The Allan factor: a new model of mathematical interpretation of heart rate variability in stable coronary artery disease. Preliminary results

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Abstract

Introduction: The current analysis of heart rate variability (HRV) is one of the noninvasive methods of cardiovascular system assessment. The quantitative characteristics of the RR interval sequence and its dynamics are still under development as regards measurement techniques and development of new HRV interpretation models. The practical clinical application of the standard measurements is still insufficient and improvement of sensitivity and specificity of HRV parameters is needed.

Aim: To assess a novel mathematical model of HRV interpretation and compare it with standard HRV measurements for patients with stable coronary artery disease (CAD), based on the virtual instrumentation technique.

Methods: The study group consisted of 24 patients with CAD confirmed by coronary angiography and a control group of 15 volunteers. Short-term electrocardiographic signals were recorded by a computer system and analysed for estimation of several HRV descriptors in time, frequency and combined time-frequency domains. Calculations included standard HRV measures and the Allan factor, a parameter based on the Haar wavelet transform.

Results: None of the investigated measurements derived from power spectral analysis has shown a statistically significant difference between healthy controls and patients with CAD, with the exception of rMSSD (Wilcoxon test: supine position *p=0.0018, erect position p=0.0708; discriminant function analysis: supine position *p=0.0069, erect position p=0.7851).

Compared with standard HRV variables, the Allan factor better discriminated patients with CAD from healthy subjects (Wilcoxon test: supine position *p=0.0172, erect position *p=0.0001; discriminant function analysis: supine position p=0.8962, erect position *p=0.0200).

Conclusions: The observations related to the novel parameter based on combined time and frequency domains may provide better quantitative measurements of heart rate variability in patients with coronary artery disease and require further investigations to assess their sensitivity and specificity.

Key words: heart rate variability, Allan factor, coronary artery disease

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Introduction

Current methods used to characterise heart rate variability (HRV) dynamics were developed as a result of the progress and continuous development of biomedical signal digital analysis techniques [1]. Heart rate variability parameters obtained using a noninvasive technique of adequate sensitivity and specificity may provide a range of diagnostic data referring to heart muscle condition [2].

The ambiguous correlation between clinical symptoms and electrocardiographic changes, and in particular angiographic findings, often gives rise to diagnostic problems. Therefore, early noninvasive evaluation of progression of ischaemic changes and risk stratification in coronary artery disease (CAD),

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which determines further pharmacological and invasive treatment, remains one of the most critical elements of the diagnostic process.

The unleashing of the ischaemic cascade during myocardial infarction (MI) causes some irreversible functional and structural changes to occur also in the autonomic nervous system. This is reflected by HRV changes which express the influence of sympathetic balance/imbalance on the cardiac sinus rhythm. The prognostic and predictive values of HRV indices in patients after MI were first assessed by Wolff et al, and then by Kleiger et al and Crisp et al. They proved that time domain indices had adequate sensitivity and specificity in sudden cardiac death risk assessment [1-3]. Unfortunately, in patients with stable CAD the variability of available standard HRV parameters prevents unequivocal identification of affected patients and accurate discrimination from healthy individuals and, thus, early detection of lesions.

The study aimed to compare patients with stable CAD and healthy individuals using standard HRV parameters and the Allan factor, a novel parameter of time-frequency domain analysis.

Methods

Patients

The study population consisted of 24 patients with stable CAD (angina pectoris, AP), including 10 females and 14 males, aged 38-69 years. Patients had clinical symptoms that were confirmed by positive results of the stress test (treadmill stress test with maximum workload, Bruce protocol), which were the indication for coronary angiography. Each patient was interviewed and underwent physical examination as well as echocardiography and laboratory tests (blood cell count, lipid profile, blood glucose, electrolytes, urea, and creatinine levels, and urinalysis). Most of the patients had a positive family history of CAD (74.1%), and 40.7% of them admitted they were habitual smokers.

The exclusion criteria were as follows:

- history of an acute coronary syndrome within 3 months before the study,
- history of MI,
- valvular heart disease,
- concomitant arrhythmias,
- heart failure,
- diabetes mellitus,
- other comorbidities that might influence sympathetic and parasympathetic modulation of the heart function (endocrinological disorders, neoplasms, etc.).

In coronary angiography, the majority of patients had single-vessel (47.62%) or two-vessel (28.57%) disease. One patient had atherosclerotic lesions in three coronary arteries despite clinical symptoms of stable CAD; in the remaining subjects the lesions were diffused (14.29%).

Control group

This group consisted of 15 healthy volunteers, 6 females and 9 males, aged 28-55 years in whom organic heart disease was excluded on the basis of medical history, physical examination, basic laboratory tests, electrocardiography, stress test, and echocardiography. Almost half of healthy individuals (46.7%) had a positive family history of CAD, whereas only 6.7% of them were smokers. Other clinical characteristics of studied groups are shown in Table I.

Patients and controls did not significantly differ with regard to age, gender, BMI, smoking, CAD family history and used HRV parameters (Fisher's exact test).

HRV analysis

All patients were examined with 5-minute electrocardiographic recordings (ECG) in two resting positions, supine position and after tilting to the erect position. The ECG tracings showed sinus rhythm and were free of arrhythmias.

During examination, patients continued their medications used for long-term treatment of CAD.

The signals were recorded by a computer using the MEDEA system (Zabrze) and were analysed using virtual tools created in the LabVIEW 7.1 Express environment (National Instruments). This system offers precise and multidimensional analysis of information contained in the ECG signal, from R wave detection and heart rate assessment (Heart Rate, HR), through classical time domain HR analysis, to the estimation of signal descriptors in frequency domain and combined time and frequency domains.

The evaluation included the standard time domain parameters SDNN and rMSSD, and the frequency parameters LF, HF, LF/HF, and VLF, determined with nonparametric fast Fourier transformation and parametric autoregressive methods, and calculation of the Allan factor [4].

The Allan factor [A(T)], a time-frequency domain analysis parameter calculated using the Haar wavelet transform, was first defined in 1996. The Allan factor is calculated as the ratio of the Allan variance (differences between successive readings of Ni(T)) to double the average value.

$$A(T)=E\{[N_{i+1}(T) - N_i(T)]2\} / 2E\{N_{i+1}(T)\}$$

where

T – sampling period (here of 2 s) in which R waves are counted

E – expected value

N_i – number of readings referring to R waves found within the sampling period of known duration.

The construction of this HRV parameter allows the nonstationarity problem of the examined signal, which occurs very frequently during ECG monitoring, to be avoided. According to the definition of the Allan factor, it is calculated as a derivative, which helps achieve the effect of correction of signal linear instability.

Statistical analysis

Statistical analysis of collected data was performed using the STATISTICA 7.0.61.0 software package. Due to the lack of normal distribution of experimental data confirmed with the Shapiro-Wilk test, apart from the standard t-Student test, for paired and unpaired variables, the Mann-Whitney test or Wilcoxon test were used, according to the model of analysis (model of paired and unpaired variables).

Discrimination analysis was used to finally differentiate between groups of studied subjects. Use of this technique may, however, seem to be unjustified due to the lack of normal distribution of the data, which is one of the principles of discrimination analysis. In the 1970s, Lindman [5] proved that violation of this assumption did not have a significant influence on the results. This statement is cited e.g. in the technical manual of the Statistica statistical package: "We have to note that the infringement of the assumption regarding normality is not usually fatal in the sense that the test results obtained for statistical significance etc. are still reliable." A statistical significance level of p=0.05 was adopted.

Results

Regarding the analysed standard time domain parameters of HRV, we found that the average values at rest in the supine position were higher in patients with CAD than in healthy subjects (Table II). Statistically significant differences were observed in the parameter calculated on the basis of differences between RR intervals – rMSSD (the square root of the mean squared differences of successive RR intervals of sinus rhythm over the studied period), which differentiated patients from healthy subjects (*p=0.0018). Definitive confirmation of these data was obtained by means of discrimination analysis (Table III) at a statistical significance level of *p=0.0069. The mean values of standard deviation of successive NN (normal-to-normal) intervals in the studied period (SDNN) in the supine position did not differ between studied groups (CAD – 21.7248 vs. controls – 18.0609). However, SDNN allowed us to discriminate patients from healthy individuals at *p=0.0396.

In patients with CAD a decrease of rMSSD after tilting to the erect position was recorded (rMSSD: S – 56.0013 vs. E – 48.5392; *p=0.0225).

The frequency domain parameters of HRV calculated using the standard Fourier method did not enable us to differentiate patients with CAD from healthy subjects. In all studied groups the body position change was not associated with statistically significant differences in mean values of the recorded spectral parameters (Table II).

The analysis of HRV using an autoregressive method was not helpful either in the differentiation between studied patient groups. Tilting to the erect position did not result in statistically significant changes in spectral parameters.

The mean values of the novel parameter of time--frequency analysis were evidently higher in controls than in CAD patients in both studied models, i.e. in supine and erect positions (CAD-S 0.1027 vs.

Table I. Selected clinical data of patients and controls

PARAMETER	Patients	Controls	p
Age	55.5±7.90	41.7±8.97	NS
BMI [kg/m^2]	27.9±2.76	23.9±4.05	NS
Systolic blood pressure [mmHg]	136.3±15.48	124.7±9.90	NS
Diastolic blood pressure [mmHg]	82.4±5.07	79.3±4.58	NS
Blood glucose [mg/dl]	97.3±15.31	90.6±8.39	NS
Na [mmol/l]	142.5±2.18	142.6±1.74	NS
K [mmol/l]	4.4±0.39	4.3±0.20	NS
Cholesterol [mg/dl]	224.0±32.59	205.7±24.94	NS
HDL-cholesterol [mg/dl]	51.5±11.17	51.5±9.40	NS
LDL-cholesterol [mg/dl]	137.3± 1.50	113.4±14.32	NS
Triglycerides [mg/dl]	183.7±87.44	148.7±81.60	NS

controls-S 0.1213; CAD-E 0.0981 vs. controls-E 0.1286). The Allan factor had the potential to differentiate patients from healthy individuals (*p=0.0172) with higher statistical significance in the erect position (*p=0.0001). This was due to a significant decrease of the Allan factor in the group of CAD patients itself (Figure 1). The potential to distinguish patients with CAD from healthy persons using the Allan factor was confirmed with discrimination analysis at a significance level of *p=0.0200 (Table III).

The correct classification of patients into particular study groups reached 74.36% in the supine position and 81.58% after tilting to the erect position.

Discussion

Heart rate variability derives from the interaction of many factors regulating the cardiovascular system and their influence on the sinus node function which generates this variability [6, 7]. The sinus node function depends on many neurohormonal mechanisms, but also, and perhaps primarily, on the perfusion of the autonomic fibres responsible for bioelectrical activity of the pacemaker cells. In various stages of vascular lesion severity in CAD, pathophysiological effects which are functional disorders of the autonomic system result from the local perfusion disturbances [8-11]. Recording ischaemic changes in their early stage could contribute to

Table II. Mean values of studied HRV parameters in patients with stable angina pectoris and healthy individuals

PARAMETER	POSITION	PATIENTS	CONTROLS	p
SDNN [ms]	S	21.7248±15.8968	18.0609±6.0983	0.9195
	E	16.4836±8.9449	24.2583±18.0234	0.1241
RMSSD [ms]	S	56.0013±19.7203	39.6991±6.0825	**0.0018**
	E	48.5392±14.3595	41.9675±16.3562	0.0708
Total power [ms²]	S	9.4900±15.9044	10.4941±9.9296	0.1659
	E	5.4237±4.5974	14.0977±12.7137	**0.0126**
LF [ms²]	S	0.3809±0.1715	0.4694±0.1793	0.1749
	E	0.4715±0.1599	0.5095±0.2243	0.2891
HF [ms²]	S	0.1853±0.1645	0.1896±0.1353	0.6861
	E	0.1673±0.1193	0.1790±0.1602	0.9405
LF/HF	S	3.9881±3.6572	3.8410±3.0519	0.9539
	E	4.5983±3.5973	5.0806±4.2692	0.7766
VLF [ms²]	S	0.1389±0.0984	0.1139±0.0784	0.5444
	E	0.1062±0.0640	0.0804±0.0749	0.2265
AR TP [ms²]	S	17.4639±2.5591	16.6674±2.0524	0.1939
	E	17.5479±1.7436	16.8676±1.5079	0.1939
AR LF [ms²]	S	0.2808±0.0473	0.2935±0.043	0.2144
	E	0.2784±0.0271	0.2926±0.0292	0.1649
AR HF [ms²]	S	0.6241±0.0690	0.6119±0.0603	0.2423
	E	0.6320±0.0373	0.6183±0.0399	0.3029
AR LF/HF	S	0.4706±0.1972	0.4916±0.1323	0.2253
	E	0.4445±0.0725	0.4778±0.0784	0.2208
AR VLF [ms²]	S	0.0825±0.0209	0.0821±0.0168	0.5933
	E	0.0777±0.0118	0.0771±0.0121	0.9643
Allan Factor	S	0.1027±0.0227	0.1213±0.0151	**0.0172**
	E	0.0981±0.0230	0.1286±0.0075	**0.0001**

S – supine position; E – erect position; frequency domain descriptors: VLF – very low frequency component, power frequency range of 0.003-0.04 Hz; LF – low frequency component, power frequency range of 0.04-0.15 Hz; HF – high frequency component, power frequency range of 0.15-0.4 Hz; AR – index referring to the power spectrum calculated with the autoregressive model, order 12, TP – total power of spectral analysis, frequency range of 0.003-0.4 Hz.

the creation of novel noninvasive methods for early diagnosis of CAD [12-17].

In the present analysis, all indices were calculated on the basis of short, one-minute segments of ECG recordings. It is known that the amount of information in such a recording is far more limited compared to 24-hour Holter monitoring and, at the same time, requires different interpretation of the obtained results [18].

It is hard to compare the SDNN and rMSSD values obtained from the presented classical time domain analysis of HRV to the results of standard 24-hour Holter ECG analysis. The relation of time domain parameters between healthy individuals and patients with CAD also differs from that obtained after relating the outcomes of HRV analysis to Holter ECG recordings. Such a situation seems to be sensible and probable on account of the proven relationship between SDNN and the daily rhythm and long-term electrocardiographic recordings [18]. Indeed, rMSSD is recognized as a more stable parameter for short-term recordings. The interpretation of its values is, however, difficult due to the lack of standards defining the values of individual HRV parameters in healthy subjects and in patients with different clinical conditions.

Estimation of the HRV spectrum using Fourier methods depends on the signal length, which remains its indisputable limitation. The shorter the duration of the studied signal, the worse the frequency resolution. The advantage of the short ECG tracing is that it is easier to fulfil the signal stationarity requirement, which is the condition of the majority of methods of HRV analysis.

The high frequency (HF) and low frequency (LF) power components of spectral analysis, for adequate reliability of measurements, may be derived from recordings of several minutes' duration. The registration of very low frequency (VLF) components requires ECG recordings of several dozen minutes' duration. Use of the autoregressive model in our study aimed to better adjust the method to the study conditions, with the use of parametric digital modelling. The autoregressive method makes appropriate interpretation of the power spectrum possible even with a relatively low number of signal samples (RR intervals), as it is present in the short-term recordings [19, 20]. However, none of the spectral analysis methods that were applied made possible the expected differentiation of CAD patients from healthy volunteers.

The time domain analysis of HRV using a parameter calculated on the basis of differences between successive RR intervals (rMSSD) resulted in the possibility to distinguish between the two studied groups. The presented data confirm better statistical performance of rMSSD compared to SDNN, which is only based on the standard deviation.

Table III. Discrimination analysis of CAD patients and the control group

Parameter	P	
	Supine position	Erect position
SDNN	0.0396	0.9310
rMSSD	0.0069	0.7852
LF	0.3014	0.5061
VLF	0.7051	0.8157
HF	0.4521	0.8359
Total power	0.1629	0.2355
Allan factor	0.8962	**0.0200**

To a large extent, the standard HRV parameters depend on and inversely correlate with heart rate. The dependence of HRV on heart rate is disadvantageous and may influence the analysis results and lead to a loss of objectivity [21]. It is possible to mathematically correct this relationship but this has not been confirmed in larger groups.

In the present study we used the novel parameter of HRV analysis in combined time and frequency domains. This enables us to assess the signal frequency changes in a given period, which means that the nature of this parameter itself prompts a wider and more thorough look at the analysis of the HRV phenomenon. Moreover, the above-mentioned Allan factor [4, 22] is independent

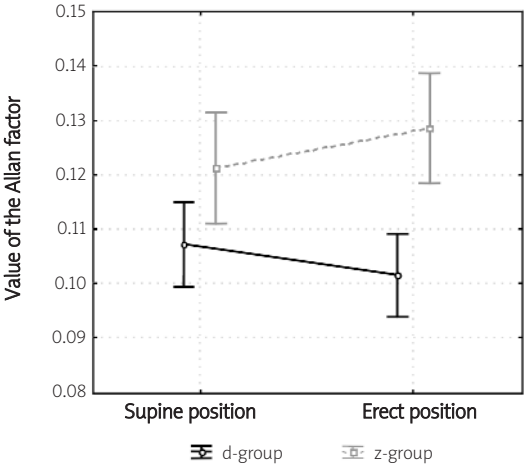

Figure 1. Mean values of the Allan factor in CAD patients and the control group and in both studied models

of the heart rate. The evaluation of this parameter involves setting a time window (in this experimental model it was set for 2 s), in which successive RR intervals are measured following the specified mathematical model. The results of our study showed the potential of the Allan factor to differentiate between the healthy group and CAD patients with relatively low severity of the disease. The statistical significance of achieved discrimination has reached the required level.

The pathophysiology of ischaemia deals also with ischaemia of autonomic innervation of the heart and the decrease of sensitivity of receptors to catecholamines [8]. Therefore, the significant decrease in the value of HRV during adrenergic activation expressed with the wavelet analysis index may be due to its certain dependence on the sympathetic part of the autonomic nervous system.

The measurements of HRV parameters fulfil the requirements of noninvasive methods and do not cause any distress to patients. However, the lack of definitive principles of standardization of both the measurement tool and analytical methods used, and insufficient sensitivity and specificity of standard HRV measurements significantly limit their application [18, 20]. It is quite likely that the analysed novel wavelet analysis factor will become a more independent and reliable measure of HRV than the standard methods used so far. This, however, requires further analysis.

Our results were of statistical significance in the studied groups of a relatively low number of patients, and did not include repeatability analysis data, which suggests the need for further studies in this field. The studied patients differed in BMI, arterial blood pressure, lipid parameters, nicotine dependence and significance of a family history of CAD. None of these factors had a statistically significant influence on the results of any of these HRV parameters. Further investigations are needed to document that the changes of the novel HRV parameter are independent of CAD risk factors and to evaluate a potential correlation with the angiographic extent of the disease.

The objective of the present study was to establish the potential value of the novel time-frequency parameter in HRV analysis. The Allan factor and its real clinical application, particularly regarding the sensitivity and specificity of the applied method, requires further investigation in larger groups. Time-frequency analysis and evaluation of the new parameter in Holter ECG recordings are other important issues.

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Wskaźnik Allana – nowy model matematycznej interpretacji zmienności rytmu zatokowego w stabilnej chorobie wieńcowej. Wyniki wstępne

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Streszczenie

Wstęp: Analiza zmienności rytmu serca (HRV) jest jedną z nieinwazyjnych metod oceny układu sercowo-naczyniowego. Ilościowa charakterystyka sekwencji odstępów RR i jej dynamiki podlega stale rozwojowi zarówno w dziedzinie technik pomiarowych, jak i tworzenia nowych modeli matematycznej interpretacji zmian HRV. Standardowe pomiary HRV, wobec wielu ograniczeń, głównie metodologicznych, nie są w zadowalającym stopniu wykorzystywane w praktyce klinicznej.

Cel: Ocena nowego modelu matematycznej interpretacji HRV w połączonych dziedzinach czasu i częstotliwości, a także jego porównanie z klasyczną analizą HRV w odniesieniu do pacjentów ze stabilną chorobą wieńcową (CAD).

Metody: Do badania zakwalifikowano grupę 24 pacjentów z potwierdzoną angiograficznie CAD oraz grupę kontrolną składającą się z 15 zdrowych ochotników. Analizie podlegały pięciominutowe fragmenty zapisów elektrokardiograficznych rejestrowanych za pomocą systemu komputerowego i analizowanych z wykorzystaniem narzędzi wirtualnych. Do interpretacji HRV użyto standardowych deskryptorów w dziedzinie czasu: SDNN, rMSSD; częstotliwości: LF, HF, LF/HF, VLF oraz wskaźnika Allana, parametru uzyskanego poprzez transformację falkową Haara.

Wyniki: Wskaźnik Allana istotnie odróżniał chorych z CAD od osób zdrowych (test Wilcoxona: pozycja leżąca *p=0,0172; pionizacja *p=0,0001; analiza dyskryminacyjna: pozycja leżąca p=0,8962, pionizacja *p=0,0200). Żaden spośród standardowych parametrów HRV nie odróżniał chorych od grupy kontrolnej na poziomie istotnym statystycznie, z wyjątkiem wskaźnika analizy czasowej rMSSD (test Wilcoxona: pozycja leżąca *p=0,0018, pionizacja p=0,0708; analiza dyskryminacyjna: pozycja leżąca *p=0,0069, pionizacja p=0,7851).

Wnioski: Wstępne obserwacje dotyczące nowego wskaźnika czasowo-częstotliwościowego HRV dają nowe możliwości oceny ilościowej HRV u pacjentów z CAD. Potwierdzenie wartości diagnostycznej wskaźnika Allana wymaga dalszych badań zmierzających do oceny jego czułości i swoistości.

Słowa kluczowe: zmienność rytmu zatokowego, wskaźnik Allana, choroba wieńcowa

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