Ectopic Beats in Heart Rate Variability Analysis: Effects of Editing on Time and Frequency Domain Measures

Mirja A. Salo, M.Sc., Heikki V. Huikuri, M.D.,
and Tapio Seppänen, Ph.D.

From the Division of Cardiology, Department of Medicine, University of Oulu, Finland

Background: Various methods can be used to edit biological and technical artefacts in heart rate variability (HRV), but there is relatively little information on the effects of such editing methods on HRV.

Methods: The effects of editing on HRV analysis were studied using R-R interval data of 10 healthy subjects and 10 patients with a previous myocardial infarction (MI). R-R interval tachograms of verified sinus beats were analyzed from short-term (~5 min) and long-term (~24 hours) recordings by eliminating different amounts of real R-R intervals. Three editing methods were applied to these segments: (1) interpolation of degree zero, (2) interpolation of degree one, and (3) deletion without replacement.

Results: In time domain analysis of short-term data, the standard deviation of normal-to-normal intervals (SDANN) was least affected by editing, and 30%-50% of the data could be edited by all the three methods without a significant error (< 5%). In the frequency domain analysis, the method of editing resulted in remarkably different changes and errors for both the high-frequency (HF) and the low-frequency (LF) spectral components. The editing methods also yielded in different results in healthy subjects and AMI patients. In 24-hour HRV analysis, up to 50% could be edited by all methods without an error larger than 5% in the analysis of the standard deviation of normal to normal intervals (SDNN). Both interpolation methods also performed well in the editing of the long-term power spectral components for 24-hour data, but with the deletion method, only 5% of the data could be edited without a significant error.

Conclusions: The amount and type of editing R-R interval data have remarkably different effects on various HRV indices. There is no universal method for editing ectopic beats that could be used in both the time-domain and the frequency-domain analysis of HRV. **A.N.E. 2001;6(1):5-17**

heart rate variability; editing; deletion; interpolation; R-R intervals

Measurement of heart rate variability (HRV) from short and long electrocardiographic (ECG) recordings has become an important tool for the assessment of cardiovascular autonomic regulation during various physiological and clinical conditions. There are, however, many potential sources of error that may cause bias in the reliable measurement of HRV. Artefacts in the ECG recordings may be due to both technical and biological factors. Technical artefacts may result from poorly fas-

tened electrodes or be motion artefacts during ambulatory recordings. Ectopic beats, atrial fibrillation, and ventricular tachycardia are examples of biological artefacts in ECG recordings. When processing noisy data, artefacts and ectopic beats are the major sources of error.

Interest in methods of editing R-R interval data that do not have a disturbing effect on the HRV analysis has increased along with the use of HRV in the assessment of the autonomic regulation of

heart rate. Several methods of handling artefacts in HRV data have been developed and tested,¹⁻¹² but there is surprisingly scant information available on the effects of the different editing methods on the analysis of various measures of HRV. Despite the recommendations of the Task Force¹³ for editing, there have been no systematic studies aimed at studying the effects of various editing methods on different HRV indices. Furthermore, it is not well known whether the same editing methods can be used in the HRV analysis of both healthy subjects and patients with heart diseases. Finally, it has not been well established how large amounts of the R-R interval data can be edited by various methods without causing significant errors in the measurement of HRV indices.

The purpose of the present work was to clarify the following important questions that have not been fully elaborated in previous studies. Does editing affect similarly the HRV analysis of healthy subjects with high overall HRV and patients with low HRV? How many qualified beats must be included in a reliable analysis of the different indices of HRV? How do the different editing methods influence the different time and frequency domain measures of HRV? This study was designed to provide insight into these questions.

PATIENTS AND METHODS

The data consisted of R-R interval tachograms of a group of 10 healthy subjects with no history of heart disease and a group of 10 patients with acute myocardial infarction (AMI). The mean age of the healthy subjects was 41 ± 11 years and that of the AMI patients 58 ± 6 years. The R-R interval tachograms of the healthy subjects contained high standard deviation of all N-N intervals ($SDNN = 175 \pm 50$ ms), and the R-R interval tachograms of the AMI patients contained low R-R interval variability ($SDNN = 76 \pm 41$ ms).

The R-R intervals were measured with a RR

recorder under controlled conditions with a metronome-guided breathing rate of 15/min. A real-time microprocessor QRS detector system¹⁴ (Polar Electro Oy, Kempele, Finland) was used, which was connected to the patient with two ECG electrodes. The RR recorder had a timing accuracy of 1 ms.¹⁴ The measured R-R intervals were saved on a computer disk for further processing. The effects of editing were studied in a HRV analysis of short-term ECG recordings. The R-R interval tachograms of the short-term recordings included 15 tachograms from healthy subjects and 15 tachograms from AMI patients. The length of the short-term data was 512 normal R-R intervals. The length of the long-term data was 24 hours and it included the 10 tachograms from healthy subjects and 10 from AMI patients. Short-term R-R interval data segments were verified to contain only pure sinus beats by printing out the ECGs of the corresponding segments. Long-term data contained 99% of pure sinus beats.

The saved R-R interval tachograms were edited on a PC computer using the HEARTS software for HRV analysis (Heart Signal Oy, Oulu, Finland). The R-R intervals, to be edited, were selected randomly and defined as artefacts. Three random selections of R-R intervals were made to analyze the average effects of the editing methods. The portion of the edited R-R intervals was gradually increased from 5% to 50% of all R-R intervals at 5% steps. The editing methods were deletion, interpolation of degree zero, and interpolation of degree one. Figure 1 shows examples of the tachograms of a healthy subject (Fig. 1a) and an AMI patient (Fig. B) edited with different methods. The edited R-R intervals are marked with triangles in Figure 1.

The deletion method simply removes the non-normal R-R intervals and replaces each removed R-R interval with the following normal R-R interval. Interpolation of degree zero replaces the edited non-normal R-R interval with a local average of the

Figure 1. (A) An example of a tachogram from a healthy subject. The small arrows above the real R-R interval tachogram (No editing) represent the abolished beats before editing. The other tachograms have been generated after the application of each editing method. The two superimposed tachograms in bottom are generated after interpolation of degree zero (white columns) and degree one (black columns). Interpolation of degree zero generates step-like shapes into the tachogram, while interpolation of degree one tends to smooth the tachogram. (B) An example of a tachogram from a patient with an acute myocardial infarction (AMI). The small arrows above the real R-R interval tachogram (No editing) represent the abolished beats before editing. The other tachograms have been generated after the application of each editing method. The two superimposed tachograms in bottom are generated after interpolation of degree zero (white columns) and degree one (black columns).

previous accepted normal R-R intervals. The local neighborhood for the interpolation of degree zero was three R-R intervals in this study. Interpolation of degree one replaces the non-normal R-R intervals with points obtained from a fitted straight line over the non-normal R-R intervals. Interpolation of degree one is computed by

$$y(x) = y_0 + (x - x_0) \frac{y_1 - y_0}{x_1 - x_0}. \quad (1)$$

The straight line passes through the points (x_0, y_0) and (x_1, y_1) . $y(x)$ is the new value for the non-normal R-R interval at location x . Unlike the deletion method, the interpolation methods preserve the number of data samples.

HRV analysis was done in the time and frequency domains using the HEARTS software. HRV analysis was performed on nonedited data that included only real sinus intervals, to obtain reference values for the HRV parameters. The HRV values of the edited data were compared to the reference values by computing the percentage differences.

Time Domain and Frequency Domain Analysis of HRV

The time and frequency domain measures of HRV were analyzed by the methods recommended by the Task Force.¹³ In the time domain analysis of short-term data, the following three parameters were computed for the short-time R-R interval data: standard deviation of the 512 R-R intervals (SDANN), root mean square of successive differences (RMSSD), and percentage of the differences between adjacent normal R-R intervals greater than 50 ms (pNN50). These parameters were computed over a data segment of 512 R-R intervals.

For the frequency domain analysis of short-term data, the power spectrum of HRV was computed with both spectrum computation methods: fast Fourier transform (FFT) and autoregressive modeling (AR).¹⁵ For the short-time R-R interval data, the frequency domain components of the power spectrum that were quantified were the low-frequency component (LF, 0.04-0.15 cycles/beat) and the high-frequency component (HF, 0.15-0.4 cycles/beat). Detrending was used to de-emphasize the unwanted trends in the data, and it was performed over a block of 512 R-R intervals. The model order for autoregressive spectrum estimation was 20.¹⁶

In the time domain analysis of long-term data the standard deviation of all normal to normal R-R

intervals (SDNN) was computed. In the frequency domain of the long-term spectrum analysis was done for the HRV data of 24 hours by the Fourier transform analysis method. Power of the very low frequency component (VLF, 0.005-0.04 cycles/beat), power of the ultra-low frequency component (ULF, < 0.03 Hz) and the slope of the HRV, slope of the regression line of the log (power)-log (frequency) of the HRV between frequencies 10^{-4} Hz and 10^{-2} Hz were estimated.^{17, 18}

Statistical Methods

The HRV values of the edited data were compared to the reference values, to assess the quality of the different editing methods. Percentage differences were computed between the reference values of the HRV parameters and the values of the randomly edited data. The mean error of the HRV parameter for the study groups was obtained by computing the average percentage difference. In addition, standard deviations and 95% confidence intervals were computed for each value of the percentage difference to show the quality of the measurements and the deviations of the HRV parameters. The acceptable error of the editing methods was chosen to be less than 5% of the reference value (the error of the mean and its upper limits of 95% confidence intervals $\leq 5\%$).

RESULTS

Short-Term Recordings

Table 1 shows the effects of the three editing methods on the short-term time domain measures of HRV in healthy subjects (left) and in AMI patients (right), and the percentage differences $\pm 95\%$ confidential intervals with different amount of edited segments are shown in Figure 2. The underlined values of the HRV parameters in Table I indicate the editing limits for each parameter at which the mean error with its 95% confidence interval exceeds the value of 5%.

In the time domain analysis of short-term data, the computation of SDANN was least affected by the editing. The best outcome of the editing process for the SDANN analysis was achieved with the deletion method in both study groups. On the contrary, both RMSSD and pNN50 were highly sensitive to editing. The performance of the interpolation of degree zero was somewhat better in the editing process compared to the other editing

Table 1. Effects of the Editing Methods on the Short-Term Time Domain Parameters in Healthy Subjects (Left) and in AMI Patients (Right)

Edit %	Healthy			AMI		
	Int 0	Int 1	Del	Int 0	Int 1	Del
SDANN [ms]						
0	84.73 ± 56.98	84.73 ± 56.98	84.73 ± 56.98	18.93 ± 13.17	18.93 ± 13.17	18.93 ± 13.17
5	84.22 ± 55.09	84.16 ± 55.03	84.53 ± 55.70	18.89 ± 12.87	18.89 ± 12.87	19.00 ± 12.82
20	82.20 ± 52.38	82.31 ± 52.54	84.18 ± 55.30	18.73 ± 12.90	18.73 ± 12.87	18.96 ± 12.93
30	81.27 ± 51.52	81.20 ± 51.81	84.38 ± 56.05	18.67 ± 12.96	18.71 ± 12.81	18.96 ± 12.90
50	78.80 ± 48.12	79.16 ± 50.30	84.38 ± 55.74	18.47 ± 12.86	18.49 ± 12.76	18.91 ± 12.89
RMSSD [ms ²]						
0	8002.9 ± 21158.9	8002.9 ± 21158.9	8002.9 ± 21158.9	96.5 ± 97.0	96.5 ± 97.0	96.5 ± 97.0
5	7818.4 ± 20082.9	7515.8 ± 19404.1	8286.6 ± 21463.8	95.0 ± 91.3	90.6 ± 88.3	98.4 ± 95.6
20	7443.0 ± 18780.1	6288.3 ± 16177.0	9154.2 ± 23552.4	89.4 ± 81.7	73.6 ± 70.2	106.4 ± 100.5
30	7011.8 ± 17656.4	5352.8 ± 13810.2	9783.8 ± 25230.2	82.4 ± 74.5	61.6 ± 58.1	111.0 ± 102.8
50	5835.0 ± 14174.1	3400.3 ± 8418.7	10213.6 ± 24737.1	70.2 ± 64.4	40.7 ± 36.5	130.3 ± 115.6
pNN50 [%]						
0	18.12 ± 27.00	18.12 ± 27.00	18.12 ± 27.00	0.080 ± 0.260	0.080 ± 0.260	0.080 ± 0.260
5	19.34 ± 27.46	18.67 ± 27.46	18.75 ± 26.41	0.100 ± 0.305	0.087 ± 0.278	0.104 ± 0.334
20	23.30 ± 31.45	19.78 ± 30.49	20.23 ± 26.43	0.151 ± 0.360	0.084 ± 0.271	0.164 ± 0.450
30	26.37 ± 34.89	20.67 ± 32.68	21.50 ± 26.48	0.149 ± 0.375	0.082 ± 0.271	0.182 ± 0.490
50	34.96 ± 46.15	21.52 ± 35.98	24.87 ± 25.95	0.178 ± 0.423	0.062 ± 0.208	0.382 ± 0.723

Mean values of the time domain parameters ± standard deviation in function of the editing percentage. The underlined values of the HRV parameters in Table 1 indicate the editing limits for each parameter at which the mean error with its 95% confidence interval exceeds the value of 5%.
 Edit % = amount of the edited R-R intervals in percentages; int 0 = interpolation of degree 0; int 1 = interpolation of degree 1; del = deletion; SDANN = standard deviation of 512 normal-to-normal R-R intervals; RMSSD = root mean square of successive differences; pNN50 = percent of difference between adjacent normal R-R interval > 50 ms.

Figure 2. Effects of the three different editing methods on the values of the time domain parameters for the R-R interval data of the healthy subjects (left) and the AMI patients (right). The percentage difference with 95% confidence intervals in function of the editing percentage. Abbreviations: SDANN = standard deviation of 512 normal-to-normal R-R intervals, RMSSD = root mean square of successive differences, and pNN50 = percent of difference between adjacent normal R-R interval greater than 50 ms.

methods in the RMSSD analysis. For the pNN50 analysis the interpolation of degree one was the best editing method in both study groups.

Table 2 shows the effects of the three editing methods on the short-term frequency domain measures of HRV with autoregressive model computation and with fast Fourier transform computation, and the percentage differences $\pm$ 95% confidential intervals with different amounts of edited segments are shown in Figure A (AR) and B (FFT). The underlined values of the percentage differences in Table 2 indicate the editing limits for the parameter in question at which the mean error with its 95% confidence interval exceeds the value of 5%.

The estimations of both the HF and the LF spectral components were dependent mostly on the

editing method. Estimation of the HF spectral component turned out to be highly sensitive to editing with any of the editing methods. However, both interpolation methods performed better than the deletion method in the editing process for HF component estimation. The deletion method was least suitable for estimating the HF spectral component in both study groups. Editing by the deletion method produced a marked increase in the mean error of the HF component, especially in healthy subjects (see Fig. 5). There were no remarkable differences between the results obtained with spectrum estimation of autoregressive modeling and fast Fourier transform.

In the estimation of the LF spectral component, the interpolation of degree one was the most suit-

Table 2. Effects of the Editing on the Frequency Domain Parameters with AR and FFT Spectrum Estimation in Health (Left) and in AMI (Right) Groups

Edit %	Healthy			AMI		
	Int 0	Int 1	Del	Int 0	Int 1	Del
AR						
HF [ms ²]						
0	2690.9 ± 7016.0	2690.9 ± 7016.0	2690.9 ± 7016.0	22.3 ± 23.9	22.3 ± 23.9	22.3 ± 23.9
5	2855.0 ± 7579.7	2837.0 ± 7558.2	2742.1 ± 6975.7	21.2 ± 22.2	21.5 ± 22.2	22.0 ± 22.4
10	2856.7 ± 7786.6	2821.0 ± 7776.2	2855.5 ± 7397.3	19.7 ± 20.8	20.7 ± 20.9	22.6 ± 22.8
15	2640.2 ± 7163.6	2520.5 ± 6930.7	2962.5 ± 7616.5	18.3 ± 18.5	19.5 ± 19.1	22.8 ± 22.2
50	2214.3 ± 5947.9	1832.9 ± 4931.4	3057.0 ± 7437.4	14.8 ± 14.3	16.0 ± 14.7	26.2 ± 24.5
LF [ms ²]						
0	2116.6 ± 3120.3	2116.6 ± 3120.3	2116.6 ± 3120.3	61.5 ± 76.4	61.5 ± 76.4	61.5 ± 76.4
5	2122.9 ± 3141.0	2157.9 ± 3192.8	2117.5 ± 3011.4	60.7 ± 73.3	61.6 ± 74.2	64.2 ± 76.4
10	2098.4 ± 3199.8	2168.8 ± 3237.3	2202.7 ± 3286.9	59.8 ± 72.0	61.9 ± 74.2	67.8 ± 78.1
15	2077.4 ± 3256.8	2249.5 ± 3524.4	2203.1 ± 3293.5	58.4 ± 69.8	61.3 ± 72.0	72.1 ± 80.9
50	1916.5 ± 3012.2	2364.4 ± 4098.9	2149.1 ± 3173.7	56.8 ± 66.8	61.1 ± 68.7	87.7 ± 102.5
FFT						
HF [ms ²]						
0	2819.5 ± 7446.0	2819.5 ± 7446.0	2819.5 ± 7446.0	23.0 ± 25.1	23.0 ± 25.1	23.0 ± 25.1
5	2958.9 ± 7911.3	2952.2 ± 7929.1	2596.3 ± 6857.6	21.6 ± 23.3	22.1 ± 23.4	21.8 ± 23.3
10	2846.0 ± 7709.4	2805.2 ± 7680.3	2691.9 ± 7214.1	20.2 ± 21.7	21.2 ± 22.0	22.9 ± 23.7
15	2587.6 ± 6928.7	2460.9 ± 6657.9	2791.3 ± 7424.7	18.7 ± 19.3	20.0 ± 20.1	23.4 ± 22.3
50	2186.6 ± 5813.5	1795.7 ± 4755.2	2881.3 ± 7251.6	15.4 ± 15.2	16.4 ± 15.9	28.1 ± 25.4
LF [ms ²]						
0	2220.1 ± 3439.3	2220.1 ± 3439.3	2220.1 ± 3439.3	63.6 ± 77.2	63.6 ± 77.2	63.6 ± 77.2
5	2206.0 ± 3392.9	2246.9 ± 3466.9	2124.8 ± 3061.6	62.8 ± 73.8	63.9 ± 74.7	67.0 ± 79.1
10	2176.5 ± 3434.7	2263.4 ± 3522.6	2219.8 ± 3303.5	62.0 ± 72.7	64.2 ± 74.7	70.6 ± 81.5
15	2139.6 ± 3429.1	2318.0 ± 3722.6	2218.0 ± 3302.9	60.8 ± 71.0	63.6 ± 72.7	74.1 ± 82.7
50	1966.7 ± 3145.8	2416.5 ± 4250.3	2175.7 ± 3161.8	59.0 ± 67.8	63.8 ± 70.2	91.6 ± 107.4

Mean values of the spectral components ± standard deviation in function of the editing percentage. The underlined values of the HRV parameters indicate the editing limits for each parameter at which the mean error with its 95% confidence interval exceeds the value of 5%.

Edit % = amount of the edited R-R intervals in percentages; int 0 = interpolation of degree 0; int 1 = interpolation of degree 1; del = deletion; LF = low frequency power (0.04–0.15 cycles/beat); HF = high frequency power (0.15–0.4 cycles/beat); AR = autoregressive spectrum estimation method; FFT = fast Fourier transform spectrum estimation method.

able editing method for the healthy group, however the results obtained with the interpolation of degree zero were almost equally good. In the AMI patients, on the other hand, the results obtained with the interpolation of degree zero were slightly better than with the interpolation of degree one. It is of particular note, that in the LF component analysis the deletion method was distinctly the least suitable editing method for the AMI patients.

There were some differences in the sensitivity to editing when the different spectrum estimation methods were used. In the healthy subjects, the performance was slightly better in the FFT spectrum computation with the interpolation of degree one, but worse with the deletion method compared to the results of the AR spectrum computation. The

AMI patients showed no significant differences between the results obtained with the two different spectrum estimation methods.

Long-Term Recordings

Table 3 shows the effects of the three editing methods on the long-term time and frequency domain measures of HRV in healthy subjects (left) and in AMI patients (right), and the percentage differences ± 95% confidential intervals with different amounts of edited segments are shown in Figure 4. The underlined values of the HRV parameters in Table 3 indicate the editing limits for each parameter at which the

A **B**

mean error with its 95% confidence interval exceeds the value of 5%.

The analysis of the SDNN was not affected remarkably by editing by any of the editing methods in both of the study groups.

In the frequency domain analysis of the long-term recordings, a remarkable difference was observed between the results with interpolation methods and with the deletion method. The performance of the interpolation methods in the editing process in the estimation of the ULF spectral component was superior to the performance of the deletion method.

In the estimation of the VLF spectral component the situation was somewhat similar to the estimation of the ULF component. Again, both interpolation methods performed better than the deletion method in the editing process in both study groups.

Editing with both interpolation methods did not affect remarkably the computation of the power-law slope (slope of the regression line of the log (power)-log (frequency) of the HRV at 10-4 Hz). Again, the deletion method was not suitable for the power-law slope analysis in either study group.

DISCUSSION

The main findings of this study are that (1) some parameters of HRV analysis are more sensitive to the editing of R-R intervals than the others. The error in the values of one parameter may not increase significantly in function of the editing proportion, while the error in another parameter may increase strongly even with a moderate proportion of editing. (2) Editing of the R-R interval tachograms should ideally be performed by using different editing methods for the different HRV analyses. The same editing method that gives a minimum error for a simple time domain analysis, such as the SDANN, was not suitable for a more complex HRV analysis, such as the estimation of the spectral components of the HRV. (3) Deletion of the artefacts or ectopic beats is not a suitable edit-

ing method for the analysis of the long-term power-spectral components of HRV. (4) Finally, there are substantial differences between healthy subjects and AMI patients in the results of HRV analysis obtained with different editing methods.

Deletion editing simply removes the edited R-R intervals. The number of samples is reduced by the amount of edited R-R intervals. This method has the largest effect on the high-frequency fluctuation in the tachogram. This is due to the step-like shapes in the deletion procedure, which result in sudden changes in the R-R interval time series. This effect is significant, especially if abrupt changes are produced in a portion of smooth natural changes. Unlike the deletion method, the interpolation methods retain the number of the samples unchanged. Both interpolation methods can be considered to serve as low-pass filters with different filter capacities. Interpolation of degree zero produces flat-like shapes in the tachogram, while interpolation of degree one produces slope-like shapes, especially in the tachograms of high-frequency fluctuation.

In the time domain analysis of the present short-time R-R interval sequences, SDANN was least affected by the editing. The deletion method performed best in the editing process for the analysis of SDANN. The situation with RMSSD and pNN50 was different. These parameters were significantly more sensitive to editing than SDANN. With only a small amount of editing, the error in the RMSSD analysis increased strongly with all three editing methods.

In the time domain analysis of the long-term R-R interval data, SDNN was not affected significantly by editing by any of the three editing methods. The mean error of the SDNN remained small even with a large amount of edited R-R intervals. Because of the large amount of the samples of the 24-hour ECG recording (approximately 90,000 R-R intervals), even a strong editing does not affect remarkably the SDNN analysis and the overall variability of the data can be retained close to the original

Figure 3. (A) Effects of the three different editing methods on the values of the frequency domain parameters with the autoregressive method for the R-R interval data of the healthy subjects (left) and the AMI patients (right). The percentage difference with 95% confidence intervals in function of the editing percentage. Abbreviations: LF = low frequency power (0.04-0.15 cycles/beat) and HF = high frequency power (0.15-0.4 cycles/beat). (B) Effects of the three different editing methods on the values of the frequency domain parameters with the fast Fourier transform method for the R-R interval data of the healthy subjects (left) and the AMI patients (right). The percentage difference with 95% confidence intervals in function of the editing percentage. Abbreviations: LF = low frequency power (0.04-0.15 cycles/beat) and HF = high frequency power (0.15-0.4 cycles/beat).

Table 3. Effects of the Editing Methods on the Long-Term Time and Frequency Domain Parameters in Healthy Subjects

Edit %	Healthy			AMI		
	Int 0	Int 1	Del	Int 0	Int 1	Del
SDNN [ms]						
0	174.70 ± 49.59	174.70 ± 49.59	174.70 ± 49.59	75.80 ± 40.94	75.80 ± 40.94	75.80 ± 40.94
5	174.53 ± 47.74	174.53 ± 47.74	174.67 ± 47.76	75.80 ± 39.51	75.80 ± 39.51	75.73 ± 39.59
10	174.40 ± 47.63	174.43 ± 47.67	174.73 ± 47.79	75.80 ± 39.51	75.80 ± 39.51	75.80 ± 39.62
30	173.60 ± 46.90	173.50 ± 47.03	174.83 ± 47.96	75.80 ± 39.51	75.80 ± 39.51	75.80 ± 39.68
50	172.77 ± 46.43	172.57 ± 46.33	175.10 ± 48.26	75.60 ± 39.63	75.53 ± 39.52	75.83 ± 39.65
ULF [ms ²]						
0	15972.5 ± 10758.3	15972.5 ± 10758.3	15972.5 ± 10758.3	3546.65 ± 2931.03	3546.65 ± 2931.03	3546.65 ± 2931.03
5	15951.2 ± 10365.6	15960.1 ± 10372.5	15835.3 ± 10009.4	3545.71 ± 2828.16	3546.48 ± 2827.92	3697.18 ± 3037.10
10	15940.5 ± 10345.8	15945.3 ± 10352.1	15594.9 ± 9521.3	3545.46 ± 2826.10	3546.26 ± 2826.94	3813.21 ± 3232.36
30	15894.3 ± 10321.0	15921.2 ± 10342.5	12752.6 ± 7009.2	3545.58 ± 2826.61	3545.30 ± 2826.62	3561.99 ± 3320.42
50	15865.6 ± 10285.4	15953.4 ± 10353.6	7387.8 ± 3908.5	3545.45 ± 2827.12	3542.97 ± 2823.50	2232.82 ± 2202.66
VLF [ms ²]						
0	2807.3 ± 2297.9	2807.3 ± 2297.9	2807.3 ± 2297.9	474.94 ± 359.93	474.94 ± 359.93	474.94 ± 359.93
5	2819.8 ± 2225.3	2817.0 ± 2217.6	2763.4 ± 2063.8	474.89 ± 347.35	475.22 ± 347.41	488.15 ± 372.28
10	2808.1 ± 2203.4	2820.8 ± 2220.8	2694.9 ± 1910.8	474.06 ± 346.83	475.20 ± 347.06	495.15 ± 388.98
30	2822.0 ± 2219.9	2871.6 ± 2268.3	2176.6 ± 1402.7	475.43 ± 348.97	476.48 ± 348.09	435.18 ± 374.16
50	2813.6 ± 2202.7	2983.2 ± 2352.5	1245.2 ± 767.8	472.31 ± 345.31	476.31 ± 348.17	252.37 ± 218.16
SLOPE						
0	-1.229 ± 0.166	-1.229 ± 0.166	-1.229 ± 0.166	-1.212 ± 0.127	-1.212 ± 0.127	-1.212 ± 0.127
5	-1.228 ± 0.160	-1.228 ± 0.158	-1.224 ± 0.152	-1.213 ± 0.123	-1.212 ± 0.123	-1.261 ± 0.129
10	-1.226 ± 0.159	-1.226 ± 0.162	-1.250 ± 0.173	-1.215 ± 0.119	-1.213 ± 0.125	-1.258 ± 0.158
30	-1.226 ± 0.164	-1.223 ± 0.165	-1.312 ± 0.164	-1.217 ± 0.122	-1.210 ± 0.129	-1.311 ± 0.169
50	-1.222 ± 0.160	-1.216 ± 0.168	-1.389 ± 0.189	-1.215 ± 0.123	-1.211 ± 0.123	-1.408 ± 0.191

Mean values of the parameters ± standard deviation in function of the editing percentage. The underlined values of the HRV parameters in table 1 indicate the editing limits for each parameter at which the mean error with its 95% confidence interval exceeds the value of 5%.
 Edit % = amount of the edited R-R intervals in percentages; int 0 = interpolation of degree 0; int 1 = interpolation of degree 1; del = deletion; SDNN = standard deviation of the normal-to-normal R-R intervals; ULF = ultra, low frequency power (<0.03 Hz); VLF = very low frequency power (0.005–0.04 Hz); Slope = slope of the regression line of the log(power) – log(frequency) of the HRV at frequency 10–4 Hz.

Figure 4. Effects of the three different editing methods on the values of the time and frequency domain parameters of the long-term R-R intervals data of the healthy subjects (left) and the AMI patients (right). The percentage difference with 95% confidence intervals in function of the editing percentage. Abbreviations: SDNN = standard deviation of all normal-to-normal R-R intervals, ULF = ultra low frequency power (< 0.03 cycles/beat), VLF = very low frequency power (0.005 - 0.04 cycles/beat), and SLOPE = slope of the regression line of the log (power)-log (frequency) of the HRV between frequencies 10^{-4} Hz and 10^{-2} Hz.

situation. These findings have some practical implications, i.e., that SDNN can be reliably analyzed even for noisy data and recordings with frequent ectopy after careful editing.

In the frequency domain analysis of short-term data, the estimation of the HF and LF spectral components was dependent on the study group and the editing method. In addition, the method of the spectral computation, either autoregressive or the fast Fourier transform, also had a slight effect on the performance of the editing process. The deletion method was not suitable for the estimation of either the HF or the LF spectral component. By increasing the HF fluctuation in the tachogram and also shortening the waveform of a signal, the deletion method produces false frequency components

in the HF parts in the power spectrum and broadens the LF, especially the HF component. By this broadband flattening of the spectra, the deletion method increases especially the power of the HF component but also the power of the LF component. This is especially obvious in the data with high R-R interval variation (the healthy study group). See Figure 5.

In the spectral analysis of the long-term data, the deletion method produced the largest errors. In the estimation of the ULF spectral component, any of the interpolation method did not affect the ULF computation remarkably, while the deletion method produced large errors in both study groups. Similar results concerned also the VLF power estimation analysis. The mean error in the

Figure 5. An example of an HRV power spectrum for a healthy subject with deletion editing. The peak of the HF component diminishes markedly in function of editing percentage, but in the same time the HF component broadens out because of the appearance of false frequency components. This results in an increase in the power of the HF spectral component.

analysis of the slope of the power-law regression line at a frequency between 10^{-4} Hz and 10^{-2} Hz also remained small with both interpolation methods, while the deletion method produced the largest errors for both study groups. The long-term spectrum components (ULF and VLF) are situated in the frequencies near the zero. The results of the long-term analysis are mostly affected by a change in the number of the samples of the R-R interval tachogram, which affects to the waveform of the tachogram. Because the deletion method reduces the number of samples in the tachogram, it is the most unsuitable method for long-term spectrum analysis.

Certain limitations of our work should be mentioned. Only a relatively small sample size was included in the study. The edited artefacts included mostly single beats and some sequences of two to four R-R intervals. The effects of editing long se-

quences of R-R intervals on the HRV analysis were not studied. Furthermore, the effects of ectopic beats on subsequent R-R intervals were not included in the present study.¹⁹ This study included only the editing methods of deletion, interpolation of degree zero, and interpolation of degree one. However, the use of the different editing methods in the present study still implies a need for not only one but several different editing methods for different HRV analyses and different types of R-R interval data.

Different studies propose different recommendations for how to deal with and edit the noise and artefacts in HRV data. Recommendations concerning both the methods of editing R-R intervals, deleting and interpolating the artefacts, have been presented depending on the study. Vybiral et al.² recommended the use of the splining with the interpolation for data files with complex arrhyth-

mias. Lippmann et al.¹ considered the deletion method of editing R-R intervals equally good or better compared to the more complicated editing methods in both time domain and frequency domain analyses with relatively short (5 min) R-R interval sequences. The present study showed the deletion method in the time domain analysis to be the most suitable method only for analysis of SDANN and SDNN. Birkett et al.⁵ reported an increase in the low-frequency (0-0.05 Hz) and mid-frequency (0.05-0.15 Hz) ranges of the HRV power spectrum with the editing methods of cubic spline and linear interpolation in the case of congestive heart failure (CHF) patients with a high degree of ectopy (> 5%). In the present study, linear interpolation (interpolation of degree one) produced an increase in the LF component (0.04-0.15 cycles/beat) in short-term data of healthy subjects and a very slight increase in the VLF component (0.005-0.04 cycles/beat) in long-term data of healthy subjects.

Various proportions of edited intervals, ranging from 1% to 30%, have usually been accepted for an analysis of HRV in scientific articles. The present study shows that none of the editing methods is superior to the others, and that investigators should perform their own validation for editing, depending on the study population and the particular HRV index used in the analysis. The findings of the present study can be partly used as a reference for the optimal editing method for different HRV parameters and the acceptable amount of edited beats for different HRV analysis methods.

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