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A methodological comparison of the Porges algorithm, fast Fourier transform and autoregressive

spectral analysis for the estimation of heart rate variability in 5-month-old infants

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Abstract

Little empirical evidence exists on the comparability of heart rate variability (HRV) quantification methods commonly used in infants. The aim was to compare three methods of HRV estimation: 1) fast Fourier transform (FFT), 2) autoregressive (AR) and 3) the Porges methods. HRV was estimated in 63 healthy 5-month-old infants. HRV parameters were strongly correlated across methods (.92 - .99) but yielded significantly different mean HRV estimates (Porges method > FFT > AR). There was no systematic bias over the whole range of values between the two spectral approaches while differences between the Porges method and the spectral estimates were systematically greater for larger values. Additional comparative studies are needed to explore the between-method agreement across a range of physiological conditions.

Keywords Heart rate variability; Methodological comparison; Spectral analysis; Fast Fourier transform; Autoregressive analysis; Porges method; Infant

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Heart rate variability (HRV) occurs at specific frequencies and is commonly used for

assessing the autonomic nervous system. Indeed, the high frequency oscillations of heart rate

(HR) (HF, from 0.15 to 1 Hz or more in infants; Rosenstock, Cassuto, & Zmora, 1999) represent

parasympathetic control. Low frequencies HRV (LF, 0.03 - 0.15 Hz) is thought to reflect both

sympathetic and vagal contributions while the exact origins of the rhythms of very low

frequencies (VLF, 0.003-0.05 Hz) remain unclear (Task Force, 1996).

The most commonly used methods of HRV estimation are based on spectral analysis,

especially through the fast Fourier transform (FFT) and autoregressive method (AR). Filtered

variance can also be used, such as the method developed by Porges (1985) which derives only the

HF component of HRV. Many authors state that these are valid methods to assess HRV

(Grossman, Van Beek, & Wientjes, 1990; Porges & Bohrer, 1990). However, considering their

respective limits and advantages, the three methods can be more or less suitable to cardiovascular

time series, depending on time series properties or population cardiac/respiratory characteristics.

Only a few studies have compared these methods in adult populations and some have

shown a marked degree of agreement in HRV estimates using AR and FFT (e.g., Grossman et al.,

1990). By contrast, other studies report between-method inconsistencies in adults, with FFT

generally providing higher HRV estimates than AR (e.g., Badilini, Maison-Blanche, & Coumel,

1998).

In infants, only one study compared the FFT and Porges methods in a sample of 8 two-

month-olds (Litvack, Oberlander, Carney, & Saul, 1995), while another compared the

conventional to the customized FFT (de Beer et al., 2004). This is insufficient to make inferences

about the comparability of HRV estimates in young populations. The validity of different

methods may however vary specifically for infant HRV because (a) infant HR is almost twice that of the adult HR (Marx, 2009), (b) infants present variable respiratory rates accompanied by apneas and sighs (de Beer et al., 2004), (c) their autonomic control is immature (Rosenstock et al., 1999). For these reasons, there is a need to assess the convergence of methods in infants.

The aim of the present study is to compare short-term HRV measurements using FFT, AR and the Porges method in 5-month-old infants.

Methods

Participants

Sixty-three infants (34 girls) without known pulmonary, cardiac or neurological diseases (corrected for gestational age of 4.94 ± 0.31 months, birth weight of 2.6 ± 0.6 kg, [mean $\pm$ *SD*] and 5 min Apgar median of 9, interquartile range 8 to 10) were randomly selected from 644 twins assessed on HRV from the Québec Newborn Twin Study (QNTS), with restriction of one infant per family and a minimum birth weight and gestational age of 1.5 kg and 29 weeks. Study was approved by the Laval University Ethics Committee, Quebec, Canada.

Materials

Surface electrocardiograms (ECG) were recorded by the Biopac acquisition system at 500 Hz sampling rate using three pregelled Ag-AgCl disposable electrodes attached to the chest in a triangular configuration (two electrodes below the shoulders and a ground near the navel). ECGs were digitalized with AcqKnowledge 3.2 for MacIntosh. As ECGs were performed during quiet sleep (assessed on the basis of eye movements), respiration data collected by means of a chest strain gauge were not used and presumed to be regular.

Design and procedure

The visit was performed between 10:00 a.m. and 3:00 p.m. and included several tasks and observations. ECGs were recorded in sleeping infants placed in a reclining infant car seat during 4-min periods in the horizontal (at +15º) and vertical (at +70º) positions.

Data reduction and analysis

Series of interbeat intervals (IBIs) were derived off-line using the AcqKnowledge Rate Detector Algorithm. Ectopic beats and artefacts were manually identified, corrected (referring to the ECG) or replaced by the mean of two adjacent IBIs.

Porges algorithm. MXedit software (Delta-Biometrics, Inc.) was used to quantify the Vagal Tone Index (V_{NA}) by averaging 10-s sequential epochs processed by a 4 Hz sampling rate and a 0.24-1.04 Hz band-pass filter.

Spectral analyses. IBIs were processed by the 6 Hz cubic interpolation and a smoothness prior approach (Tarvainen, Ranta-aho, & Karjalainen, 2002). Harmonic components were analyzed by means of HRV Analysis Software 2.0 for Windows (Biomedical Signal Analysis Group, Department of Applied Physics, University of Kuopio; Kuopio, Finland). AR was estimated using the forward-backward linear least-square algorithm with a 20th-order model. FFT estimates were derived with Welch's periodogram applied on 50 % overlapping Hanning window of 1024 points. Standard HRV parameters (Task Force, 1996) in absolute values (ms^2) and in normalized units (n.u.) were estimated from the entire 4-min series but also averaged from four consecutive 1-min epochs. Due to the perfect relationship between HF and LF in n.u., only LF n.u. was reported.

The bandwidths for VLF and LF were 0-0.04 Hz and 0.04-0.15 Hz, respectively. Also, as the respiratory frequencies in infants exceed 0.40 Hz (Marx, 2009), HF bandwidth was fixed at 0.15-1.0 Hz to include respiratory HR fluctuations. In addition, the HF component was also obtained with the Porges method bandwidth (0.24-1.04 Hz). As the V_{NA} is a log-transformed

measure and because both FFT and AR distributions were not normal, logarithmic

transformations were applied to LF and HF estimates.

Statistical analysis

HRV parameters were tested using within-subject ANOVAs with method (2 or 3,

depending on the parameters) and position (2) factors. Significant main effects were followed up

by Bonferroni posthoc comparisons. Between-method agreement was assessed using Pearson

correlations. Finally, plots of the differences between pairs of methods against their means (Bland

& Altman, 1986) were analysed. Statistical analyses were completed with SPSS 13.0 for

Windows.

Results

HRV means and ANOVAs results are presented in Table 1. A main Method effect was

obtained for all HRV parameters, except for the total power and HF. FFT provided higher values

in comparison to AR for LF components and LF/HF ratio in both positions, while VLF was

higher when estimated by the AR. Also, the Porges method provided higher log-transformed HF

than the two spectral methods while FFT and AR did not differ significantly, independently of

the number of epochs used or the HF bandwidth. The postural change did not yield differences in

HRV estimates, except for the log-transformed LF estimated from the entire IBIs series. In

addition, no significant Method x Position interaction was observed suggesting the between-

method agreement is condition independent.

As reported in Table 2, estimates from the three methods were strongly correlated in the

two positions (all $r_s \geq .92$). However, to test whether the methods agree equally well over the

whole range of log-transformed HF values, differences between pairs of methods were plotted

against their means, used as best estimates of the true values. As the ANOVAs and correlational

analyses showed no differences between positions, data for the horizontal position only are

shown (see Figure 1). The differences in scores between the Porges and the two spectral methods were all positive (Figures 1A and 1B) indicating systematically larger HF estimates obtained with the Porges method while the mean difference in scores between FFT and AR was near zero (Figure 1C). In addition, points clustered around a line in Figures 1A and 1B suggest a systematic increase in bias for greater values when comparing the Porges and the spectral methods. By contrast, a random scatter for HF spectral estimates indicates no systematic bias.

Discussion

This study is the first to compare common HRV estimation methods in healthy infants. The principal findings are (a) the three quantification methods yield highly correlated HRV estimates, and (b) significant between-method differences make estimates from different methods not interchangeable.

FFT Versus AR

A combination of statistical phenomena may lead to the observed discrepancies for VLF and LF estimates. First, the methods may respond differently to signal preprocessing, i.e. interpolation or detrending procedures, known to alter the lower frequency components (Task Force, 1996). Also, discrepancies may be explained by method computational properties. As AR uses the more significant peaks and FFT includes all the components within a frequency band, the tails of neighboring components could be assigned to different bands by the FFT and AR (e.g., Badilini et al., 1998). Furthermore, the short segment duration may induce additional discrepancies, especially for VLF and LF components. Indeed, FFT's discriminative capacity is inversely proportional to the record duration whereas AR provides better spectral resolution within short data frames (Kay & Marple, 1981).

The Porges Method Versus the Spectral Techniques

The Porges method provided systematically greater values of HF compared to the spectral methods, with a better agreement for lower values, independently of the number of epochs analyzed or the type of bandwidth used. Litvack and colleagues (1995) proposed a possible explanation for the greater number of discrepancies observed for higher HF values. Using simulated data, they observed an altered HF component with an amplified peak near 0.43 Hz induced by the Porges filter. Undoubtedly, if a large portion of the time series variance is near this frequency, the overestimation of HF would be all the more important.

Postural Changes

All quantification methods were in strong concordance in both positions. However, condition-dependent differences between HRV estimation methods have also been reported in infants (Litvack et al., 1995). Considering the scarcity of evidence, additional studies are needed to assess between-method agreement in different physiological conditions.

Limitations

No conclusion can be drawn from this study about the accuracy of quantification methods. If there were methodological biases, all three methods were similarly affected by them. In addition, because of the autonomic immaturity during the first year of life, these results cannot be generalized to older infants or children. Finally, HRV estimates were not adjusted for respiration as it was presumed to be regular in sleeping infants.

In conclusion, when individual differences are considered, the three methods provide similar results but there is significant between-method discordance especially at low and very low frequencies. Additional comparative studies are needed to explore between-method agreement across a range of physiological conditions in infants.

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Table 1

HRV Parameters Obtained with the FFT, AR Methods and the Porges Approach at Vertical and Horizontal Positions

Parameter	FFT		AR		Porges		F [a]		
	H	V	H	V	H	V	F1	F2	F1 x F2
TP (ms^2)	403.8 ± 398.6	474.4 ± 414.5	409.3 ± 419.1	443.1 ± 365.3			1.32	1.60	2.33
VLF (ms^2)	26.2 ± 53.0	27.8 ± 29.8	47.3 ± 48.5	52.1 ± 52.6			50.11 **	0.25	0.25
LF (ms^2)	195.2 ± 186.8	242.3 ± 226.7	175.3 ± 183.2	189.6 ± 150.1			20.91 **	1.62	3.66
HF (ms^2)	182.4 ± 254.8	204.3 ± 253.8	186.7 ± 249.8	201.3 ± 245.1			0.02	0.77	0.66
log LF	2.1 ± 0.45	2.2 ± 0.41	2.0 ± 0.45	2.1 ± 0.39			40.65 **	4.65 *	1.03
log HF	2.0 ± 0.46	2.1 ± 0.48	2.0 ± 0.45	2.1 ± 0.46	4.1 ± 1.2	4.2 ± 1.2	498.93 **	1.03	0.24 [b]
log HF[c]	2.0 ± 0.45	2.1 ± 0.47	2.0 ± 0.45	2.1 ± 0.47	4.1 ± 1.2	4.2 ± 1.2	491.46 **	1.05	0.25 [b]
log HF[d]	1.9 ± 0.48	1.9 ± 0.51	1.9 ± 0.48	2.0 ± 0.51	4.1 ± 1.2	4.2 ± 1.2	642.45 **	1.48	0.07 [b]
LF nu	54.0 ± 19.3	57.2 ± 20.9	50.9 ± 19.2	53.4 ± 20.3			51.64 **	2.71	0.45
LF/HF	1.8 ± 1.6	2.2 ± 2.1	1.5 ± 1.3	1.7 ± 1.6			31.90 **	3.44	4.03

Note. AR = autoregressive modeling; FFT = fast Fourier transform modeling; H = Horizontal; HF = high frequency band; LF = low frequency band; nu = normalized units; TP = total power; VLF = very low frequency band; V = Vertical. Values are means ± SD.

[a]*F* statistic of the two-way repeated ANOVAs with (2,61) *df* for log HF Factor 1(Method) and Factor 1 x Factor 2 (Method x Position) interaction and with (1,62)

df for all the other Factor 1(Method) and Factor 2 (Position) analyses.

[b]Mauchly's test indicated that the assumption of sphericity for Method and for Method x Position had been violated, by consequence, the Huynh-Feldt correction

was applied.

[c] These log HF parameters were obtained with the FFT and AR methods applied on four subsequent 1-min epochs. The reported data relate to averaged spectra

with the HF component fixed at 0.15 -1.00 Hz.

[d] These log HF parameters were obtained from four averaged 1-min epochs with the same frequency range for HF band as used in the Porges approach, i.e. 0.24 –

1.04 Hz.

*$p \leq .05$, **$p \leq .001$.

Table 2.

Correlations Between HRV Parameters Estimated by the AR, FFT and Porges Methods in the Horizontal/Vertical Positions

HRV Parameters	FFT						V_{NA}
	1	2	3	4	5	6	
AR							
1. LF	.92/.92						
2. log LF		.96/.95					
3. LF nu			.96/.98				
4. HF				.98/.99			
5. log HF					.98/.98		.94/.96
6. LF/HF						.95/.97	
V_{NA}					.93/.94		

Note. AR = autoregressive modeling; FFT = fast Fourier transform modeling; V_{NA} = Vagal Tone Index from the Porges approach; TP = total power; VLF = very low frequency band; LF = low frequency band; HF = high frequency band; nu: normalized units.

All *p's* < .001.

Figure legend

Figure 1.

Distribution plot of the difference between methods on their mean for A) V_{NA} and the AR ($r =$ .96, $p < .001$); B) V_{NA} and the FFT ($r = .95$, $p < .001$) and C) the AR and FFT ($r = .03$, $p = .79$), log-transformed HF in the horizontal position.