USA) were introduced), and via the common femoral artery (an 8F vascular sheath was used).

A combined endocardial left ventricular access was performed retrogradely via the arterial sheath and using the transseptal access. Puncture of the interatrial septum was performed using the Brockenbrough BRK-1 needle (Abbott, USA) with a small amount of contrast media used to confirm appropriate access to the left atrium (Optiray 300, Mallickrodt, Germany).

After successful transseptal puncture the transseptal sheath was advanced into the left

ventricle. Following left-sided access intravenous heparin was administered (100 IU* kg-1) to prevent thrombosis. A 6F quadripolar diagnostic catheter (Webster, Johnson and Johnson, USA) was placed into the right ventricle apex for stimulation and/or time annotation of the bipolar intracardiac signals.

Electrogram mapping was performed using both a duodecapolar Pentaray catheter (Biosense Webster, USA) and a 3.5-mm tip quadripolar irrigated mapping and ablation catheter NaviStar ThermoCool (Biosense Webster, USA). Electrophysiological mapping was performed under the non-fluoroscopic three-dimensional mapping system CARTO 3 (Biosense Webster, USA).

Three-dimensional shells were created using the "FAM (Fast Anatomical Model)" module and automatic point acquirement using the "Confidense" module with a maximum 2 mm distance between points. Electrophysiological signals from mapping catheters were recorded and stored simultaneously with surface ECG signals on the CardioLab (GE, USA) system.

When epicardial mapping was indicated and planned, fluoroscopically-guided subxyphoid puncture was performed first; the technique was previously described in details (Simonova, Lebedev, Mikhaylov, 2017; Simonova, Mikhaylov, Tatarskiy et al., 2019). The non-steerable 8F multipurpose sheath was inserted into pericardial space for introducing and manipulating a mapping catheter.

Endo- and epicardial mapping was performed during sinus rhythm or during right ventricle stimulation at a rate 600 ms per min. Normal bipolar signals were characterized by two high-frequency deflections (a positive and a negative consecutive deflections). Abnormal signals were characterized by splitting, notching, slurring, fragmentation, doubling (the presence of an isoline between two components), and by the late activity (signals widely separated from the main signals and located after the end of QRS on the surface ECG).

2.3 Electrophysiological Signals' Extraction

Tracings with normal and abnormal bipolar signals were manually annotated on the electrophysiological system, and tracings containing the ECG and intracardiac/epicardial bipolar signals were extracted from the electrophysiological system in .txt format. The extraction was performed using an integrated module which allowed marking the cut-off timings on the whole registration. The raw signal was recorded at 1000 Hz sampling rate.

3 PROBLEMS SOLVING

3.1 Forming of the Synchronous Records Base of Endocardial Electrograms and Surface ECG Signal

After selecting the most informative segments of the signals and storing them, the logic of constructing a database of synchronous records was formulated: a hierarchical structure of the presentation was chosen. Its use makes it easy to find records of interest by type of heart rhythm disturbance and to reveal the dynamics of the parameters before and after invasive treatment (radiofrequency catheter ablation of a tachycardia critical isthmus and/or areas with local abnormal electrical potentials).

The first level of division is the type of observed ventricular disturbance: fibrillation, flutter, tachycardia, bradycardia, extrasystole and late potentials (Yuldashev, Nemirko, Manilo et al., 2019).

After dividing the recordings by type of disturbance, the signals were divided into 3 additional levels: recordings before RF ablation, during and after the ablation. Using this division allows to track the change in the characteristics of the electrical heart activity throughout the operation.

Surface ECG signals were recorded in three or twelve leads. Signal record database contains 3 channels of surface ECG: I, II and III. For disorders associated with the ventricles, all 12 ECG channels were used. Intracardiac activity is represented by the following leads:

1) dABL – distal lead of the ablation catheter electrode;
2) ABL – proximal lead of the ablation catheter electrode;
3) CS12, CS34, CS 56, CS78, CS910 – leads of the catheter electrode located in the coronary sinus;
4) RV – signals from distal bipoles of the diagnostic catheter placed in the right ventricle apex;
5) Pentaray – bipolar signals recorded from the duodecapolar steerable mapping catheter roving in and on the ventricles.

The database of records consists of 296 records lasting from 10 to 20 minutes, including records of the norm and atrial pathology – 128 records, various ventricular pathologies – 168 records.

3.2 FQRS Complex and Ventricular Late Potentials Detection Algorithms

The following algorithm was proposed to detect fragmented QRS (FQRS) complexes (figure 1). At the first stage, the surface ECG signal was subjected to low-pass filtering with a cutoff frequency of the filter fCH = 100 Hz to reduce the influence of high-frequency noise during the extraction of QRS complexes.

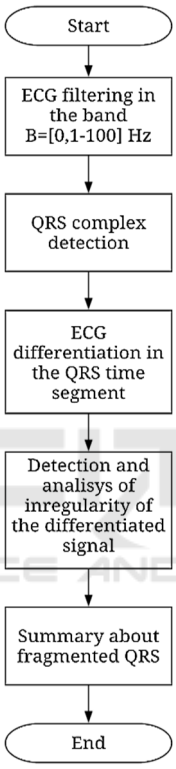

Figure 1: Fragmented QRS detection algorithm.

In the reason of the fragmented QRS complex is characterized by the presence of notches, patterns in the areas of Q, R and S waves (figure 2), to detect them, the initial ECG signal in the segment of the selected QRS complex undergoes differentiation. Next, the irregularity of the differentiated signal is established and its analysis. A smooth change in the differentiated signal from a negative value to a positive value means the absence of fragmented QRS complexes. Its stepwise change reflects the presence of fragmented complexes.

Methods of temporal or spatial summation are used to detect ventricular late potentials. It should be noted that the ventricular late potentials appear on the ST segment and are characterized by a very low amplitude (tens of μV), high frequency (up to hundreds of Hz), short duration (up to 150 ms) and significant variability of characteristics from one cardiocycle to another. This fact makes it difficult to detect and analyze ventricular late potentials (VLP).

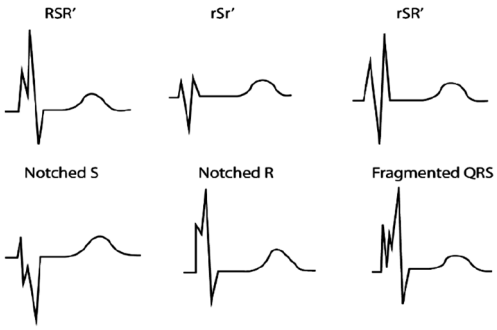

Figure 2: Types of fragmented QRS complex.

Methods of temporal or spatial summation are used to detect ventricular late potentials (figure 3). It should be noted that the ventricular late potentials appear on the ST segment and are characterized by a very low amplitude (tens of μV), high frequency (up to hundreds of Hz), short duration (up to 150 ms) and significant variability of characteristics from one

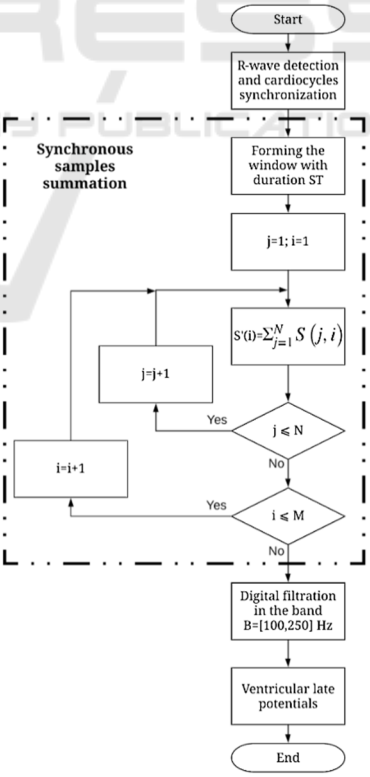

Figure 3: Temporal summation VLP detection method.

cardiocycle to another. This fact makes it difficult to detect and analyze ventricular late potentials (VLP).

When using temporary summation (figure 3), R prongs are first allocated on the ECG signal, relative to which a window that coincides with the ST segment is formed. Within this window, for all N (usually up to 150) cardiocycles, synchronous accumulation (summation) of discrete ECG signal counts is performed.

For one cardiocycle, the number of samples can reach m = 200. With synchronous accumulation, the amplitude of the late ventricular potential increases N times and reaches a level of tens of mV. It is filtered by a band-pass filter in the range from 100 to 250 Hz in order to eliminate the low-frequency components of the ST segment. The rest of the signal represents the ventricular late potential. The considered method of synchronous signal accumulation for detecting the ventricular late potential has advantages and disadvantages. The advantage is the simplicity and using only one channel of the surface ECG signal. Disadvantages exceed advantages. The presence of noise fluctuations in the ECG signal leads to the detection of R prongs and the formation of a window within which synchronous accumulation is performed, with an error of up to 2-3 reports of the sampling signal at a sampling frequency of 1,0 kHz, which in turn smears the ventricular late potential and distorts the high-frequency components. Another disadvantage is the inability to assess the dynamics of the characteristics of the VLP and their duration due to the long stage of accumulation (up to 150 cardiocycles).

The spatial accumulation method (figure 4) is devoid of these disadvantages. However, it requires performing synchronous recordings of surface ECG signals over 12 channels, detecting R prongs, forming the window for detecting the samples of ECG signals on ST segment, summing up identical discrete samples across all channels, band-pass filtering of the resulting signal in the range from 100 to 250 Hz.

The resulting signal represents the ventricular late potential obtained from the spatial summation of multichannel ECG signals. The advantage of the considered method is that it allows reflecting the dynamics of the characteristics of the VLP signal, and is less sensitive to fluctuation noise, because the formation of the window and synchronization of the summation of the samples is carried out simultaneously on all channels. However, this method has a drawback. It does not allow to significantly increase the amplitude of the VLP signal, the gain does not exceed 12.

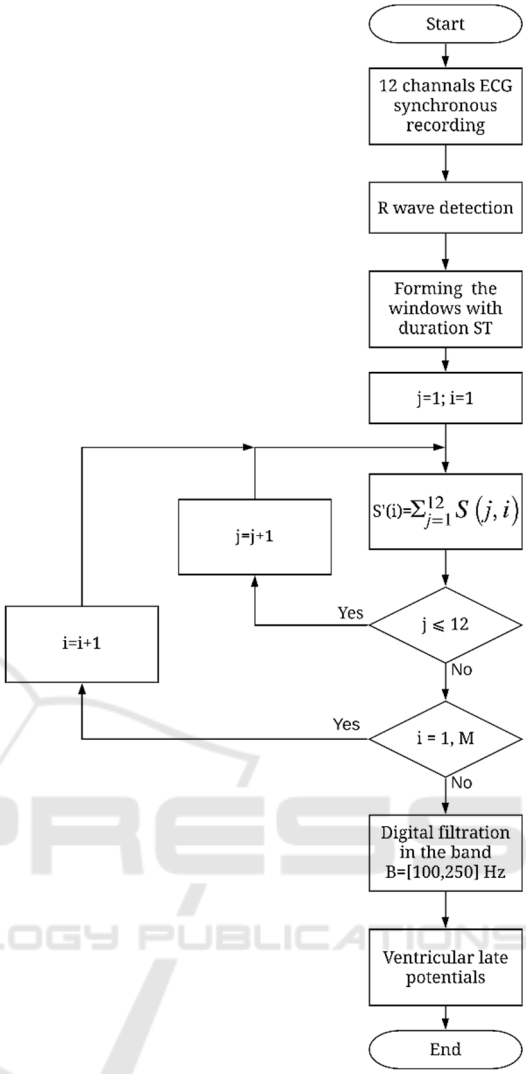

Figure 4: Spatial accumulation VLP detection method.

3.3 Fragmented QRS and VLP Research

Studies of ventricular late potentials were performed on 16 patients using synchronous recording of intracardiac ventricular electrograms and 12 leads of surface ECG (Yuldashev, Anisimov, Nemirko et al., 2019). The ventricular late potentials were detected on intracardiac electrograms in all cases, while surface ECGs did not visually reveal these abnormalities due to very low levels of late potentials amplitude, short duration, and high frequency of electrical vibrations (figures 5 -7).

The ventricular late potentials detected by intracardiac electrograms almost in most cases correlate well with various ventricular myocardial disorders. As the results of studies [1, 4, 6, 7, 8] show, the accuracy and sensitivity of the diagnosis of both

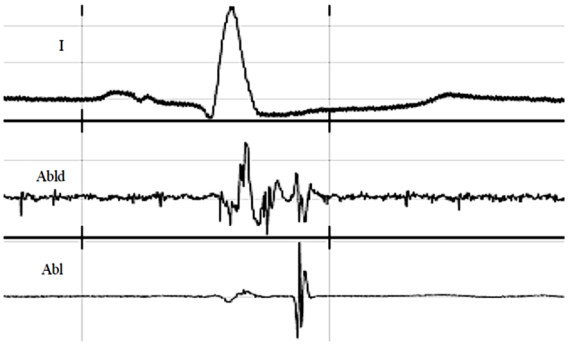

Figure 5: Example of VLP detection.

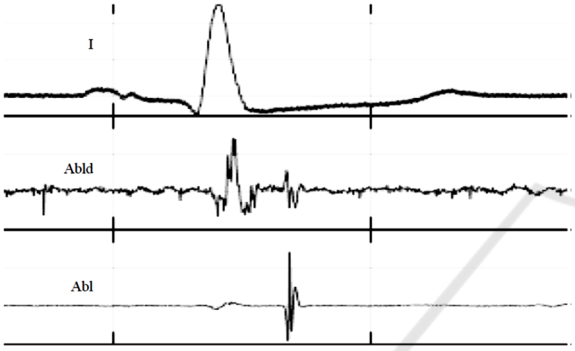

Figure 6: Example of VLP detection.

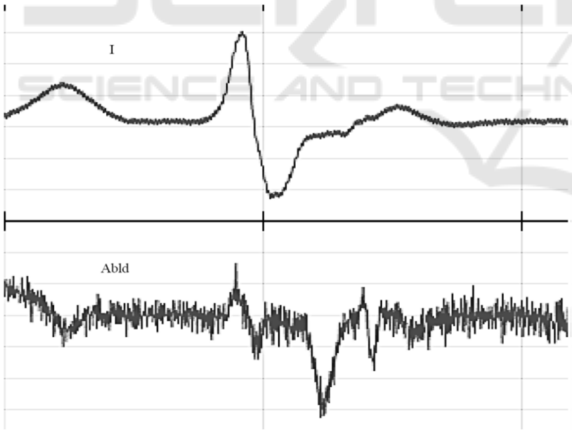

Figure 7: Example of VLP detection.

dangerous cardiac arrhythmias due to cardiac conduction disorders and myocardial cell morphology using ventricular late potentials is at least 92%.

The results of these studies confirm the need for further improvement of methods and technologies for identifying fragmented and late potentials using surface ECGs and verifying their results using intracardiac electrograms.

3.4 Clinical and Development Perspective

To the best of our knowledge, the signal database created within the scope of this work is one of the first of its kind and will be used in future research.

Processing algorithms for automatic local electrical abnormal potentials detection are under development in this project, and, once developed, will be useful with potential future implementation into invasive electrophysiological diagnostic systems.

The prediction algorithms based on surface ECG analysis could be useful in estimation of the presence and localization of local abnormal electrical activity and will be of clinical importance, since might be implemented into pre-procedure planning of the access and extent of catheter ablation.

4 CONCLUSIONS

The results of the studies confirm the conclusions about the need and feasibility of using the ventricular late potentials and fragmented potentials for the diagnosis of dangerous heart disorders. Of course, in a clinical setting, the results of recording intracardiac electrograms can be used to diagnose that disorders. However, often there is a need for the diagnosis of cardiac abnormalities outside the clinic, in particular at home using a wide range of electrocardiographs. To diagnose heart disorders that pose a threat to the patient's life, at home it is necessary to use tools and software that will record surface ECG signals and identify fragmented and late heart potentials hidden in surface ECG signals. Given that the accuracy of the diagnosis of such heart disorders using methods of pre-processing and synchronous signal accumulation is quite high, such devices will significantly improve the quality of medical care for cardiac patients.

ACKNOWLEDGEMENTS

This research was supported by Russian Foundation for Basic Research (RFBR), research projects 18-29-02036, 19-29-01009.

REFERENCES

Breithardt, G., Borggrefe, M., Martinez-Rubio, A. et al, 1988. Prognostic significance of ventricular late

potentials in the postmyocardial infarction period. In *Herz*. Bd 13, №3, pp.180-187.

Simson, M. B., Euter, D. E., Michelson E. L., et al, 1981. Detection of delayed ventricular activation on the body surface in dogs. In *Amer. J. Physiol*. Vol. 241, pp. H363-H369.

Simson, M. B., 1983. Clinical application of signal averaging. In *Cardiol. Clin.* Vol. 1, pp. 109-190.

Breithardt, G., Cain, M. E., El-Sherif, N. et al., 1991. Standards for analysis of ventricular late potentials using high resolution or signal-averaged electrocardiography. A statement by a Task Force Committee between the European Society of Cardiology, the American Heart Association and the American College of Cardiology. In E*ur. Heart. Journal*. Vol. 12(4), pp. 473-480.

Kreiner, G., Gottlieb, C. D., Furukawa, S. et al., 1992. Late potentials in an ovine model of acute transmural myocardial infarction. In *J. Appl. Physiol*. Vol. 73(3), pp. 841-846.

Wong, C. B., Windle, J. R., 1994. Clinical applications of signal averaged electrocardiography in patients after myo cardial infarction. In *Nebraska Medical Journal*. Vol. 79(2), pp. 28-31.

Teptin, G. M., Latfullin, I. A., Konturov, S. W., Mamedova, L. E., 2004. Analysis of low amplitude cardiac signals and its interpretation. In *Environmental Radioecology and applied ecology*. Vol. 10, №1, pp. 3-7.

Ohisa, N., Ohira, M., Mizonobe, K. et al., 2002. Comparative study of T-wave alternans, QT c dispersion and late potential for predicting ventricular tachycardia in patients with ischemic heart disease. In *Rinsho Byori*. Vol. 50(2), pp.191-195.

Simonova, K. A, Lebedev, D. S, Mikhaylov, E. N., 2017. Epicardial mapping and ablation in management of ventricular tachycardia. In *Complex Issues of Cardiovascular Diseases*. Vol 6(4), pp. 138-145.

Simonova, K. A, Mikhaylov, E. N, Tatarskiy, R. B et al., 2019. Epicardial arrhythmogenic substrate in patients with postinfarction ventricular tachycardia: a pilot study. In *Journal of Arrhythmology*. Vol 1(95), pp. 38-46.

Yuldashev, Z., Nemirko, A., Manilo, L. et al., 2019. Processing of Synchronous Recordings of Surface ECG and Intracardiac Potentials for Diagnostics of Dangerous Heart Rate Disturbances. In *Proceedings Ural Symposium on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT)*. PP. 102-105.

Yuldashev, Z., Anisimov, A., Nemirko, A. et al., 2019. Heart rate disorders identification using superficial ECG and invasive electrogram. In *AIP Conference Proceedings.*