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Remnants of respiratory peaks in heart rate variability spectrum of an adult man with tachypnea and bradycardia

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Pozostałości pików oddechowych w widmie zmienności rytmu serca dorosłego człowieka z szybkim rytmem oddechowym i wolnym rytmem serca

Wstęp: *Analiza zmienności rytmu serca (HRV) w dziedzinie częstotliwości jest użytecznym narzędziem do badania fluktuacji rytmu zatokowego powodowanych przez autonomiczny układ nerwowy. Jednakże, nie jest jasne, jaka jest górna granica częstotliwości, która może być analizowana w widmie HRV.*

Materiał i metody: *Badamy widma HRV dorosłego ochotnika z szybkim rytmem oddechowym, gdy jego rytm serca jest zwalniany bądź przyspieszany. Stosując szybką transformatę Fouriera (FFT), analizujemy serie odstępów między uderzeniami serca w dziedzinie częstotliwości. Przeprowadzamy również komputerowe symulacje mierzonych sygnałów i porównujemy otrzymane widma z widmami ochotnika.*

Wyniki: *Jeżeli częstość oddechów przekracza połowę średniej częstości uderzeń serca, w widmie HRV są obecne dwa piki reprezentujące ten sam sygnał oddechowy. Jeden z pików jest wynikiem zjawiska aliasingu, natomiast drugi jest pozostałością prawdziwego piku oddechowego, jako efekt właściwości symetrii FFT. Żaden z nich nie przynosi rzetelnej, ilościowej informacji o fali oddechowej w widmie HRV.*

Wnioski: *Górna granica częstotliwości w widmie HRV jest zdeterminowana przez połowę średniej częstotliwości serca. Przed obliczaniem widma należy więc określić górny możliwy do analizy limit częstotliwości, by uniknąć sytuacji, w której analizowane zakresy lokalizują się poza tą granicą. Sytuacja taka jest wielce prawdopodobna w przypadku, gdy pacjent wykazuje wolną akcję serca.* (Folia Cardiol. 2002; 9: 67–74)

zmienność rytmu serca, autonomiczny układ nerwowy, analiza Fouriera, sercowy *aliasing*

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Introduction

Analogue signals, which we usually deal with in a physical situation, can be converted to digital signals by sampling the former at discrete moments of time [1]. The sampling rate must be high enough to reflect changes of an analogue signal. In this matter the Nyquist criterion determines the upper limit of the signal's frequency that can be properly detected by the sampling procedure [1]. The Nyquist critical frequency is equal to half of the sampling frequency. Thus, to convert all information of an analogue signal into a digital one we have to sample the former with a frequency at least twice greater then the (maximal) original frequency of the analogue signal. The frequency spectrum, obtained by means of Fast Fourier Transform (FFT), is usually analysed in a range up to the Nyquist critical value, because the only reliable information can be contained in this frequency band [1]. However, sometimes one faces higher frequencies even though it is not apparent. The situation may take place in the spectral analysis of heart rate variability (HRV). The analysis allows one to quantify oscillations of time intervals between consecutive heartbeats caused by sympathovagal interactions [2–4]. In HRV, the heartbeat rate plays the role of the sampling rate while, e.g., the respiratory wave corresponds to the analogue signal. The Nyquist frequency, in this example, is equal to half of the heartbeat frequency, which is the highest value that can be properly detected by the heartbeats.

In the sampling theory there is also another important phenomenon, i.e. the aliasing effect [1]. If the frequency of an analogue signal exceeds half of the sampling rate (i.e. exceeds the Nyquist critical value), then, in the FFT spectrum, the real frequency components are falsely translated into the lower frequency range (below the Nyquist value). In neonates [5–8] and animals [5, 9], the respiration rate is often higher than half of the heartbeat rate and consequently the respiratory peak is not located in a proper frequency range of the HRV spectrum but, due to the aliasing phenomenon, is shifted to the lower frequency band. However, little is known what information is contained in the range over the Nyquist frequency in the HRV spectrum.

In the present work we investigate HRV spectra of an adult subject, when the respiration rate exceeds half of the heartbeat rate, paying attention to the frequency range over half of the heartbeat rate.

Material and methods

A healthy 29-year-old male volunteer participated in the examination. The man was carefully instructed about the study and gave his written consent. At rest, his heart rate was 64 beats/minute, systolic and diastolic blood pressure was 115 and 80 mm Hg, respectively. All electrocardiograms (ECG) for HRV spectral analysis were carried out in a sitting position. First, for patient's background, the ECG recording in normal condition was done. Next, to slow down the heartbeat rate, the patient received 50 mg of Metoprolol per os and we performed ten minute ECG measurements for four different respiratory rates — i.e. the patient was breathing with a metronome with four different rates: f_R = 10, 20, 30 and 40 breaths per minute. Between the measurements there were ten-minute breaks. The next day, we examined the volunteer in different circumstances, i.e. when his heart rate was accelerated. That is, before each ten-minute ECG measurement, the man passed an exercise test and was administered an inhaled orcyprenaline, before and after the stress test. The tests corresponded to a workload of 250 W on a cycle ergometer lasting 3 minutes. During the ECG recordings heart rate did not fall under 80 beats/minute. As in the first case we did four ECG measurements for the subject breathing with rates: f_R = 10, 20, 30 and 40 breaths per minute. ECG recordings were performed using a stationary three-channel ECG-device. The device, which allowed a signal to be obtained with a high accuracy, was made to order. The signals were digitised on-line at 2048 Hz per channel with 12-bit resolution, and stored on a computer hard disk. Spectral analyses were carried out using Santis program Version 1.1 (Copyright ©1996 Institute of Physiology, RWTH Aachen, Germany). To estimate the HRV spectrum the 512-second period was isolated from the original ECG signal, and the discrete event series (DES), i.e. a plot of R_{i+1}–R_i intervals versus time (indicated at R_i occurrence) [3], was prepared. The DES was sampled with frequency of 4 Hz to achieve the interpolated DES. Power spectrum was computed by means of the FFT algorithm with the Hanning windowing [1].

We also did simulations of the measured spectra. To this end we generated sinusoids that imitated respiratory waves with four different frequencies, i.e. 0.17 Hz (corresponding to 10 breaths/min), 0.33 Hz (20 breaths/min), 0.5 Hz (30 breaths/min) and 0.67 Hz (40 breaths/min), which were sampled regularly with the same rates as the average patient's heartbeat rates during the measurements.

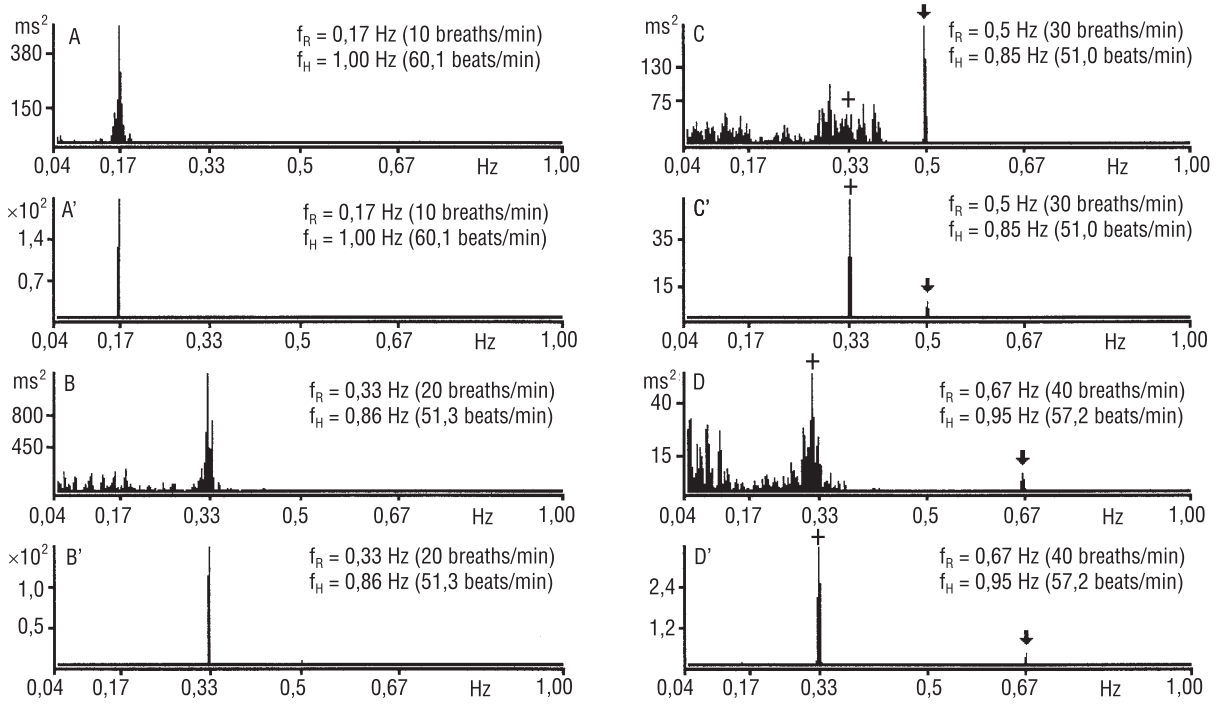

Figure 1. The heart rate variability spectra (panels a, b, c, d) of a patient, corresponding to different respiratory rates (f_R = 10, 20, 30, 40 breaths per minute as indicated in the panels), after administration of Metoprolol. Panels a', b', c' and d' depict simulations of the spectra showed in the panels a, b, c and d, respectively. In the panels a, a', b, b' the respiratory peaks are situated at frequency around f_R as expected. In the panels c, c', d, d', the amplitudes of the respiratory peaks at f_R frequencies (marked by arrows) are reduced and additional peaks (marked by crosses) appear in the lower frequency range around f_H–f_R. The appearance of the additional peaks is an effect of the aliasing phenomenon while the peaks at f_R are actually the remnants of the true respiratory peaks only. That is, when the heartbeat rate is lower than twice the respiratory frequency, according to the Nyquist criterion, it is not able to detect properly the respiratory wave. Note that the positions of the peaks in the simulations coincide with the positions of the corresponding peaks in the measured spectra. The vertical scale in panels c' and d' is enlarged in order to show small peaks situated at frequencies f_R

The next such discrete series were interpolated by sampling with frequency of 4 Hz and we performed FFT of the resulting signals obtaining artificial spectra. The spectra were compared with the corresponding HRV spectra of the volunteer.

Results

In figures 1 and 2, power spectra of HRV of the patient and the simulations of the corresponding respiratory peaks are depicted. Figure 1 reflects the situation when the patient breathes with different rates but his heart rate is slow. A respiratory peak is located in a proper frequency range (i.e. around f_R) if the average heartbeat frequency (i.e. f_H) is at least twice as great as the respiratory frequency (fig. 1a, b) — the heartbeat rate satisfies the Nyquist criterion and is able to detect properly the respiration wave. There is also a nice agreement between the positions of the respiratory peaks in the measured spectra and in the corresponding simulated signals (fig. 1a, a', b, b'). When the respiratory rate becomes sufficiently high, the heartbeat frequency cannot properly identify the respiratory wave and the aliasing phenomenon takes place, see (fig. 1c, c', d, d'). In figures 1c, c' and 1d, d' the respiratory peak turns up at a frequency around f_H–f_R, though real respiration frequency f_R is much higher. This discrepancy is called "cardiac aliasing" [5] and is caused by deficit of sampling — here, a deficit of the number of heartbeats per respiratory period. Importantly, we have succeeded in observing that a small peak is still present at frequency f_R (fig. 1c, c', d, d'). The position of this peak is in agreement with the respiration frequency but it cannot be interpreted as a representation of respiratory arrhythmia, because its amplitude has been strongly reduced. This is actually only a remnant of respiratory peak.

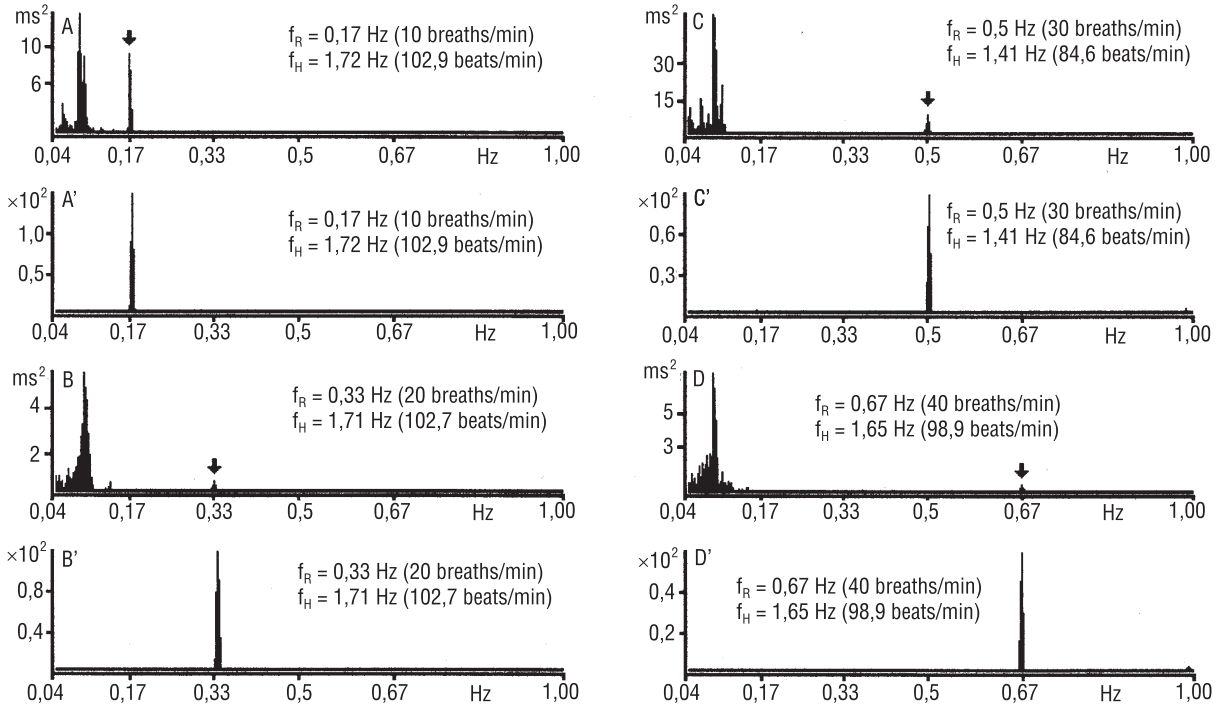

Figure 2. The HRV spectra (panels a, b, c, d) of a patient and the corresponding simulations (panels a′, b′, c′, d′) for the case when heart rate is accelerated (i.e. after stress tests and administration of inhaled orcyprenaline). The respiratory rates, in panels a, b, c, d, are f_R = 10, 20, 30, 40 breaths per minute, respectively. As expected, the respiratory peaks (marked by arrows) in the measured spectra are located at frequencies f_R in agreement with the simulations (panels a′, b′, c′, d′). Small amplitudes of the peaks (in measured spectra) result from the low parasympathetic activity during an increase of heart rate. Note that in the low frequency range (i.e. LF: 0.04–0.15 Hz) the peaks representing sympathetic nervous activity are considerably higher with a strong maximum at the same frequency (0.09 Hz) in all spectra (panels a, b, c, d)

Figure 2 depicts the HRV spectra of the patient after the stress tests, during which heartbeats have been accelerated, and the corresponding simulations. In the present case "sampling frequency", i.e. heartbeat frequency, is high enough to satisfy the Nyquist criterion for each breathing rate and consequently the respiratory peaks are located in a proper frequency range. Note that the amplitudes of the peaks are small, which results from a decrease of parasympathetic activity and an increase of sympathetic activity after stress tests and during administration of orcyprenaline. The positions of the respiratory peaks in patient's spectra coincide with the positions of the peaks in the corresponding simulations.

Discussion

Heart rate variability measurement is widely used to investigate the oscillations of time intervals between consecutive heartbeats [3, 4]. In the spectral HRV analysis we can quantify the oscillations in the frequency domain, i.e. we can measure the amplitude of each particular fluctuation. To calculate the HRV spectrum, usually a discrete event series (DES) is prepared (see methods) [3]. The DES is an irregularly sampled signal with values indicated at heartbeat occurrence. Fast Fourier Transform involves regular sampling [1], therefore the DES has to be interpolated by sampling with a constant frequency (e.g. 4 Hz). This interpolation does not mean that DES becomes a continuous signal — such a secondary sampling allows only a signal suitable for FFT to be obtained in order to compute the HRV spectrum. According to the Nyquist criterion, the reliable part of the frequency spectrum extends only up to half of the frequency of the original discrete signal, i.e. half of the average heartbeat frequency (one should not take half of the frequency of the secondary sampling as the Nyquist critical value because such a procedure serves as an interpolation only and does not bring any additional information to the signal). Any other fluctuations with higher frequencies cannot be reliably

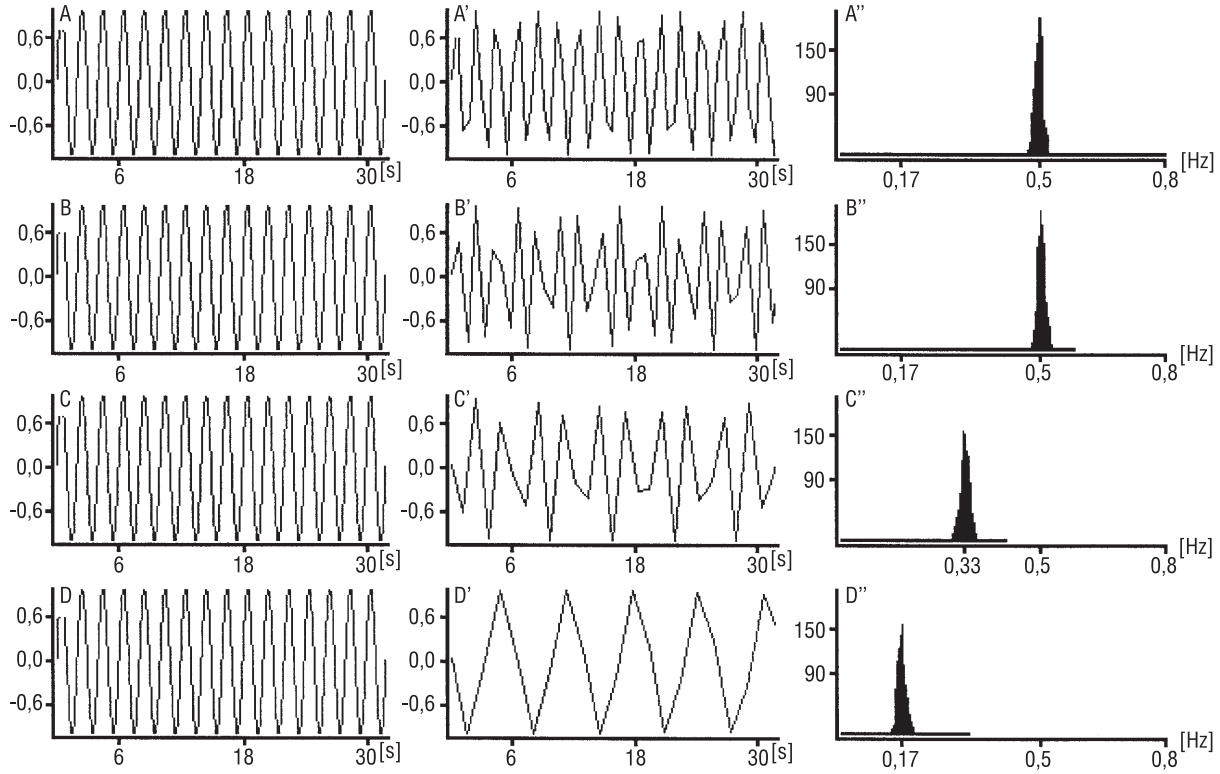

Figure 3. Explanation of aliasing phenomenon in HRV spectrum. In the panels a, b, c, d the same sinusoid, corresponding to the frequency of 0.5 Hz, is depicted. The sinusoid imitates a respiratory wave corresponding to f_R = 30 breaths per minute. Such a signal has been sampled with rates f_H = 100, 70, 50, and 40 times per minute (i.e. 1.67, 1.17, 0.83 and 0.67 Hz) and the resulting discrete signals (connected by spline lines) are shown in panels a', b', c', d', respectively. Different sampling rates may be thought of as different average heartbeat rates of a patient. From panels c' and d' it is evident that if the sampling frequency falls below $2f_R$, i.e. when the Nyquist criterion is not fulfilled, the frequency of the original signal is not properly reproduced. In effect, the resulting signal appears as if it has a frequency much smaller than f_R. Quantitatively it is shown in panels a'', b'', c'', d'' where power spectra of the signals a', b', c', d' are depicted. If $f_H > 2f_R$, there is a strong peak at frequency f_R (panels a'', b'') but when such a condition is not fulfilled, a peak with reduced amplitude is located at f_H–f_R (panels c'', d''). In HRV analysis the phenomenon is called cardiac aliasing. In panels a'', b'', c'', d'' the spectra are presented up to $f_H/2$ only

reproduced in the spectrum. Moreover, the higher frequencies can be falsely translated to the frequency range below the Nyquist value due to the aliasing phenomenon [1] — the mechanism of the aliasing is briefly explained in figure 3. In our consideration, the aliasing effect is clearly presented in the cases when the frequency of the respiratory wave, f_R, exceeds half of the average heartbeat rate [5–9], $f_H/2$ (fig. 1c, d). That is, in the frequency range below $f_H/2$, there appears a peak at frequency around f_H–f_R which contaminates the spectrum. To prevent this phenomenon, one should apply low-pass filtering between the respiratory signal and the detector [1], which is impossible because the sinus node works as the detector in our case.

However, an interesting and even surprising thing is the presence of the small peak at the respiratory frequency f_R in the HRV spectrum although the Nyquist criterion is not fulfilled (fig. 1c, d). In our work we call it a remnant of the respiratory peak. Its appearance is not due to the fact that the heart rate is irregular and potentially for some period of time might satisfy the Nyquist criterion. In figure 1d the remnant is present despite the fact that the heart rate does not speed up so much to fulfil the criterion at any moment. The remnants can also be found in the simulations where the simulated respiratory waves are sampled regularly.

The genesis of the peaks lies in the properties of FFT of discrete signals. That is, suppose we have a harmonic signal of frequency f_R which we sample with rate f_H. If the Nyquist criterion is fulfilled (i.e. $f_R < f_H/2$), a peak at frequency f_R appears in the FFT spectrum in the range up to $f_H/2$. One of the basic

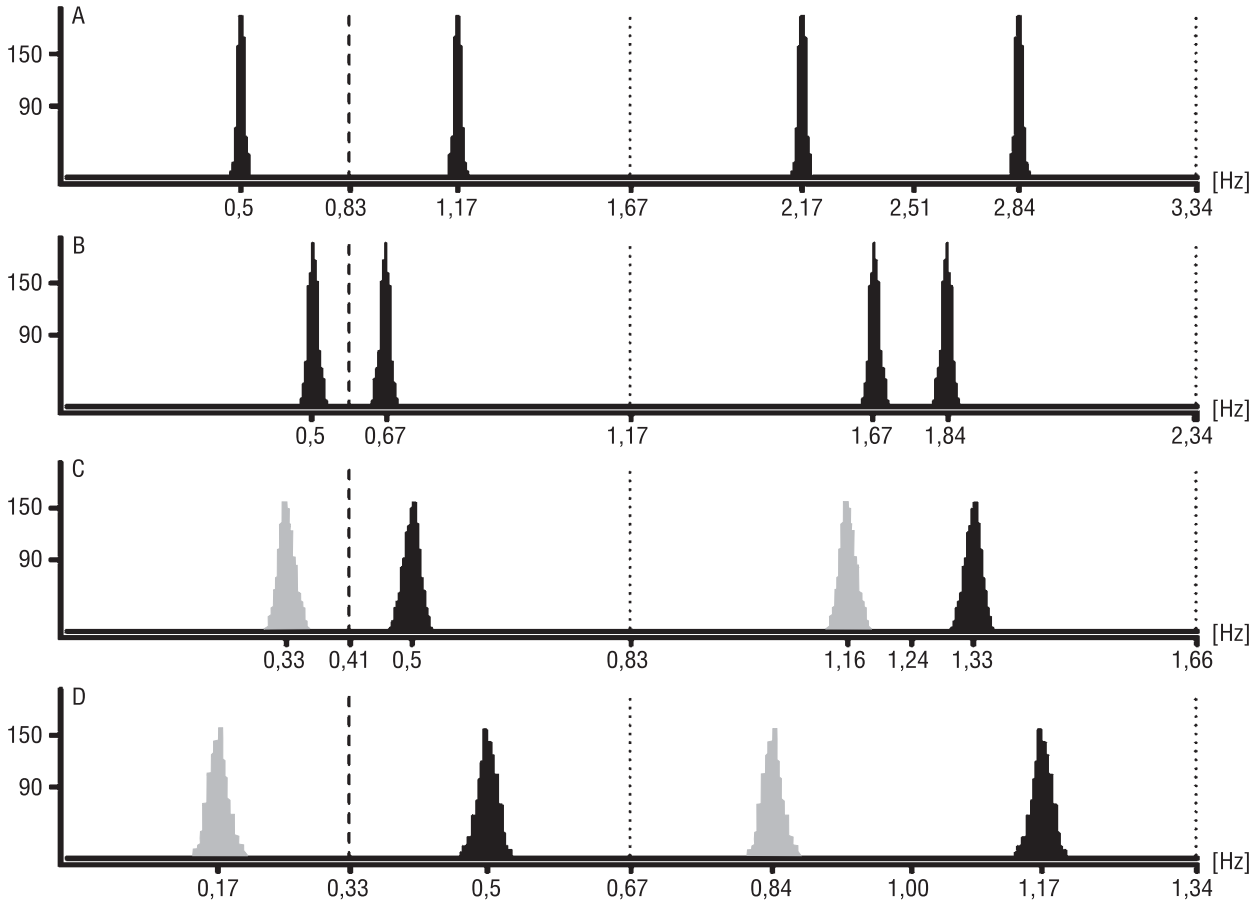

Figure 4. Panels a, b, c, d: the same FFT power spectra as in the panels a'', b'', c'' and d'' of fig. 3, respectively, but in a much wider horizontal range. The dashed vertical lines indicate positions of the Nyquist critical frequencies $f_H/2$ while the dotted lines are plotted at the values of multiples of the f_H frequencies. The relevant frequency range in the FFT extends up to the Nyquist value $f_H/2$. However, if one looks at higher frequencies, the symmetries of an FFT spectrum can be observed. For the cases when $f_R < f_H/2$ (panels a, b) a strong peak at f_R and a symmetric (with respect to $f_H/2$ value) peak at $f_H–f_R$ are visible in the range up to f_H. Such a structure is repeated in the frequency interval from f_H to $2f_H$ and in the next such intervals (not shown in the figure). For the cases when $f_R > f_H/2$ (panels c, d) in the range up to f_H, first, due to the aliasing effect, a peak at $f_H–f_R$ (i.e. a peak in grey colour in a panel) appears and then a remnant peak at f_R turns up and the whole structure is reproduced in the next frequency intervals. Note that the amplitudes of the peaks in panels a and b are the same while in the panels c and d, where the Nyquist criterion is not fulfilled, the amplitudes are reduced

properties of the FFT is that the spectrum is symmetrical with respect to the Nyquist frequency $f_H/2$ [1]. Hence, when one looks at the spectrum in the interval between $f_H/2$ and f_H, an additional peak at frequency $f_H–f_R$ is present (fig. 4). The amplitudes of both peaks are the same [1]. For the case when the Nyquist criterion is not satisfied, in the frequency range up to $f_H/2$, a peak at $f_H–f_R$ appears due to the aliasing phenomenon. Consequently, because of the symmetry properties, in the range from $f_H/2$ to f_H, a symmetrical peak at frequency f_R is present, which is nothing but our remnant peak (fig. 4). The described structure of the spectrum applies if FFT is carried out on an original, regularly sampled signal. FFT programs usually produce a frequency spectrum up to the $f_H/2$ value only. This is basically because in the next frequency intervals there is no additional information — everything that is contained in the range up to $f_H/2$ is only repeated in the next intervals (fig. 4). However, in the HRV spectral analysis, the secondary sampling is applied, which allows us to look at the frequency range above $f_H/2$ and therefore our remnants peaks are observed. One should keep in mind that when the secondary sampling is used, the amplitudes of the peaks at $f_H–f_R$ and f_R cannot be the same — that is,

the remnant peak possesses a significantly reduced amplitude. The moral of the story is that if the frequency of the signal we are looking for in the FFT spectrum satisfies the Nyquist requirement, a peak with a proper amplitude appears in the relevant range up to the Nyquist critical value. When the Nyquist criterion is not fulfilled, neither the amplitude of the peak coming from the aliasing effect nor the amplitude of the remnant peak can be identified as a quantitative representation of the fluctuation in the spectrum [1].

The above observations have significant consequences in HRV studies. We demonstrate the phenomena in an adult subject (in abnormal situation, i.e. during simultaneous tachypnoea and bradycardia), but the implications apply in HRV measurements, especially in neonates and animals. Neonates and animals often reveal a higher respiration rate than half of the heartbeat rate. Researchers are aware of the aliasing effect in these cases but the possibility of the appearance of the remnant peaks has not been realised. In animals and neonates the remnant peaks are usually spread due to irregular breathing, thus it is not easy to demonstrate them. To observe well-separated peaks one would have to encourage, e.g., an animal to breathe regularly. Nevertheless, also in adults one should be careful in the HRV analysis because, if the frequency of the fluctuation we are looking for in the HRV spectrum does not fulfil the Nyquist criterion, a remnant peak can be taken as a true peak. Such a situation may happen in patients with bradycardia (e.g. being under influence of β-blockers) or in some healthy subjects, particularly in sportsmen when the heart rate falls even below 40 beats/min (the usually analysed frequency range in HRV extends up to 0.4 Hz — such a band lies within the relevant Nyquist range if the heart rate is at least 48 beats/min).

To conclude, we would like to stress that before the spectral HRV analysis is performed, one should first determine the upper frequency limit in the spectrum and check whether the frequency of the fluctuation under consideration is not situated beyond this limit, especially if a subject exhibits a relatively slow heart rate.

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Streszczenie

Remnants of respiratory peaks in HRV spectrum

Introduction: *Heart rate variability (HRV) analysis in frequency domain is a useful tool to investigate fluctuations of the sinus rhythm caused by the autonomic nervous system. However, it is not clear what the upper limit of the frequency where the HRV spectrum is reliable is.*

Material and methods: *We investigated HRV spectra of an adult man with high respiratory rate when his heartbeat rate was slowed down or accelerated. We applied Fast Fourier Transform (FFT) to analyse the discrete event series in the frequency domain. We also performed numerical simulations of measured signals and compared the resulting spectra with those of the man.*

Results: *If the respiration rate exceeds half of the average heartbeat rate, two peaks corresponding to the same respiratory signal can be found in the spectrum. One of them results from the aliasing phenomenon but the other is a remnant of the true respiratory peak whose origin lies in the symmetry properties of FFT. None of the peaks brings reliable, quantitative information about the respiration wave in the HRV spectrum.*

Conclusions: *The upper frequency limit in a HRV spectrum is determined by half of the average heartbeat frequency. Consequently, one should check if any considered fluctuation lies within this frequency range, otherwise there is no reliable information about the fluctuation in the HRV spectrum. Such a situation is likely to occur when a patient exhibits slow heart rate.*
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heart rate variability, autonomic nervous system, Fourier analysis, cardiac *aliasing*

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