Effects of the ECG Sampling Frequency on the Multiscale Entropy of Heart Rate Variability

Paolo Castiglioni1, Andrea Faini2

1IRCCS Fondazione Don Carlo Gnocchi, Milan, Italy
2Istituto Auxologico Italiano, IRCCS, Department of Cardiovascular, Neural and Metabolic Sciences, S.Luca Hospital, Milan, Italy

Abstract

It is known that the spectral analysis of heart rate variability requires an ECG sampling frequency F_S > 100 Hz with parabolic interpolation to refine the R peak if F_S < 250 Hz. By contrast, the effects of quantization errors in Multiscale Entropy (MSE) analysis due to low F_S have never been evaluated systematically. Our aim is thus to describe the effects of low F_S and parabolic interpolation on MSE. We considered 21 ECG recordings of 10' duration sampled at 500 Hz (reference). We decimated the ECG to simulate F_S between 250 and 50 Hz, we extracted the tachograms without and with parabolic interpolation and estimated MSE at scales between 1 beat (=SampEn) and 50 beats. The estimates were expressed as the percentage of the reference and the error was quantified by the interquartile range (IQR) of their distribution.

SampEn showed high sensitivity to F_S with IQR > 10% at 250 Hz and > 16% at 167 Hz; however, the parabolic interpolation dramatically decreased the IQR below 2% up to F_S = 71 Hz. The MSE estimates at larger scales were less sensitive to F_S with IQR < 2% even at F_S = 50 Hz. Thus the ECG sampling rate is more critical for SampEn than for MSE at larger scales and interpolation procedures are required when F_S < 250 Hz.

1. Introduction

Any algorithm for the analysis of heart rate variability (HRV) requires that the position of the R peak is identified from the ECG signal with sufficient precision. The sampling rate of the ECG influences importantly how well the R peak is identified, relevantly determining the level of noise affecting the tachogram.

The required minimum level of precision for detecting the position of the R peak depends on the nature of the HRV analysis. As regards the spectral analysis, the Guidelines on HRV defined the optimal range for the ECG sampling rate to be between 250 and 500 Hz, recommending to refine the time position of the R peak with a parabolic interpolation in case of sampling rates between 100 and 250 Hz [1].

More recently new complexity-based estimators of the heart rate dynamics have been proposed. Among them, the Multiscale Entropy (MSE) is arousing interest because of its ability to detect cardiovascular alterations [2]. The clinical value of MSE has been demonstrated in several HRV studies (see a short review in [3]). However, the effects of errors introduced by low sampling rates have never been evaluated systematically.

Therefore, the aim of this work is to assess the effects on the MSE estimates of low sampling rates of the ECG with and without reconstruction of the R peak by parabolic interpolation.

2. Methods

We considered the ECG recordings in 21 participants (17 women, 4 men) that constitute the EuroBavar data set available at www.eurobavar.altervista.org. Subjects were recorded for about 10-12 minutes twice, in supine and standing position. The ECG was sampled at 500 Hz with 16 bits resolution (see details on data collection in [4]). To simulate a sampling frequency (F_s) lower than 500 Hz, each ECG was decimated taking 1 sample every 2 samples (F_S = 250 Hz), 3 samples (F_S = 167 Hz), 4 samples (F_S = 125 Hz), 5 samples (F_S = 100 Hz), 7 samples (F_S = 71 Hz) and 10 samples (F_S = 50 Hz).

The R wave was identified with a derivative-and-threshold algorithm. The tachogram was extracted in two ways: without and with the refining of the position of the R peak by a parabolic interpolation, which identifies the R peak as the maximum of the parabola passing through the highest sample of the R wave and the samples immediately preceding and following the highest sample.

The tachograms extracted from the ECGs at 500 Hz without parabolic interpolation represent the reference for
studying the effects of the sampling rate without R-peak
reconstruction, those extracted with parabolic
interpolation are the reference for studying the effects
with R-peak reconstruction. Therefore, for each
participant and posture (supine or standing), we derived 2
reference tachograms (without and with parabolic
interpolation) and 12 decimated tachograms (6 without
and 6 with interpolation).

The MSE analysis was performed by the algorithm
described in [3] employing a Butterworth filter for coarse
graining, with embedding dimensions $m=1$ and $m=2$,
setting the tolerance $r$ to 20% the standard deviation of
the time series and applying a fixed-tolerance strategy [5].
The algorithm provided MSE coefficients for scales $s$
between 1 beat (corresponding to the Sample Entropy,
SampEn) and 50 beats. To concisely describe the MSE($s$)
profile, we defined a short-term MSE index, MSE$_{HF}$,
average of MSE($s$) over $7\leq s \leq 25$ beats (approximately
responding to the low-frequency spectral components).
The estimates of SampEn, MSE$_{HF}$, and MSE$_{LF}$ were
expressed as the percentage of their reference value (thus
estimates greater or lower than 100% indicate an over- or
under-estimation error respectively) and reported
statistically by the median and the interquartile range over
the group. This was done separately for the tachograms
with and without interpolation, for each subsampling,
each embedding dimension, and each posture.

3. Results

Figure 1 shows the profiles of MSE($s$) in the supine
position at decreasing sampling rates. SampEn ($s=1$) is
substantially overestimated reaching the largest values for
$F_s=100$ Hz. Deviations from the 500-Hz reference are
much lower at $s>2$ and consist in a progressive
underestimation as $F_s$ decreases. The parabolic
starts decreasing. This trend can be explained considering up to 100 Hz but at sampling rates lower than 100 Hz it trend with

Unexpectedly, the bias error does not show a monotonic
to the popular SampEn estimator of entropy.

MSE estimated at the scale of 1 beat, which corresponds relatively low ECG sampling rates can be important for

4. Conclusions

This work reports for the first time that the effects of relatively low ECG sampling rates can be important for MSE estimated at the scale of 1 beat, which corresponds to the popular SampEn estimator of entropy. Unexpectedly, the bias error does not show a monotonic trend with \( F_s \); it increases when \( F_s \) decreases from 500 Hz up to 100 Hz but at sampling rates lower than 100 Hz it starts decreasing. This trend can be explained considering

the specific nature of the errors associated with a low sampling rate. On one hand, a low \( F_s \) introduces a white noise distributed over \( \Delta T=1/F_s \) segment centered around the true position of the R-peak: this white noise artifically increases the estimate of entropy. On the other hand, a low \( F_s \) also introduces a quantization of the measured R-R intervals, which are a multiple of \( \Delta T \). This reduces the number of possible levels of the tachogram increasing the probability that the series repeats specific values of the R-R intervals eventually decreasing the entropy estimate. Interestingly, at \( s=2 \) beats we observed an underestimation of SampEn at \( 71 \leq F_s \leq 125 \) Hz: as to \( m=2 \) (the more used embedding dimension in HRV) the last quartile of the distribution shows overestimations greater than 24-31% in supine and 28-47% in standing. By contrast, evidence of small underestimations appears in the MSE\(_{HF} \) and MSE\(_{LF} \) indices at the lowest sampling rates. The interpolation almost corrects the estimation bias and reduces dramatically the amplitude of the interquartile ranges.

Table 1. Median [Q3-Q1] of MSE indices in supine as percentage of their reference value at decreasing \( F_s \).

<table>
<thead>
<tr>
<th>Embedding Dimension</th>
<th>Interpolation without</th>
<th>with</th>
<th>m=1</th>
<th>without</th>
<th>with</th>
</tr>
</thead>
<tbody>
<tr>
<td>SampEn (% of the reference)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_s = 50 ) Hz</td>
<td>95.3 [91.6-106.2]</td>
<td>99.9 [99.7-100]</td>
<td>94.6 [92.5-104.7]</td>
<td>99.8 [99.6-100.3]</td>
<td></td>
</tr>
<tr>
<td>( F_s = 167 ) Hz</td>
<td>100.6 [92.2-125.3]</td>
<td>100.1 [99.8-100.2]</td>
<td>101.3 [92.2-126.4]</td>
<td>99.8 [99.2-100.2]</td>
<td></td>
</tr>
<tr>
<td>( F_s = 250 ) Hz</td>
<td>106.6 [94.9-119.7]</td>
<td>100 [99.9-100.2]</td>
<td>109.8 [94.4-124.3]</td>
<td>100.2 [99.8-100.7]</td>
<td></td>
</tr>
<tr>
<td>( F_s = 100 ) Hz</td>
<td>107 [93.3-118.5]</td>
<td>100.1 [99.9-100.3]</td>
<td>113.1 [95.7-118.4]</td>
<td>100.3 [99.7-100.8]</td>
<td></td>
</tr>
<tr>
<td>( F_s = 71 ) Hz</td>
<td>104.2 [90.6-128.4]</td>
<td>100.2 [100-100.8]</td>
<td>107.4 [97-131.3]</td>
<td>101.1 [99.9-102.1]</td>
<td></td>
</tr>
<tr>
<td>( F_s = 50 ) Hz</td>
<td>98.7 [81.3-107.7]</td>
<td>101 [96.8-102.7]</td>
<td>96.9 [85.8-108.9]</td>
<td>101.2 [97.4-103.1]</td>
<td></td>
</tr>
</tbody>
</table>

| MSE\(_{HF} \) (% of the reference) | | | | | |
| \( F_s = 50 \) Hz | 100 [99.8-100.1] | 100 [100-100] | 100.2 [99.8-100.3] | 100 [99.9-100.1] | |
| \( F_s = 167 \) Hz | 99.9 [99.8-100.1] | 100 [100-100] | 100.2 [99.8-100.4] | 100 [99.9-100.1] | |
| \( F_s = 250 \) Hz | 99.9 [99.7-100.1] | 100 [100-100] | 99.8 [99.6-100.2] | 100 [99.9-100.1] | |
| \( F_s = 100 \) Hz | 99.8 [99.4-99.9] | 100 [99.9-100] | 99.7 [99.5-99.9] | 100.1 [99.9-100.1] | |
| \( F_s = 71 \) Hz | 99.7 [99.4-99.9] | 100 [99.9-100.1] | 99.8 [99.5-100.6] | 100 [99.9-100.2] | |
| \( F_s = 50 \) Hz | 98.9 [97.9-99.5] | 99.8 [99.7-100] | 99.6 [99.4-100.1] | 99.9 [99.7-100.7] | |

| MSE\(_{LF} \) (% of the reference) | | | | | |
| \( F_s = 50 \) Hz | 100 [99.9-100.1] | 100 [100-100] | 99.9 [99.9-100] | 100 [100-100] | |
| \( F_s = 167 \) Hz | 99.9 [99.6-100] | 100 [100-100] | 99.7 [99.6-100] | 100 [100-100] | |
| \( F_s = 250 \) Hz | 99.9 [99.5-99.9] | 100 [100-100] | 99.9 [99.4-100] | 100 [100-100] | |
| \( F_s = 100 \) Hz | 99.7 [99.2-99.8] | 100 [99.9-100] | 99.7 [99.2-99.9] | 100 [99.9-100] | |
| \( F_s = 71 \) Hz | 99.1 [98.4-99.8] | 99.9 [99.9-100] | 99.4 [98.5-99.8] | 100 [99.8-100] | |
| \( F_s = 50 \) Hz | 98.6 [97.6-99.3] | 98.8 [95.3-99.8] | 98.3 [96.9-99.1] | 99.7 [99.4-99.9] | |
multiples of AT only. The present study shows that this refining procedure works remarkably well and that the MSE estimates present negligible errors at all the scales even with ECG sampling rates of 100 Hz only.

References


Address for correspondence:

Paolo Castiglioni.
IRCCS Fondazione Don C. Gnocchi
Via Capecelatro 66, I 20148, Milano, Italy.
pcastiglioni@dongnocchi.it

<table>
<thead>
<tr>
<th>Interpolation</th>
<th>SampEn (% of the reference)</th>
<th>MSEHF (% of the reference)</th>
<th>MSELF (% of the reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_s=250$ Hz</td>
<td>109.2 [92.9-111.1]</td>
<td>100 [99.9-100.1]</td>
<td>100 [99.9-100.1]</td>
</tr>
<tr>
<td>$F_s=167$ Hz</td>
<td>89.1 [85.3-101.3]</td>
<td>99.9 [99.9-100.1]</td>
<td>99.8 [99.7-100.4]</td>
</tr>
<tr>
<td>$F_s=125$ Hz</td>
<td>133.5 [97.8-142.7]</td>
<td>100 [99.8-100.2]</td>
<td>100 [99.5-101.1]</td>
</tr>
<tr>
<td>$F_s=100$ Hz</td>
<td>126.5 [117.2-137.4]</td>
<td>100.2 [100.1-100.7]</td>
<td>100.7 [100.4-101.2]</td>
</tr>
<tr>
<td>$F_s=71$ Hz</td>
<td>111.9 [104.7-124.4]</td>
<td>100.8 [100.1-101.6]</td>
<td>102.2 [101.5-102.9]</td>
</tr>
<tr>
<td>$F_s=50$ Hz</td>
<td>97.1 [90.3-110.4]</td>
<td>100.5 [98.7-104.3]</td>
<td>105.9 [101-109.6]</td>
</tr>
</tbody>
</table>

Table 2. Median [Q3-Q1] of MSE indices in standing as percentage of their reference value at decreasing $F_s$. |