ELECTROCARDIOGRAM SAMPLING FREQUENCY ERRORS IN PR INTERVAL SPECTRAL ANALYSIS

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Abstract – The PR interval extracted from the surface electrocardiogram (ECG) may be used for the noninvasive assessment of autonomic nervous system (ANS) activity at the atrioventricular (AV) node. Accurate automated detection of the characteristic P wave onset and QRS complex onset is complicated by a number of factors including varying wave morphology, external noise sources, and errors introduced by the sampling rate of the underlying ECG signal. In this work we investigate the impact of different ECG sampling frequency choices on the PR interval time series and resulting spectra.

I. INTRODUCTION

The AV node controls the propagation of electrical impulses from the atria to the ventricles, facilitating priming of the ventricles for contraction. It is highly innervated by the ANS with parasympathetic and sympathetic activity decreasing and increasing respectively the conduction time through the node. This conduction time may be assessed noninvasively using the PR interval [1], which is measured from the onset of the P wave to the onset of the following QRS complex (see Fig. 1). However, the impact of ECG sampling frequency on PR interval variability analysis using spectral methods remains unclear. In this paper, we analyse the effect of the choice of sampling frequency on the PR interval without the use of interpolation, using techniques similar to those applied by Merri *et al.* [2] to interbeat (RR peak-peak) interval sampling errors.

II. METHODS

The theoretical and measured PR interval from the ECG is shown in Fig. 1. The RR (or PP) interval may be considered to have a single sampling error sequence $e_R(n)$ related to either the R peak (or QRS onset) sampling error. Also the sampling error at the end of an RR interval is the same as the first error of the succeeding interval. In contrast, sampling errors at the beginning and end of the PR (and indeed the QT) interval are independent from the sampling errors of the next PR interval. Thus, there are effectively two sampling error sequences, one relating to P onsets and the other to QRS onsets. The sampled fiducial points of these onsets are defined as the samples that fall closest to the actual onsets. The relationship between the "true" and measured intervals is:

$$x_m(n) = x_t(n) + e_R(n) - e_P(n) = x_t(n) + d(n)$$

$x_t(n)$ and $x_m(n)$ are the assumed n[th] true and measured PR interval respectively. $e_P(n)$ and $e_R(n)$ are the errors due to the sampling of the P and QRS onsets and $d(n)$ is the total error due to both P and QRS onset sampling.

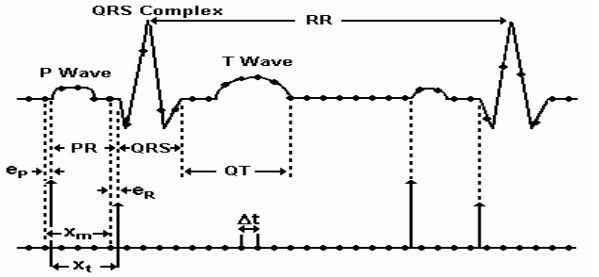

Fig 1. Schematic representation of true and sampled PR interval.

Both the P and QRS onset error sequences, $e_P(n)$ and $e_R(n)$ are assumed to be zero mean random variables independently, identically and uniformly distributed in the interval $-\Delta t/2 \le e \le \Delta t/2$, where $\Delta t = 1/f$ is the ECG sampling rate. The sequences $\{x_t\}$, $\{e_P\}$ and $\{e_R\}$ are uncorrelated, $\{x_t\}$ is wide sense stationary. Both $e_P(n)$ and $e_R(n)$ are therefore white noise with zero mean and variance $\Delta t^2/12$. The autocorrelation functions (ACF) of the error sequence is therefore

$$R_{e_P e_P}(k) = R_{e_R e_R}(k) = \frac{\Delta t^2}{12}\delta(k)$$

where δ(k) is the Kronecker delta function. The power spectral density (PSD) of the error sequences is

$$S_{e_P e_P}(\varphi) = S_{e_R e_R}(\varphi) = \frac{\Delta t^2}{12} \qquad |\varphi| \le 0.5$$

where φ represents the fact that the sequences are expressed in cardiac beats rather than at a fixed sampling rate. The ACF, variance and the PSD of the total error sequence $d(n)$ are therefore:

$$R_{dd}(k) = R_{e_P e_P}(k) + R_{e_R e_R}(k) = \frac{\Delta t^2}{6}\delta(k)$$

$$Var(d) = R_{dd}(0) = \frac{\Delta t^2}{6}$$

$$S_{dd}(\varphi) = \frac{\Delta t^2}{6} \qquad |\varphi| \le 0.5$$

The PSD of the measured PR interval sequence $x_m(n)$ is:

$$S_{x_m x_m}(\varphi) = S_{x_t x_t}(\varphi) + S_{dd}(\varphi) = S_{x_t x_t}(\varphi) + \frac{\Delta t^2}{6} \quad |\varphi| \le 0.5$$

Therefore, unlike with RR interval analysis where the total error due to finite sampling is a coloured noise sequence with high pass characteristics, the total error on the PR, QT or any other intrabeat interval of the cardiac cycle will be white with a flat spectrum at $1/6f^2$, where $f = 1/\Delta t$ is the sampling frequency.

To simulate these effects, we obtained a sequence of 512 PR intervals extracted from an ECG sampled at 1 kHz. Both the P wave onsets and the QRS complex onsets were marked by an automated system. A train of 1024 delta functions was generated to represent the P and QRS onsets as shown in Fig. 1. This signal was then resampled at 128, 256 and 512 Hz and the new measured intervals were examined in relation to the original 1 kHz sampled signal, which is assumed to be the "true" measure. The error signal represented the difference between the 1 kHz signal and the resampled signal. The statistical values for the measured intervals $x_m(n)$ and the total error $d(n)$ at each sampling frequency are shown in Table 1.

TABLE I
Summary of expected value E[] and variance Var[] of measured total error sequence {d} and measured PR intervals {x_m}

Frequency (Hz)	E[d] (sec)	Var[d] (sec^2)	E[x_m] (sec)	Var[x_m] (sec^2)
128	6.213e-5	9.399e-6	0.14232	1.6834e-5
256	-1.057e-4	2.812e-6	0.14249	9.9651e-6
512	5.069e-5	7.201e-7	0.14233	8.0232e-6
1000	-	-	0.14238	7.5709e-6

The power spectral density (PSD) of the "true" intervals, the measured intervals and the total error were estimated using Welch's averaged, modified periodogram method. The intervals were analysed on a beat by beat basis. The ratio of the measured interval power spectra and the total error spectra were evaluated for each frequency using the following signal-to-noise (SNR) estimation

$$SNR = 10\log_{10}\left|\frac{S_{x_m x_m}(\varphi)}{S_{dd}(\varphi)} - 1\right| \qquad |\varphi| \le 0.5$$

III. RESULTS

The PSDs for the measured intervals and the error signals are shown in Figs. 2 and 3. It is clear from these plots that the error due to sampling can introduce quite considerable error into the spectra of the PR interval. Fig. 3 shows the theoretical and measured total error. Due to the non-overlapping nature of intracardiac intervals, (sampling error at fiducial point only contributes to one interval), the total error is a relatively flat spectral additive white noise component, which affects both the low and high frequency components in a similar manner. As the noise power is inversely proportional to the sampling frequency squared, considerable improvement is made by moving from a sampling rate of 128 Hz up to 512 Hz. The SNR ratios indicate that all three frequencies perform badly at higher frequencies where there is less power in the PR interval spectra. The level of SNR will vary depending on the number of ECG intervals measured and on the strength of the periodic components within the intervals measured.

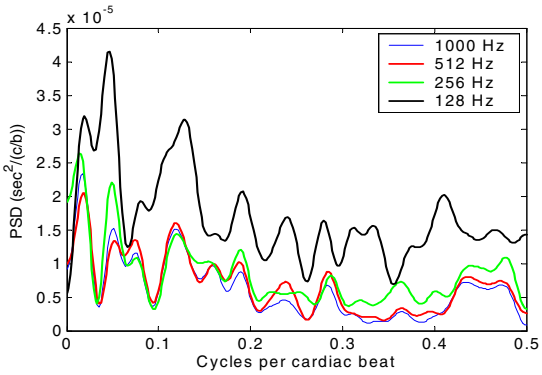

Fig 2. PSD of measured intervals x_m for each sampling frequency.

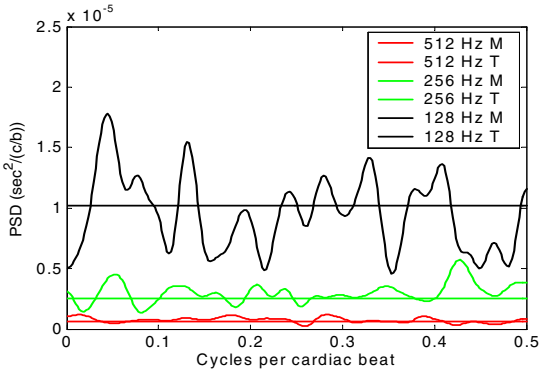

Fig 3. PSD of total error d. Solid straight lines are the theoretical (T) values while the broken lines are the measured (M).

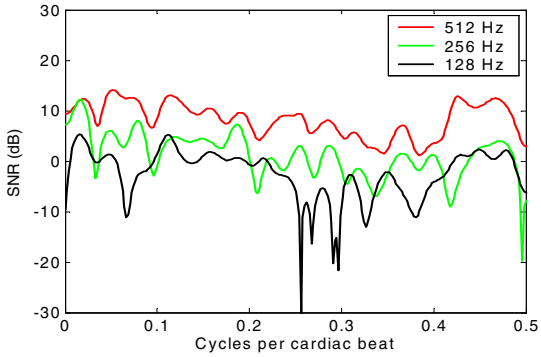

Fig 4. Signal to noise ratios SNR(dB) for each sampling frequency.

IV. CONCLUSIONS

The total error produced by the finite sampling of the ECG contributes an additive white noise component to the spectra of the PR interval, which is inversely proportional to the frequency squared. Due to the shorter duration and inherent limited variability of intrabeat cardiac intervals such as the PR or QT intervals, sampling frequencies of 512 Hz or higher should be considered. These sampling rates may be implemented by direct sampling of the ECG or through interpolation methods.

REFERENCES

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