Assessment of Heart Rate Variability by Short-Time Fourier Transform and Data Analysis

J Clairambault[1], L Curzi-Dascalova[2], F Kauffmann[3,1], C Médigue[1], C Leffler[4]

[1]INRIA-Rocquencourt, [2]INSERM-Clamart,
[3]Department of Mathematics, University of Caen, FRANCE
[4]Harvard-MIT Division of Health Science and Technology, Cambridge, MA

Abstract

Heart Rate Variability (HRV) analysis of 24 healthy newborn sleeping babies was performed by Short-Time Fourier Transform in 3 frequency bands, reflecting the activity of both branches of the Autonomic Nervous System (ANS), vagal and sympathetic. The means of the 3 extracted time signals, computed over records of 512 heartbeats, were used as a material for principal component analysis, and for discriminant factor analyses, to separate sleep states and conceptional age (CA) groups. This study suggests that: 1/ sleep state discrimination, on the basis of an opposition between high (purely vagal in its origin) and low (vagal and sympathetic) frequency HRV, is regularly improved from 31 to 41 weeks CA, and 2/ a strong increase in ANS activity, mainly vagal, as reflected by high frequency HRV, occurs precociously, not later than 38 weeks CA.

Introduction

Heart Rate Variability (HRV) analysis is a noninvasive means to investigate the Autonomic Nervous System (ANS) [1, 6]. It has proved useful in domains as various as obstetrical surveillance, diabetic neuropathy, and sudden cardiac death. It is known that short-term (or high frequency, HF) variability reflects vagal tone alone, whereas long-term (mid and low frequency, MF, LF) variability is due to both sympathetic and vagal components of the ANS [1, 6]. It has also been reported that HF variability in newborns is at its top in Quiet Sleep (QS = non REM Sleep), whereas MF and LF variabilities reach their highest levels in Active Sleep (AS = REM Sleep) [2, 7]. HRV has been used to assess maturation of the ANS in normal infants, from 1 week to 6 months [7], and it is used here in very young healthy newborns, pre-term and full-term, to analyze, according to conceptional age (CA), maturation of the ANS, in both its components, vagal and sympathetic. This is done by studying: 1/ the differentiation between sleep states, as measured by HRV variables and 2/ the age-related modifications of these variables, from the pre-term to the full-term group.

*Supported by grants RGR62 INSERM-CNAMTS and INSERM CJF8909

Methods

8 pre-term (31-36 weeks CA), 8 near-term (37-38 weeks CA), and 8 full-term (39-41 weeks CA) newborn infants, all clinically and neurophysiologically healthy, were submitted to polygraphic recordings during sleep, at an age varying between 2 and 11 days. The EEG and eye movement channels were used to code sleep state visually on paper tracings, in AS or QS, whereas the ECG signal was digitized at 281 Hz, to be used for HRV analysis. A signal-to-noise-ratio algorithm [3, 4] allowed detection of the QRS complex of the ECG, to yield the *RR signal*, which associates to each heartbeat the duration between the current R wave and its predecessor. Too long or too short RR's were replaced by the value of the *RR* baseline, according to an automatic correction algorithm, and classified as 'artefacts'. Records of 512 consecutive heartbeats (statistical observation units) containing more than 10% artefacts were later discarded from data analysis.

Short-Time Fourier Transform (STFT,[5], see also [8]), in 3 frequency bands: high (HF: period 3 to 8 heartbeats), mid (MF: 10 to 25) and low (LF: 30 to 100), was performed on the *RR signal* of the total sleep duration (2 hours or more), producing 3 'instantaneous spectral amplitude' signals, one for each frequency band. These bands are comparable to the ones used by Harper, Schechtman, and Kluge [2, 7], if one converts heartbeats to 'equivalent seconds', multiplying number of beats by mean RR over the record under study (on our data, [1.2 , 4] equivalent seconds was the mean period range in the HF band, [4.5 , 12] was for the MF band, and [12.5 , 50] for the LF band).

0-8186-2485-X/92 $3.00 © 1992 IEEE

For the frequency band $[f_0 - \varepsilon\ ,\ f_0 + \varepsilon]$, measured in cycles/beat, the complex demodulation formula runs as follows:

$$A_{f_0}(n) = \left| \sum_{k=0}^{n} RR_{f_0}(k) w_{f_0,\varepsilon}(n-k) e^{-2\pi i f_0 k} \right|$$

where $(w_{f_0,\varepsilon})$ is a low-pass iir filter with $[0\ ,\ \varepsilon]$ pass-band, and RR_{f_0} has been prefiltered from RR in the band $[f_0 - \varepsilon\ ,\ f_0 + \varepsilon]$. RR has been decimated by 4 for MF demodulation, and by 8 for LF demodulation.

Fig. 1 shows an example of the results of STFT, with simultaneous sleep state coding (AS=Active Sleep=REMS, QS=Quiet Sleep=nREMS):

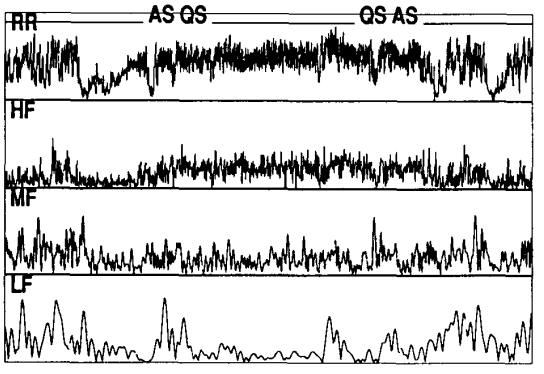

Fig. 1. *Result of STFT processing, on a sequence of 4096 heartbeats (about 30 min.) of a full-term newborn, exhibiting a period of intense HF activity and low LF activity, recorded in QS, bordered by epochs with opposite characteristics, recorded in AS. y-scales range from 350 to 650 ms for RR, and from 0 to 100 ms for the other three signals.*

Mean, variance, and 50-class histograms were calculated over 512-heartbeat epochs for each one of the 3 extracted signals. Simple and cumulated histograms were used for factor analyses on distance tables, according to methods which are presently under assessment in our institute. The means (HF, MF, and LF) were used for a 3d-representation of all epochs consisting of pure AS or pure QS, on which a principal component analysis, and 2-group discriminant factor analyses (between sleep states and age groups), were performed.

Results

Fig. 2 shows the results of a (normed) principal component analysis performed on the set of all 334 512-heartbeat epochs under study:

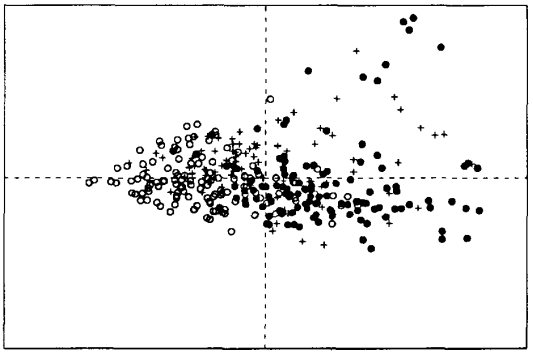

Fig. 2. *Projection of all epochs onto the principal factor plane ($x = 0.64HF + 0.94MF + 0.83LF$, y=$0.76HF - 0.08MF - 0.49LF$); full dots (•) represent full-term neonate epochs (39-41 w.CA), crosses (+) near-term ones (37-38), and empty dots (○) preterm ones (31-36).*

Premature and full-term epochs appear relatively well separated, but near-term epochs are strongly intricated with the other two groups. The first factor (x, 66% of total variance) is clearly related to total HRV, and may be seen as a 'maturity factor'; the second factor (y, 27% of total variance) is, roughly speaking, an opposition HF – LF, and may thus reflect the balance between vagal and sympathetic tones. This may be lightened by Fig. 3, where, on the same principal factor plane, points are distinguished not by age group, but by sleep state:

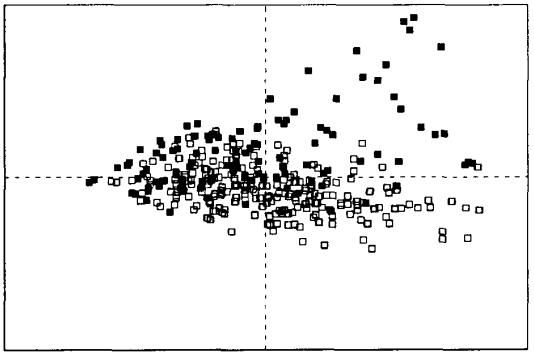

Fig. 3. *Same as Fig. 2; empty squares (□) represent AS epochs, full squares (■) represent QS epochs.*

Comparing the last two figures suggests that sleep state discrimination on HRV parameters is likely to be mediocre in prematures, but more satisfying in full-

term newborns. This may be seen on the next table, which shows the results of linear discriminant analyses between sleep states, first for all epochs, and then according to age group:

Table 1. *Evolution of between-state discrimination: discriminant analyses, using HF, MF, and LF, performed on all 334 epochs of 512 heartbeats (All epochs), 119 epochs (Full-term), 91 epochs (Near-term), and 124 epochs (Pre-term):*

Age group	L D	M D	r_{HF}	r_{MF}	r_{LF}
All epochs	75%	1.87	−.65	.23	.60
Full-term	81%	3.52	−.78	.19	.71
Near-term	74%	2.68	−.86	−.05	.28
Pre-term	69%	1.24	.02	.79	.98

(LD, Linear Discrimination: percentages of well-classified epochs, globally or within one given age group; MD, Mahalanobis distance between the centres of gravity of groups, a complementary measure of the quality of discrimination; r_{xF}, correlation coefficient of Discriminant Linear Form with HRV variables.)

This table shows that sleep state discrimination is regularly improved with age, and that it is, at least for near- and full-term newborns, mainly due to an opposition HF/LF.

Now trying to discriminate between age groups, we were confronted to the problem of an intrication between the three groups, as is illustrated by Fig. 2; so we performed 2-group discriminant analyses for each possible pair of groups. The results of these 3 linear discriminant analyses, are shown on Table 2:

Table 2. *Between-2-age-group discrimination: Between full-term and pre-term (119 + 124 = 243 epochs, top), between near-term and pre-term (91 + 124 = 215 epochs, middle), and between full-term and near-term (119 + 91 = 210 epochs, bottom), all sleep states mixed:*

All states	L D	M D	r_{HF}	r_{MF}	r_{LF}
Full/pre-term	84%	4.26	.63	.97	.82
Near/pre-term	72%	1.50	.97	.70	.46
Full/near-term	72%	1.15	.04	.90	.88

(Same legends as in Table 1.)

There is a striking evolution of the correlation coefficient between the last two lines of this table: discrimination between near-term and pre-term epochs rests mainly on HF (related to vagal tone), whereas discrimination between full-term and near-term epochs rests not at all on HF, but essentially on MF and LF (related to sympathetic tone). The best results for near/pre-term discrimination are obtained in QS (77 epochs):

QS only	L D	M D	r_{HF}	r_{MF}	r_{LF}
Near/pre-term	81%	2.95	.99	.82	.67

and, for full/near-term discrimination, in AS (136 epochs):

AS only	L D	M D	r_{HF}	r_{MF}	r_{LF}
Full/near-term	76%	1.92	.15	.89	.88

Since inspection of values averaged within each individual shows that all HRV variables rise with age, one can conclude from these tables that a strong increase in ANS activity, both sympathetic and vagal, but mainly vagal, occurs between 31-36 weeks and 37-38 weeks CA, and that only sympathetic tone remains on the increase after 38 weeks.

Discussion

Short-Time Fourier Transform (STFT) is a method used to process non-stationary time series. The *RR signal* certainly is non-stationary, but the interest of using such a tool is not apparent in this study, since we do not present here the results of 50-class histogram (probability density and repartition functions) processing, and variances within each 512-point epoch (highly correlated, on our data, to the corresponding means) are not used in linear discriminant analyses. In the same way, means calculated over 512-point epochs, HF, MF, and LF, present high correlations with FFT amplitudes in the same frequency bands (.99, .98, and .94, respectively, on our data), so that one may think of them as classical FFT variables, for the results presented here. Still STFT (as other time-frequency methods) yields multidimensional online spectral analysis of the ANS, via HRV. This may be exploited by calculating distance measures between time signals (raw RR, but also HF+MF+LF, HF-LF...) according to methods using finer time resolution than the one used in this study (512 heartbeats). These methods are presently under assessment.

Data analyses were performed on 334 512-point epochs, whereas only 24 real (independent) babies exist. But we also performed hypothesis tests (t-test, Mann-Whitney test) on within-individual means, which widely confirmed the results of discriminant analyses, as regards ANS maturation: our results suggest that, according to HRV parameters, vagal tone and, to a lesser extent, sympathetic tone, undergo

a rather steep increase at 37-38 weeks CA, but that only sympathetic tone goes on growing in the last week(s) of gestation. This was also found by hypothesis tests, which showed highly significant differences ($p < .001$) between pre-term and near-term groups, and non-significant differences between near-term and full-term groups for HF, but stable differences ($p = .06$) on the same groups for LF. In the same way, the fact that MF plays no role in sleep state discrimination was confirmed by hypothesis tests (paired t-test, Wilcoxon test) performed on within-individual means, which showed non-significant differences between the means in MF (but not in HF nor in LF), whatever the age group.

Moreover, an analysis of variance, performed with the 3 variables under study, on all 334 512-heartbeat epochs, and on the 'baby factor' showed that within-individual variance explained between 48 and 65 % of total variance, according to age group. This encouraged us to consider 512-point epochs as statistical observation units, rather than within-individual means on the same variables.

In conclusion, we think that, between classical hypothesis tests on means calculated over 2-hour (or more) duration sleeps, and on-line comparison of signals by distance measures, there remains a place for data analysis on restricted duration (512 heartbeats here) observation units. Our results suggest that such a method of analysis is appropriate for describing and comparing long-duration time signals.

References

[1] Akselrod, S., Gordon, D., Ubel, F.A., Shannon, D.C., Barger A.C., Cohen, R.J. (1981): Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat to beat cardiovascular control. *Science*, 213,220-222.

[2] Harper, R.M., Schechtman, V.L., Kluge, K.A. (1987): Machine classification of infant sleep state using cardiorespiratory measures. *Electroencephalogr. Clin. Neurophysiol.*, 67,379-387.

[3] Kauffmann, F., Clairambault, J., Médigue, C. (1991): Un système d' analyse des signaux biomédicaux. *Bulletin de Liaison de la Recherche en Informatique et Automatique (INRIA)*, 131,38-41.

[4] Kauffmann, F., Cauchemez, B. (1991): Extraction of cardio-respiratory parameters. In: *Sleep and cardio-respiratory control*, pp. 105-112. Editors: Cl. Gaultier, P. Escourrou, L. Curzi-Dascalova. John Libbey, London.

[5] Nawab, S.H., Quatieri, T.F. (1988): Short-Time Fourier Transform. In: *Advanced topics in signal processing*, pp. 289-337. Editors: J. S. Lim, A. V. Oppenheim. Prentice-Hall, Englewood Cliffs, NJ.

[6] Pomeranz, B., Macaulay, R.J.B., Caudill, M.A., Kutz, I., Adam, D., Gordon, D., Kilborn, K.M., Barger, A.C., Shannon, D.C., Cohen, R.J., Benson, H. (1985): Assessment of autonomic function in humans by heart rate spectral analysis. *Am.J.Physiol.*, 248,H151-H153.

[7] Schechtman, V.L., Harper, R.M., Kluge, K.A. (1989): Development of heart rate variation over the first 6 months of life in normal infants. *Pediatr. Res.*, 26,343-346.

[8] Shaw-Jyh Shin (1989): Assessment of autonomic regulation of heart rate variability by the method of complex demodulation. *IEEE Trans.Biomed.Eng.*, 36,274-283.