cor et vasa xxx (2018) e1–e7

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/crvasa

Review article

Heart rate variability in atrial septal defect both before and after operation

V.A. Shvartz [a], *A.R. Kiselev* [a,b,*], *O.L. Bockeria* [a]

[a] *Department of Surgical Treatment for Interactive Pathology, Bakoulev Scientific Center for Cardiovascular Surgery, Moscow, Russia*

[b] *Department of Innovative Cardiological Information Technology, Institute of Cardiological Research, V.I. Razumovsky Saratov State Medical University, Saratov, Russia*

ARTICLE INFO

Article history:
Received 11 July 2018
Accepted 3 August 2018
Available online xxx

Keywords:
Cardiovascular system
Heart rate variability
Atrial septum defect
Children
Neurovegetative homeostasis
Vegetative abnormalities
Mortality

ABSTRACT

Over the recent decades, study of vegetative influence on the heart and its evaluation as a predictor of mortality due to cardiac problems and development of cardiovascular complications raised a considerable interest. Heart rate variability (HRV) analysis is a simple, noninvasive and safe method to study vegetative regulation of the human cardiovascular system. In the view of some authors, in patients suffering from structural heart defects, a decrease in HRV due to volume overload of the heart may cause elevation of pressure in the heart cavities, possible dysfunction of baroreceptors and can result in vegetative imbalance. During surgery, the neurovegetative homeostasis is extremely vulnerable that makes one think about the surgical stress influence on the autonomic nervous system. Despite numerous studies, there is still no holistic approach in determining the body response to surgical interventions in cardiosurgical patients. Generally, decreased heart rate variability after cardiac surgery gradually restores in the postoperative period within several months. This article is a literature review of the data on the characteristics of HRV in patients with atrial septal defect (ASD), as well as the regularities of its dynamics after surgical and X-ray endovascular correction of the defect. The article also highlights possible pathophysiology of these vegetative abnormalities.

Contents

Introduction 000
The main idea and clinical application of HRV 000
HRV in case of ASD 000
Features of HRV dynamics after surgical and endovascular correction of ASD 000
Conclusion 000

* *Corresponding author at*: Institute of Cardiological Research, V.I. Razumovsky State Medical University of Saratov, 112, Bolshaya Kazachya str., Saratov 410012, Russia.

E-mail addresses: shvartz-va@ya.ru (V.A. Shvartz), kiselev@cardio-it.ru (A.R. Kiselev), soleo2003@gmail.com (O.L. Bockeria).
https://doi.org/10.1016/j.crvasa.2018.08.001

Ethical statement . . . 000
References . . . 000

Introduction

Heart rate variability (HRV) is a physiological feature that characterizes vegetative regulation of the heart rhythm. The interest to study HRV appeared more than 40 years ago, when the association of the decrease in HRV in patients with acute myocardial infarction (AMI), with an increase in mortality in this group of patients was first described [1]. Currently, the analysis of HRV is actively studied in the clinical practice to determine the influence of parasympathetic and sympathetic systems on the sinus node function, as well as the likelihood of cardiovascular complications and lethality [2,3]. Decrease in HRV has been described in patients with various heart diseases, such as ischemic heart disease (IHD), including AMI, congestive heart failure (CHF), mitral insufficiency of various etiologies, as well as in patients with congenital heart disease (CHD), including atrial septal defect (ASD) [4–6].

Secondary ASD holds one of the leading positions among heart defects and is found in 10% of cases among all CHDs diagnosed in infancy. Moreover, in adulthood, it occurs in 30–40% of cases [7]. HRV decrease at ASD has been described for both temporal and frequency ranges of the HRV spectrum, with assumptions being made about the etiology of changes in autonomic nervous system activity in this category of patients [8,9].

The current article is a review of literature data on the characteristics of HRV in patients with ASD, as well as the patterns of its dynamics after surgical and X-ray endovascular correction of the defect. The article also highlights the possible pathophysiology questions of these vegetative features.

The main idea and clinical application of HRV

HRV is a physiological marker of the effects of the autonomic nervous system on the regulation of heart rhythm. In 1996, a team of scientists from the European Society of Cardiology and the North American Society of Electrophysiology issued recommendations on the standards for the determination of HRV, physiological interpretation of results and clinical application of the method [10]. In Russia, the first symposium on mathematical analysis of the heart rhythm was held in Moscow in 1966, the first monograph on HRV was published in 1984, and recommendations for the analysis of short HRV records appeared in 1999 [11,12].

HRV can be evaluated in several ways. The simplest of these is the assessment of the time range. It uses parameters such as standard deviation of R–R (NN) intervals (SDNN); percentage of consecutive intervals differing by more than 50 ms (pNN50); square root of the mean sum of squared differences between adjacent normal R–R intervals (r-MSSD); the mean value of standard deviations of R–R intervals for all 5-min fragments (SDANN), etc. A lot of research work around the world has been devoted to the study of the physiological and clinical significance of the said time-domain parameters of HRV. There is an opinion that the overall tone of the autonomic nervous system can be assessed from the value of the SDNN parameter; the tone of the parasympathetic nervous system can be assessed according to pNN50 and r-MSSD; the tone of the sympathetic nervous system can be assessed according to SDANN [12].

Various methods of spectral analysis of HRV have been proposed since the late 1960s. Spectral analysis makes it possible to study the variability of the heart rhythm in dynamics, while time-domain methods show only the averaged variability parameters over a fixed time interval. Currently, the following parameters are used to analyze the spectral range of HRV: maximum total power of the spectrum (Total Power, TP), high-frequency spectral power (High Frequency, HF: 0.15–0.35 Hz), low-frequency spectral power (Low Frequency, LF: 0.05–0.15 Hz), very low-frequency spectral power (Very Low Frequency, VLF: 0.0033–0.05 Hz) and ultra-low frequency spectral power (Ultra Low Frequency, ULF: 0–0.0033 Hz) of components, as well as the LF/HF ratio.

The main problem of spectral analysis is the evaluation of the physiological and clinical significance of the obtained results [3]. Nevertheless, according to the classical physiological interpretation, for the short stationary recording sections (5-min samples), the high-frequency component of the spectrum (HF) reflects primarily the level of respiratory arrhythmia and parasympathetic influences on the heart rhythm, the low-frequency component (LF) – mainly sympathetic influences, but parasympathetic tone also affects its formation [13]. Sometimes the ratio of low frequencies to high frequencies (LF/HF) that reflects the level of vagosympathetic balance is also being calculated, although it is believed that this ratio can serve as an indicator of the activity of the sympathetic part of the autonomic nervous system. The LF/HF index shows its clinical effectiveness, in particular in the diagnosis of posttortostatic tachycardia and syncopal conditions caused by vegetative dysfunction [13].

The clinical evaluation of the peculiarities of vegetative regulation and its influence on the cardiovascular system is of great interest both in adult and in pediatric cardiology, since HRV analysis can be used to assess the risks of cardiovascular complications and mortality in patients with cardiovascular pathology [10]. The negative effect of the dominance of sympathetic activity over the parasympathetic activity and, on the contrary, the protective role of the predominance of vagal activity in patients with diseases of the cardiovascular system are widely described in the literature. The features of treatment aimed at decreasing sympathetic activity and/or increasing vagal activity have been shown to reduce mortality from cardiac causes [14].

HRV in case of ASD

The hemodynamics of isolated ASD is characterized by the presence of a communication at the level of the atria, leading to left–right venting, volume overload and, subsequently, to an increase in the right heart, increased pulmonary artery pressure and its expansion. It has now been proven that a prolonged overload of the right atrium, right ventricle, and pulmonary artery leads to the development of CHF, and also increases the risk of arrhythmias and thromboembolic complications, which naturally increases lethality [15].

Patients with ASD with enlarged right heart have a decrease in HRV for both adults and children. It is important, however, to note that HRV in children is generally increased during the first 2 years of life. It is subjected to significant fluctuations that depend on age, which in turn is associated with high dynamics of heart growth. This complicates the analysis of HRV in children of this age [16].

Finley et al. in their research analyzed the age-dependent changes of HRV [17]. The study included 29 healthy individuals without concomitant pathology (17 men and 12 women), who were distributed in three groups: 9 young people aged 20–24 years, 9 teenagers aged 10–12 years and 11 children aged 5–7 years. The rhythm of the heart and respiratory waves were recorded in a standing and lying position for 3–4 min. As a result, the following data were obtained: the values of LF and HF decreased with age in the prone position. The greatest difference was noted between groups of adolescents and children. In all three groups, there was a wide variability in the LF parameter, which was most pronounced in the group of children (more than 100 ms^2). As for the high-frequency spectrum, its variability was lower than in the low-frequency spectrum, in all groups. The vagosympathetic interaction index (LF/HF) decreases with age, the greatest change was observed between 5 and 12 years. In the standing position, the results were similar.

The same Finley et al. in further researches, as well as Massin and his group, showed a significant decrease in the temporal parameters of HRV in children with ASD and showed an increase in the sympathetic activity of heart regulation and a decrease in parasympathetic activity [18,19].

In the work of Bakari et al. [8], the HRV analysis was performed both in the time and frequency ranges. 28 patients with ASD at the age of 4.5 years to 8.7 years and 32 healthy children of the same age without hemodynamic disorders were studied. The analysis of time- and frequency-domain parameters was carried out. All HRV parameters appeared to be decreased in children with ASD compared with healthy children. The SDNN parameter in sick children was 103.0 ± 50.6 ms, while in the control group this parameter was 138.7 ± 36.2 ms. The r-MSSD parameter in the group of children with ASD was 41.3 ± 32.9, and in the control group – 69.0 ± 34.2 ms. In the frequency spectrum, a significant decrease in the total power of the spectrum was revealed, as well as a decrease in HF and LF/HF. The obtained results showed a decrease in HRV in both methods of analysis, which confirms the dominance of sympathetic activity and a decrease in vagal effect in children with ASD [11].

The decrease in HRV, according to several authors, is associated with a volume overload of the right heart, which leads to an increase in the end-diastolic pressure in the right ventricle and possible dysfunction of the ventricular baroreceptors and, consequently, to a violation of the sympathetic balance [8,18,19]. Massin and Fergusson report that the dependence of the decrease in HRV on the degree of hemodynamic changes in case of the heart defect, such as increased right ventricular pressure and pulmonary hypertension [8,20].

Hata et al. in their paper made an interesting comparison of HRV parameters in two groups of patients: with ASD and a ventricular septal defect (VSD) to confirm the hypothesis of HRV relations with anatomical and hemodynamic changes [21]. For this, the correlation between HRV, respiratory vibrations (RSA – the amplitude of respiratory sinus arrhythmia) and the ratio of pulmonary blood flow to the systemic one, measured with the help of echocardiogram (Qp/Qs parameter) was evaluated. The study included 43 children with ASD at the age of 4.6 ± 3.6 years and 40 children with VSD at the age of 4.1 ± 6.4 years. All children underwent spectral analysis of HRV, as well as an assessment of RSA and Qp/Qs.

As a result, it was shown that LF/HF ratio and Qp/Qs parameter have an average but positive correlation in both groups of patients (in the group with ASD $r = 0.6$, in the group with VSD $r = 0.47$). The ratio of low-frequency oscillations to respiratory vibrations (LF/RSA) also positively correlates with Qp/Qs in the group with ASD ($r = 0.65$), and negative correlation in the group with VSD ($r = 0.41$). In the group of patients with ASD there was a negative correlation between respiratory vibrations and the total power of the RSA/TP and Qp/Qs spectrum ($r = -0.58$), whereas in patients with VSD these correlations were positive ($r = 0.58$). While the hemodynamics of both defects is characterized by the presence of a left–right discharge with an overload of the right heart, the effects of an increase in volume and pressure in the atrium or ventricle appear to be different, which is manifested in various changes in HRV. An overload of the right atrium with volume and pressure in case of ASD leads to the atrium overstretching and a decrease in the respiratory vagal innervation of the sinus node (negative correlation of RSA/TP and Qp/Qs). In case of VSD, an increase of pressure in the pulmonary artery is the cause of a decrease in HRV, and the LF/RSA and RSA/TP parameters show an increase in the respiratory vagal activity associated with an increase in Qp/Qs. The change in HRV in patients with ASD and VSD shows the involvement of respiratory stretch receptors, associated with respiratory movements, and baroreceptors in the right atrium that contribute to the high-frequency component of HRV.

Supraventricular cardiac arrhythmias in patients with ASD are the result of stretching and dilatation of the right atrium. Supraventricular cardiac tachyarrhythmias are often found in adult patients with secondary ASD and lead to a significant increase in the incidence of cardiovascular events in this category of patients [22].

Edwards et al. showed that the atrial stretching (as a result of volume overload) is the main factor stimulating the secretion of the atrial natriuretic peptide. According to the results of this study, it can be assumed that the lack of volume and pressure overload, as well as a decrease in the influence of neurohumoral factors, leads to the normalization of HRV in patients with ASD [23].

Horner et al. in their experimental study on pigs showed that mechanical stretching of the zone of the sino-atrial node in the right atrium due to volume overload of the right heart can affect HRV via the direct effect on a slow diastolic depolarization through mechanically activated heart channels or through the afferent nerve stretching reflex [24].

Bakari et al. also describe a connection between tachycardia with an increase in LF variability and a decrease in HF variability. The increase in the right atrium that is characteristic of this defect is considered by the authors to be responsible for respiratory vibrations ``muffling''. According to their paper, this explains the decrease in HRV revealed by spectral analysis. The progressive decrease in the time- and frequency-domain parameters of HRV reflects a decrease in the nervous regulation of the sinoatrial node, which appears due to an increase in the level of norepinephrine in the blood plasma, and authors call it as one of the factors that lead to the development of supraventricular arrhythmias [8].

Features of HRV dynamics after surgical and endovascular correction of ASD

Currently, the fact of the surgical treatment of ASD necessity is undeniable, however, the search for an ``ideal'' method of the disease correction continues to this day. Increasingly, the literature describes the benefits of catheter closure of the ASD with an occluder, as a safe and effective procedure that is simple in technical terms and has a small number of possible complications, as well as shorter periods of the patient's stay in the hospital. At the same time, catheter closure of ASD has a number of limitations, such as the anatomical location of the defect or the age of the child. This makes the procedure impossible and leads to the need for open surgery under conditions of artificial blood circulation (ABC) [25,26].

There are many non-specific factors, both at the stage of preoperative preparation of the patient, as well as during the intervention, which may influence the decrease in HRV after the operation (for example, stress, pain, and medications receipt). The most important factor that affects the dysfunction of the autonomic nervous system is the IR itself.

Heragu and Scott describe the decrease in all time- and frequency-domain parameters of HRV in a group of 36 children with various congenital heart defects aged from 2 weeks to 15 years after 6 days from the open heart surgery compared with the control group of healthy children. In the group of children, the SDNN parameter after the operation was 48 ± 22 ms, while in the control group its value was 93 ± 41 ms. The LF and HF spectra were also sharply decreased. The authors suggest a possible connection between the decrease in HRV and a decrease in the sensitivity of the sinus node to the autonomic stimulation in the early postoperative period [16].

Finley et al. [18] in their study showed that HRV in children with ASD is significantly decreased when compared with a healthy group of children, but all parameters increase and approach the parameters of healthy patients after surgical correction. The authors studied children with ASD at the age of 4–16 years (n = 10) who made up the comparison group, and 10 practically healthy children aged 5–7 years who made up the control group. All the sick children had no clinical manifestations of the defect, but there were signs of a volume overload of the right heart in the X-ray and ultrasound studies. The HRV analysis was performed in the time and frequency ranges. Prior to surgery, a significant decrease in SDNN was observed in sick children compared to the control group. A similar picture is described for the frequency spectrum. All children of the first group underwent ASD suturing or plastic surgery under conditions of infrared radiation. The HRV parameters in them immediately after the operation remained lowered (compared to the control group), which, likely, was due to a complex of factors including both the artificial circulation, the painfulness of the operation, and duration of the postoperative period in the hospital, as well as stress. The authors of the study emphasize that, despite the residual decrease in HRV after the operation, its parameters still increased in comparison with the data before the operation, which confirms the relationship of HRV with anatomical changes in the heart. The main factors influencing the development of sinus arrhythmia in healthy individuals are right atrial dilatation that is associated with an increase in systemic venous return, and inhibition of the carotid sinus reflex upon inhaling, which leads to the development of tachycardia. Due to the hemodynamics of ASD (volume overload of the right half of the heart), respiratory waves are muted, which can contribute to a decrease in HRV.

In contrast to the surgical method, in the case of catheter closure of ASD, all parameters of HRV demonstrate a significant early increase in the post-procedure [9,27]. Such results may be due to less invasive intervention, than after surgical closure of ASD.

Białkowski et al. [27] in their comparative study describe 19 children aged from 2.5 to 14 years with non-symptomatic ASD, who were divided into two groups: 11 children had implantation of the occluder, whereas other 8 children were performed surgical closure of ASD. The temporal parameters of HRV were analyzed. Before the operation, the HRV of children in both groups did not differ. Thus, SDNN in the group with implanted occluder was 94 ± 14 ms, and r-MSSD – 32 ± 11 ms; the group with the surgery – 85 ± 25 ms and 32 ± 15 ms, respectively. The authors describe the increase in HRV parameters in the period from 1 to 3 months after implantation of the occluder. The SDNN and rMSSD parameters were 119 ± 23 ms and 40 ± 10 ms after 1 month and 135 ± 27 ms and 46 ± 10 ms after 3 months respectively. The difference was statistically significant in the dynamics for SDNN and SDANN after 1 month ($p < 0.05$) and for all HRV parameters after 3 months ($p < 0.01$).

In contrast, in the group with ASD surgery, there was an even greater decrease in all HRV parameters compared to the initial ones and 1 month after intervention ($p < 0.001$). Three months after the operation, the parameters of the HRV significantly increased ($p = 0.005$) when compared with the measurements 1 month from the operation, but did not reach the values of the HRV of the endovascular group. The SDNN and r-MSSD parameters in 1 month were 60 ± 13 ms and 19 ± 7 ms, respectively, while after 3 months the parameters increased to 112 ± 37 ms and 30 ± 12 ms, respectively.

The authors consider the lack of a spectral analysis of HRV as a major drawback of their research, which, according to many researchers, is the best indicator of the activity of vegetative regulation of the heart.

Özyılmaz et al. [28] in their study observed children with ASD before and after the endovascular treatment. The criteria for inclusion in the study were: ASD of more than 12 mm in diameter; signs of congestion of the right heart according to ECHO data and the possibility of catheter closure of the defect. The time and frequency ranges of HRV were analyzed by daily monitoring of the ECG according to the Holter. In total, the study included 47 children with ASD (mean age – 9.6 years), who made up the study group. The control group included 30 almost healthy children without hemodynamic disorders (mean age – 10.4 years). HRV parameters were assessed the day before implantation of the occluder, the day after the procedure and 6 months later. As a result, the data obtained showed a decrease in the time-related parameters of HRV in the study group before the operation compared with the control group. The SDNN and r-MSSD parameters in sick children before the operation were 90.3 ± 28.1 ms and 42.3 ± 22.4 ms, respectively, with SDNN and r-MSSD values equal to 137.5 ± 42.5 ms and 58.1 ± 28.5 ms, respectively, in the control group. The next day after the catheter correction of the defect, the parameters of the time range of HRV in patients showed a significant increase. The SDNN was 108.3 ± 26.2 ms, and the r-MSSD was 59.0 ± 27.4 ms. After 6 months, the parameters of the time range of HRV in sick children were comparable to the control group.

The spectral analysis initially showed increased parameters of the LF spectrum and decreased parameters of the HF spectrum in ill children compared to those in the control group: LF = 58.63 ± 13.23 ms^2 in the group of patients and 45.69 ± 15.13 ms^2 in the control group; HF was 29.78 ± 10.65 ms^2 in the group of patients and 44.29 ± 13.14 ms^2 in the control group. These results perfectly correlate with the hypothesis of an increase in parasympathetic activity and a decrease in sympathetic activity in patients with ASD. Immediately after the procedure, there is a notable decrease in parasympathetic activity (LF = 46.83 ± 14.38 ms^2) and an increase in sympathetic activity (HF = 34.51 ± 10.15 ms^2). After 6 months, the parameters of the frequency spectrum turned out to be the same as in the control group (LF = 50.40 ± 24.09 ms^2, HF = 39.28 ± 19.86 ms^2). The authors consider the confirmation of a decrease in both HRV ranges in patients with ASD compared with the control group, an increase in the parameters in the early postoperative period and their normalization in 6 months after the intervention as the most important conclusions. The obtained results can be explained by changes in the autonomic regulation of the cardiovascular system, namely, in the increase of vagal activity and in the decrease in sympathetic activity.

The study of Cansel et al. [9] is devoted to the study of the influence of the endovascular treatment of ASD on HRV in adult patients. The study included 30 patients with ASD (diameter from 8.8 mm to 22.4 mm) at the age of 18–64 years who made up the study group and 30 people without hemodynamic disorders aged 19–40 years who made up the control group. The HRV parameters were studied before and after the interventional treatment of ASD and were also compared with the control group. HRV analysis was performed in the time range and showed that the HRV parameters in the study group before implantation of the occluder significantly differed from the control one. Thus, SDNN was 103.9 ± 29.4 ms in the group of patients and 139.2 ± 30.3 ms in the control group; the r-MSSD in the group of patients was 27.1 ± 16.1 ms and 31.1 ± 7.9 ms in the control group. The occluder was implanted in all patients. The repeated HRV analysis was performed 6 months after the surgery and showed normalization of HRV parameters. The SDNN parameter was 131.1 ± 41.3 ms, the r-MSSD parameter was 31.5 ± 13.8 ms. This study once again emphasizes the effect of changes in hemodynamics in case of ASD (overload of the right heart with volume) on the temporal parameters of HRV.

The weakening of the influence of the autonomic nervous system is associated with an increased risk of sudden death in patients with congenital heart diseases [29]. The above-mentioned studies demonstrate a decrease in vagal activity and HRV parameters in patients with ASD, which is associated with hemodynamic changes. In both adults and children with ASD, the closure of the defect leads to an increase in vagal influences and a decrease in sympathetic activity, which is manifested in an increase in the HRV parameters in the time and frequency range with their normalization in 3–6 months. This can be explained by a decrease of the blood volume flowing into the right atrium, due to the elimination of left–right drop at the level of the atria.

Conclusion

The change in hemodynamics in case of ASD, namely, the volume overload of the right heart and the development of pulmonary hypertension, as well as the change in the geometry of the right heart with this defect, according to the literature, leads to a change in the autonomic nervous system functioning and to a decrease in HRV parameters in both temporal and frequency range.

Taking the hemodynamics of ASD into account, we can assume similar HRV characteristics in case of other pale vices, however, these changes in patients with ASD and VSD correlate differently with Qp/Qs (ratio of pulmonary blood flow to systemic) [21]. This fact suggests that a key role in the characteristics of HRV in case of ASD is played by an overload with volume and pressure of the right atrium only and not of all sections of the right heart. Experimental studies show that mechanical stretching of the sinus node in the right atrium can directly affect the function of the autonomic nervous system through mechanically activated channels of the heart or through the afferent nerve of the stretching reflex [24].

The treatment of ASD is aimed at the elimination of the left–right discharge of blood, and, as a consequence, the elimination of the geometric changes in the heart caused by the volumetric overload. The consequence of the reverse heart remodeling is, apparently, the normalization of HRV. Both surgical and transcatheter correction of ASD meet the outlined above conditions, however, each method has its limitations. According to available data, the recovery of HRV occurs more rapidly after endovascular treatment. Moreover, this method is deprived of such factors that accompany cardiac surgery, as a severe postoperative period, the use of infrared radiation, as well as such nonspecific factors as pain and fear, which undoubtedly contribute to the change in HRV after an open heart surgery.

The possibilities and prognostic significance of the clinical use of HRV encourage researchers to further develop mathe-

Please cite this article in press as: V.A. Shvartz et al., Heart rate variability in atrial septal defect both before and after operation, Cor et Vasa (2018), https://doi.org/10.1016/j.crvasa.2018.08.001

matical methods for HRV analysis, as well as to search for new techniques for studying the features of vegetative regulation of the circulatory system and their clinical significance in various pathologies [30–32]. The continuation of the problem studying can help in understanding the connection of autonomic regulation of the heart with the development of postoperative complications and mortality in this category of patients. This will also lead to the creation of diagnostic criteria for identifying patients at a high risk.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

Funding body

The article is written in the framework of the project of the Russian Science Foundation, grant no. 18-74-10064.

REFERENCES

[1] B. Lown, R.L. Verrier, Neural activity and ventricular fibrillation, The New England Journal of Medicine 294 (21) (1976) 1165–1170. , http://dx.doi.org/10.1056/NEJM197605202942107.

[2] E.A. Volchkova, A.A. Zateishchikova, I.V. Shavrin, et al., The influence of the vegetative balance on the development of atrial fibrillation in patients with chronic obstructive pulmonary disease, Annaly Aritmologii 11 (1) (2014) 24–31. , http://dx.doi.org/10.15275/annaritmol.2014.1.3 (Russian).

[3] M. Tulppo, H.V. Huikuri, Origin and significance of heart rate variability, Journal of the American College of Cardiology 43 (12) (2004) 2278–2280. , http://dx.doi.org/10.1016/j.jacc.2004.03.034.

[4] A.R. Kiselev, V.I. Gridnev, O.M. Posnenkova, et al., Changes in the power of the low- and high-frequency bands of the heart rate variability spectrum in coronary heart disease patients with different severities of coronary atherosclerosis in the course of load tests, Human Physiology 34 (3) (2008) 312–318. , http://dx.doi.org/10.1134/S0362119708030079.

[5] V.A. Shvartz, A.S. Karavaev, E.I. Borovkova, et al., Investigation of statistical characteristics of interaction between the low-frequency oscillations in heart rate variability and photoplethysmographic waveform variability in healthy subjects and myocardial infarction patients, Russian Open Medical Journal 5 (2016) e0203, http://dx.doi.org/10.15275/rusomj.2016.0203.

[6] M.M. Massin, B. Derkenne, G. von Bernuth, Heart rate behavior in children with atrial septal defect, Cardiology 90 (1998) 269–273. , http://dx.doi.org/10.1159/000006857.

[7] M.Y. Abd El Rahman, W. Hui, J. Timme, et al., Analysis of atrial and ventricular performance by tissue Doppler imaging in patients with atrial septal defects before and after surgical and catheter closure, Echocardiography 22 (7) (2005) 579–585. , http://dx.doi.org/10.1111/j.1540-8175.2005.40019.x.

[8] S. Bakari, B. Koca, F. Oztunç, M. Abuhandan, Heart rate variability in patients with atrial septal defect and healthy children, Journal of Cardiology 61 (6) (2013) 436–439. , http://dx.doi.org/10.1016/j.jjcc.2013.01.014.

[9] M. Cansel, J. Yagmur, N. Ermis, et al., Effects of transcatheter closure of atrial septal defects on heart rate variability, The Journal of International Medical Research 39 (2) (2011) 654–661. , http://dx.doi.org/10.1177/147323001103900235.

[10] Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, Circulation 93 (1996) 1043–1065.

[11] R.M. Baevskii, O.I. Kirillov, S.Z. Kletskin, Mathematical Analysis of Cardiac Rhythm Changes Under Stress, USSR: Nauka, Moscow, 1984 (Russian).

[12] R.M. Baevskii, G.G. Ivanov, L.V. Chireikin, et al., Analysis of heart rate variability with the use of various electrocardiographic systems, Vestnik Aritmologii (24) (2001) 65–87 (Russian).

[13] A.R. Kiselev, V.I. Gridnev, Oscillatory processes in vegetative regulation of cardiovascular system, Saratov Journal of Medical Scientific Research 7 (1) (2011) 34–39 (Russian).

[14] A.M. Alieva, N.I. Bulaeva, O.I. Gromova, E.Z. Golukhova, Heart rhythm variability in assessment of clinical state and prognosis in congestive heart failure, Creative Cardiology 9 (3) (2015) 42–55 (Russian).

[15] G.A. Reyes del Paso, W. Langewitz, L.J. Mulder, et al., The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: a review with emphasis on a reanalysis of previous studies, Psychophysiology 50 (5) (2013) 477–487. , http://dx.doi.org/10.1111/psyp.12027.

[16] N.P. Heragu, W.A. Scott, Heart rate variability in healthy children and in those with congenital heart disease both before and after operation, The American Journal of Cardiology 83 (12) (1999) 1654–1657. , http://dx.doi.org/10.1016/S0002-9149(99)00173-3.

[17] J.P. Finley, S.T. Nugent, W. Hellenbrand, Heart-rate variability in children. Spectral analysis of developmental changes between 5 and 24 years, Canadian Journal of Physiology and Pharmacology 65 (10) (1987) 2048–2052. , http://dx.doi.org/10.1139/y87-320.

[18] J.P. Finley, S.T. Nugent, W. Hellenbrand, et al., Sinus arrhythmia in children with atrial septal defect: an analysis of heart rate variability before and after surgical repair, British Heart Journal 61 (3) (1989) 280–284. , http://dx.doi.org/10.1136/hrt.61.3.280.

[19] M.M. Massin, B. Derkenne, G. von Bernuth, Heart rate behavior in children with atrial septal defect, Cardiology 90 (1998) 269–273. , http://dx.doi.org/10.1159/000006857.

[20] J.J. Ferguson 3rd, M.J. Miller, J.M. Aroesty, et al., Assessment of right atrial pressure-volume relations in patients with and without an atrial septal defect, Journal of the American College of Cardiology 13 (3) (1989) 630–636. , http://dx.doi.org/10.1016/0735-1097(89)90604-9.

[21] T. Hata, S. Mano, M. Kusuki, et al., Difference in autonomic nervous control between ventricular septal defect and atrial septal defect based on heart rate variability, Pacing and Clinical Electrophysiology 30 (Suppl. 1) (2007) S212–S214. , http://dx.doi.org/10.1111/j.1540-8159.2007.00640.x.

[22] G. Webb, M.A. Gatzoulis, Atrial septal defects in the adult: recent progress and overview, Circulation 114 (15) (2006) 1645–1653. , http://dx.doi.org/10.1161/CirculationAHA.105.592055.

[23] B.S. Edwards, R.S. Zimmerman, T.R. Schwab, et al., Atrial stretch, not pressure, is the principal determinant controlling the acute release of atrial natriuretic factor, Circulation Research 62 (2) (1988) 191–195.

[24] S.M. Horner, C.F. Murphy, B. Coen, et al., Contribution to heart rate variability by mechanoelectric feedback. Stretch of the sinoatrial node reduces heart rate variability, Circulation 94 (7) (1996) 1762–1767. , http://dx.doi.org/10.1161/01.CIR.94.7.1762.

[25] Z.D. Du, Z.M. Hijazi, C.S. Kleinman, et al., Comparison between transcatheter and surgical closure of secundum atrial septal defect in children and adults: results of a multicenter nonrandomized trial, Journal of the American College of Cardiology 39 (11) (2002) 1836–1844. , http://dx.doi.org/10.1016/S0735-1097(02)01862-4.

[26] A. Marie Valente, J.F. Rhodes, Current indications and contraindications for transcatheter atrial septal defect and patent foramen ovale device closure, American Heart Journal 153 (4 Suppl.) (2007) 81–84. , http://dx.doi.org/10.1016/j.ahj.2007.01.011.

[27] J. Białkowski, B. Karwot, M. Szkutnik, et al., Comparison of heart rate variability between surgical and interventional closure of atrial septal defect in children, The American Journal of Cardiology 92 (3) (2003) 356–358. , http://dx.doi.org/10.1016/S0002-9149(03)00648-9.

[28] İ Özyılmaz, Y. Ergül, H.T. Tola, et al., Heart rate variability improvement in children using transcatheter atrial septal defect closure, The Anatolian Journal of Cardiology 16 (4) (2016) 290–295. , http://dx.doi.org/10.5152/akd.2015.5922.

[29] A. Lammers, H. Kaemmerer, R. Hollweck, et al., Impaired cardiac autonomic nervous activity predicts sudden cardiac death in patients with operated and unoperated congenital cardiac disease, The Journal of Thoracic and Cardiovascular Surgery 132 (3) (2006) 647–655. , http://dx.doi.org/10.1016/j.jtcvs.2006.03.057.

[30] V.I. Gridnev, A.R. Kiselev, O.M. Posnenkova, V.A. Shvartz, Using of spectral analysis of heart rate variability for increasing reliability of bicycle ergometry results, Health 3 (8) (2011) 477–481. , http://dx.doi.org/10.4236/Health.2011.38078.

[31] A.R. Kiselev, V.S. Khorev, V.I. Gridnev, et al., Interaction of 0.1-Hz oscillations in heart rate variability and distal blood flow variability, Human Physiology 38 (3) (2012) 303–309. , http://dx.doi.org/10.1134/S0362119712020107.

[32] A.S. Karavaev, Y.M. Ishbulatov, V.I. Ponomarenko, et al., Model of human cardiovascular system with a loop of autonomic regulation of the mean arterial pressure, Journal of the American Society of Hypertension 10 (3) (2016) 235–243. , http://dx.doi.org/10.1016/j.jash.2015.12.014.

Please cite this article in press as: V.A. Shvartz et al., Heart rate variability in atrial septal defect both before and after operation, Cor et Vasa (2018), https://doi.org/10.1016/j.crvasa.2018.08.001