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Spectral Analysis of Heart Variability in the Newborn Infant

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Heart rate · Physiology · Spectral analysis · Autonomic dysfunction

Abstract
We investigated the relationship between spectral power and both mean heart rate (HR) and heart rate variability (HRV). Spectral power was calculated using digital heart rate recordings from term infants. Regression analysis revealed a positive correlation between low-frequency (LF) sympathetic power and HR, and a negative correlation between high-frequency (HF) parasympathetic power and HR. HRV correlated positively in all regions of the power spectrum. In awake infants, the contribution of HF power to total power (HF/TP) was significantly decreased. LF power tended to be greater, however, this trend was not statistically significant. By following expected autonomic patterns, the findings of this study confirm that spectral analysis provides a noninvasive method for the assessment of autonomic activity influencing the newborn heart. The correlation between spectral power and HRV can serve as an additional tool in the study of autonomic dysfunction.

Introduction

The noninvasive assessment of autonomic function in the newborn has recently become a growing research interest. Much of the work on heart rate variability has been conducted in the area of sudden infant death syndrome (SIDS) [1–18]. However, normative and developmental data have also been the focus of research efforts [19–29]. In the 1980s, the development of spectral analysis techniques gave researchers a new tool with which to quantify the cyclic nature of variations in instantaneous heart rate [30–41].

In humans, the adult [31, 32], child [37], and infant [40] heart rate variability power spectra contain two principle peaks. The first is a 'low frequency' (LF) peak occurring between 0 and 0.15 Hz. The amplitude of this peak is influenced by both the sympathetic and parasympathetic nervous system, and is believed to be mediated by such parameters as baroreceptors and thermoregulatory changes [41]. The second, or 'high frequency (HF) peak' occurs at respiratory frequency, and is a reflection of the sinus arrhythmia caused by respiration. HF fluctuations are modulated primarily by the parasympathetic nervous system.

We obtained heart rate variability power spectra on term and near-term infants. Correlations were made between spectral power and both mean heart rate and heart rate variability. Comparisons were also made between data from sleeping and awake infants. By establishing that

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the changes in spectral power parallel the expected changes in autonomic activity and balance, we aimed to further substantiate the use of spectral analysis as a noninvasive assessment of autonomic control in the newborn.

Methods

Patient Selection

We chose 20 healthy infants, all >36 weeks of gestation. All were studied during the first 24 h of life in the well-infant nursery at St. Peter's Medical Center (New Brunswick, N.J.). These infants had experienced benign prenatal courses, with either uncomplicated vaginal or elective repeat cesarean deliveries. Infants born to mothers receiving narcotic or sedative analgesia were excluded. The infants had no perinatal complications, and achieved Apgar scores of at least 8/9. All infants were >8 h of age, thus allowing for a period of time between birth and the time of study during which the infant's cardiorespiratory stability could be assured. In order to avoid iatrogenic elevations in heart rate due to painful stimuli, the infants chosen had not yet received immunizations, and males had not yet been circumcised. Institutional Review Board approval was obtained before the start of data collection.

Data Collection and Heart Rate Variability Analysis

Infants, in bassinets, were positioned on their right sides, propped by a blanket roll. They were wrapped by a single blanket, and were loosely covered by a second. All recordings were made under quiet conditions in the well-infant nursery, with recordings beginning within 1 h of feeding. The infants were under observation by the investigator and a diary was kept identifying their sleep or wakefulness, and identifying any motor activity.

Each infant's heart rate was tracked and recorded for a period of between 1 and 2 h by the Log-a-Rhythm Signal Acquisition Unit (Nian-Crae Inc., Somerset, N.J.) using conventional ECG monitoring techniques at a sampling rate of 1 kHz. The ECG data were digitized and RR intervals were stored with a resolution of 4 ms. The RR interval series was converted digitally into an instantaneous heart rate (IHR) tracing. In order to provide equally spaced samples, the final sampling rate of the IHR series was 4 Hz. Using IBM-compatible software, developed by Nian-Crae Inc., the IHR data were analyzed to determine the power spectrum of heart rate variability for each infant. The algorithm for analysis was based upon established techniques. For each subject, 150-second, artifact-free recording segments were selected by visual inspection to generate power spectra. Because infant activity can cause recording artifacts, the segments chosen corresponded to periods during which the infants exhibited little or no motor activity (quiet sleep and quiet wakefulness). Multiple segments were obtained from each heart rate tracing. The number of segments obtained from each tracing varied according to the number of artifact-free recording intervals available for analysis. The subsequent analyses were based upon each individual recorded segment, not upon the mean values per infant. The area under each power spectrum was then calculated for three frequency bands: 0.003–0.03 Hz (very LF, VLF); 0.03–0.15 Hz (LF), and 0.15–1.0 Hz (HF). Ratios of LF power to HF power (LF/HF) were calculated, and also of the spectral power in each frequency band to the total spectral power (TP). Comparisons were then made between spectral power, and the mean heart rate and heart rate coefficient of variation during each respective segment. Comparisons were also made between recording segments obtained during quiet sleep, and during quiet wakefulness. Data obtained from individual infants were not averaged.

Table 1. Patient population

Variable	
Gestation, weeks	38 ± 1.0[1]
Age, h	16.1 ± 5.0
Weight, kg	3.47 ± 0.46
Race	
Black	5
White	12
Other	3
Sex	
Female	11
Male	9
Delivery	
Vaginal	17
Cesarean section	3

[1] Mean ± SD.

Statistical Analysis

Comparisons between spectral power, and both the corresponding mean heart rate and heart rate coefficient of variation were conducted by calculating correlation coefficients and using multiple regression analysis. Student's t test comparisons were made between data from segments obtained during periods of sleep, and those recorded while infants were awake but quiet. All statistical analyses were performing using Statistica for Windows, Version 4.5, by Statsoft, Inc.

Results

We obtained recordings from 20 infants (gestational age 38.8 ± 1.0 weeks) during the first 24 h of life (age 16.1 ± 5.0 h). The patients' characteristics are itemized in table 1. The mean and standard deviation for the three bands of the power spectrum included an average power of 10.9 ± 14.0 (beats/min)^2 in the VLF band, an average power of 12.9 ± 11.1 (beats/min)^2 in the LF band, and an average power of 3.78 ± 3.64 (beats/min)^2 in the HF band.

Correlations between mean heart rate and the spectral power in sleeping infants are shown in table 2. Positive correlations were found between mean heart rate and LF power, while negative correlations were identified between mean heart rate and HF power. Similarly, a positive correlation existed between mean heart rate and the ratio of LF power to TP (HR vs. LF/TP). Negative correlations were identified between mean heart rate and the

Table 2. Spectral power as a function of mean heart rate

Variable	Correlation coefficient
VLF	0.08
LF	0.14*
HF	−0.50*
TP	0.01
LF/HF	0.35*
VLF/TP	0.03
LF/TP	0.28*
HF/TP	−0.25*

* Statistically significant: $p < 0.05$.

Table 3. Spectral power as a function of heart rate variability

Region	Correlation coefficient
VLF	0.64*
LF	0.64*
HF	0.67*
TP	0.81*

* Statistically significant: $p < 0.05$.

ratio of HF power to TP (HR vs. HF/TP). The ratio of LF power to HF power (HR vs. LF/HF) had a positive correlation with the mean heart rate. These correlations are all statistically significant.

Multiple regression analysis revealed that changes in mean heart rate were significantly correlated with LF power ($\beta = 0.14$), and HF power ($\beta = -0.50$). Mean heart rate was also significantly correlated with ratios of LF power to TP ($\beta = 0.28$), HF power to TP ($\beta = -0.25$), and the ratio of LF power to HF power ($\beta = 0.35$).

The correlations between heart rate variability and spectral power in sleeping infants are demonstrated in table 3. When we analyzed heart rate variability, defined as the coefficient of variation, significant positive correlations were found with VLF power, LF power, HF power, and TP. Multiple regression analysis indicated that heart rate variability was significantly correlated with changes in all regions of the power spectrum: β for VLF = 0.65; β for LF = 0.63; β for HF = 0.49, and β for TP = 0.80.

Table 4 shows the mean heart rate, heart rate variability, and spectral power in infants both during periods of sleep and while awake. Mean heart rate was significantly

Table 4. Heart rate, heart rate variability, and spectral power in sleeping and awake infants (mean ± SD)

Variable	Awake (quiet)	Asleep	p
Mean HR	131.1±8.9	123.8±13.0	0.002*
Coefficient of variation	0.042±0.014	0.041±0.018	0.748
VLF	13.1±16.4	10.6±13.6	0.341
LF	15.9±11.0	12.4±11.1	0.098
HF	3.35±2.17	3.85±4.73	0.540
TP	32.3±22.1	26.8±24.0	0.220
LF/HF	19.2±15.0	15.7±15.4	0.200
VLF/TP	0.39±0.18	0.34±0.19	0.187
LF/TP	0.48±0.18	0.48±0.17	0.930
HF/TP	0.13±0.08	0.18±0.130	0.040*

* Statistically significant.

greater in awake infants than in sleeping infants. In awake infants, the contribution of HF power to total power (HF/TP) was significantly less than during sleep. LF power tended to be greater when awake than while asleep, however, this result did not achieve statistical significance.

Discussion

It has long been recognized that the electrical activity of the heart varies both in amplitude, and in the actual interval between beats [30]. Such variability in instantaneous heart rate is under the regulation of the autonomic nervous system. The technique of spectral analysis allows this variability to be quantified, and correlated with cardiac effects of the autonomic nervous system.

Though there are numerous papers describing heart rate and heart rate variability in infants, most of the work specifically involving the use of spectral analysis, has been conducted in the adult population. Included among the many adult studies are works on the effects of syncope, hyperthyroidism, and heart disease upon spectral power [33–35]. Because the presence of a dysfunction in autonomic control has been theorized to contribute to SIDS, SIDS research has generated the most reports involving spectral analysis in infants [13–15, 17, 18]. The results, however, have been conflicting. Kluge et al. [13] and Schechtman et al. [14] reported that, overall, SIDS infants have a smaller degree of respiratory sinus arrhythmia than control infants. The overlap between the 2 groups, however, precluded conclusions regarding the predictive value of respiratory sinus arrhythmia. Other investigators have also found a decrease in high frequency oscillations in

SIDS victims [14, 17]. Gordon et al. [15] demonstrated enhancement of low frequency power in the spectral graphs of SIDS infants, as compared to their control group. On the other hand, some researchers have found no significant differences when analyzing heart rate variability [3, 8].

Finley et al. [38] assessed developmental changes in sympathetic and parasympathetic activity, using spectral analysis of heart rate variability, in patients between 5 and 25 years of age. They suggested that sympathetic activity and, to a lesser extent, parasympathetic activity decreases between 5 and 10 years of age. Nugent and Finley [39] also reported on heart rate variability as a function of the sleep state. Upon spectral analysis, they found that power in the LF band was higher during active sleep as compared to quiet sleep. These findings corroborate that there is an increase in sympathetic activity during active sleep. No differences were found in the HF band.

This study sought to assess the relationships between power spectra, mean heart rate, and heart rate variability in a group of healthy newborn infants. The power spectrum was investigated up to a frequency of 1 Hz. The lower frequency regions of the spectrum, extending to 0.15 Hz, were divided into two segments for analysis. The first, identified as VLF, ranged from 0.003 to 0.03 Hz. This region was analyzed separately to control for any artifactual contributions to the power spectrum from isolated or randomly occurring events. The remainder, 0.03–0.15 Hz, was analyzed to identify the LF region. The upper limit of the LF region is similar to the limit chosen by other investigators, typically to 0.15–0.2 Hz [17, 22, 38, 39, 41]. The HF region was selected as ranging from 0.15 to 1 Hz. Since HF variations occur at the respiratory frequency, this range encompasses normal newborn respiratory rates which can occur at up to 60 breaths/min.

Infants in this study were delivered by normal spontaneous vaginal delivery, or elective repeat cesarean section. Thus, any history of perinatal complications led to exclusion from the study. None of the mothers of infants in this study received narcotic or sedative analgesia. Although some mothers did deliver with lumbar epidural analgesia, this method of maternal pain relief has, by design, no effect on the neonate. Thus, maternal drug exposure was eliminated as a potential confounding variable.

Newborn infants are known to experience a catecholamine surge in the immediate perinatal period. This catecholamine surge, which is associated with birth, has been described as falling rapidly within the first few minutes of life, and then decreasing further after 3 h of life [42]. Furthermore, although the degree of the initial catecholamine surge may differ between infants delivered vaginally and by cesarean section, cardioavascular function and the distribution of cardiac output are comparable [43]. This surge would, therefore, not have any significant bearing on data collection at 8 h of life.

The infants state of arousal is an important confounder of heart rate and heart rate variability. Infant sleep states can be divided into 5 types: quiet sleep; active sleep; drowsiness; quiet wakefulness, and active wakefulness. During quiet sleep, infants are fully at rest, with regular respirations and generally absent body movements. During active sleep, on the other hand, there are irregular respirations and a variety of body movements. In the quiet awake state, infants are alert and able to focus their attention, but with minimal motor activity. When actively awake, there is frequent movement of the extremities and head as well as vocalization. Because heart rates can differ during times of sleep vs. waking, as well as during different sleep states [18, 23, 39], the recording segments analyzed were obtained from periods when the infants were noted, by direct observation, to be sleeping quietly or quiet and awake.

Spectral analysis of heart rate in the newborn revealed a strong peak spanning the VLF and LF regions of the power spectrum. A second small peak was found spanning the HF bands of the spectrum. This general pattern is consistent with the data described previously [13–17, 19, 22, 30–32, 38, 39, 41]. The standard deviations for mean power in each of the spectral bands were large, and the diversity in the values for spectral power persisted when sleeping and awake groups were analyzed independently. One must bear in mind that the mean values for mean spectral power encompass all patients, regardless of the mean heart rate during each recorded segment. These standard deviations thus reflect the diversity in both intrasubject (as a function of heart rate and other known physiologic mediators of heart rate variability) and perhaps intersubject values for spectral power. Future analyses, for example, could compare averaged values for different individuals, while controlling for mean heart rate.

Our data demonstrated that the peak within the HF band is typically broadened. Thus, the heart rate variations, which occur as a reflection of respiratory sinus arrhythmia, span a wide range of frequencies. Since parasympathetic activity is reflected in the HF peak, these findings suggest the presence of broad fluctuations in the autonomic cardiovascular tone of the newborn, reflected by a wider range of normal respiratory rates than in adults. These findings contrast with data from adults, in which both the respiratory rate and HF peak are well defined [22].

To assess the relationships between heart rate power spectra and autonomic control, we first compared the mean heart rate to the spectral power in each frequency band. Only data from sleeping infants was used for this analysis in order to avoid the potential confounding effects of sleep vs. wakefulness. We found that as mean heart rate increases LF power tends to increase, as would be expected if power in the low frequency band were influenced largely by sympathetic tone. HF power, however, decreased as mean heart rate increased, corroborating that HF power is a reflection of parasympathetic tone.

The data were also analyzed to assess the relative contributions of power in each spectral band to the total spectral power. To accomplish this analysis we calculated ratios of VLF/TP, LF/TP, and HF/TP. We found that, as mean heart rate increases, the contribution of LF power to TP increases, while the contribution of HF power decreases. These relationships are believed to reflect increasing sympathetic tone, and decreasing parasympathetic tone as heart rate increases. The relative contributions of LF power and HF power are also seen when comparing the LF:HF ratio as heart rate increases. Here, again, a positive correlation indicates increasing LF power, relative to HF power, as the mean heart rate increases.

Next, we examined how spectral power was related to heart rate variability (coefficient of variation). As heart rate variability increased we found that VLF, LF and HF power increased as well. The correlation between the coefficient of variation and total spectral power was strongest ($r = 0.80$). Thus, spectral power is indeed a reflection of overall heart rate variability. Because heart rate variability may be affected by a number of pathologic processes [20, 21, 36, 37], spectral analysis as an index of heart rate variability has the potential to serve as an objective tool in the study of infants.

When awake, sympathetic tone is expected to be higher than when asleep. Conversely, the relative contribution of parasympathetic tone should be decreased. To see if these autonomic findings are reflected in the heart rate variability power spectra, we compared data obtained during periods of sleep to those obtained during wakefulness. Mean heart rate was significantly greater in awake infants as compared to their sleeping counterparts. The contribution of HF power to total power (HF/TP) while awake was significantly less than during sleep. This finding corroborates that the relative contribution of the parasympathetic system to heart rate variability is decreased in awake infants. LF power tended to be greater when awake than when asleep, however, this difference did not achieve statistical significance. Relatively few data points (a total of 33) were available from awake infants. Infants slept during most of the data collection period, and motion artifact precluded data analysis from many 'awake' heart rate records. Data were passively collected, and infants were neither awakened nor kept awake to allow for additional data collection from awake infants. The small number of data points from awake infants may be responsible for the lack of statistical significance in some of our comparisons. This lack of significant trends, precludes the conclusion that both increased sympathetic and decreased parasympathetic activity in awake infants can be reflected in their heart rate power spectra. Further data collection is needed to elucidate the degree to which spectral power changes with sleep vs. wakefulness.

The overall findings of this study corroborate that spectral power parallels the expected autonomic effects on mean heart rate. Thus, spectral analysis of heart rate provides a useful, noninvasive method for the evaluation of autonomic cardiovascular activity in the newborn by providing indices of sympathetic and parasympathetic activity. Further research utilizing spectral heart rate analysis, will shed light on the subject of autonomic function in normal neonates, and will lay a foundation for the discovery of the relationship between autonomic cardiovascular activity and a wide variety of neonatal disorders with the potential of affecting cardiorespiratory control.

References

1 Matthews TG: The autonomic nervous system: A role in sudden infant death syndrome. Arch Dis Child 1992;67:654–656.

2 Sadeh D, Shannon DC, Abboud S, Saul JP, Akselrod S, Cohen RJ: Altered cardiac repolarization in some victims of sudden infant death syndrome. N Engl J Med 1987;317:1501–1505.

3 Haddad GG, Epstein MAF, Epstein RA, Mazza NM, Mellins RB, Krongrad E: The QT interval in aborted SIDS infants. Pediatr Res 1979; 13:136–138.

4 Southall DP, Richards JM, de Swiet M, Arrowsmith WA, Cree JE, Fleming PJ, Franklin AJ, L'E Orm R, Radford MJ, Wilson AJ, Shannon DC, Alexander JR, Brown NJ, Shinebourne EA: Identification of infants destined to die unexpectedly during infancy: Evaluation of predictive importance of prolonged apnoea and disorders of cardiac rhythm or conductance. Br Med J 1983;286:1092–1096.

5 Wynn VT, Southall DP: Normal relation between heart rate and cardiac repolarization in sudden infant death syndrome. Br Heart J 1992;67:84–88.

6 Perticone F, Ceravolo R, Maio R, Cosco C, Mattioli PL: Heart rate variability and sudden infant death syndrome. Pacing Clin Electrophysiol 1990;13:2096–2099.

7 Harper RM, Leake B, Hoppenbrouwers T, Sterman MB, McGinty DJ, Hodgman J: Polygraphic studies of normal infants and infants at risk for the sudden infant death syndrome: Heart rate and variability as a function of state. Pediatr Res 1978;12:778–785.
8 Leistner HL, Haddad GG, Epstein RA, Lai TL, Epstein MAF, Mellins RB: Heart rate variability during sleep in aborted sudden infant death syndrome. J Pediatr 1980;97:51–55.
9 Harper RM, Leake B, Hodgman JE, Hoppenbrouwers T: Developmental patterns of heart rate and heart rate variability during sleep and waking in normal infants and infants at risk for the sudden infant death syndrome. Sleep 1982; 5:28–38.
10 Schechtman VL, Harper RM, Kluge KA, Wilson AJ, Hoffman HJ, Southall DP: Cardiac and respiratory patterns in normal infants and victims of the sudden infant death syndrome. Sleep 1988;11:413–424.
11 Schechtman VL, Raetz SL, Harper RK, Garfinkel A, Wilson AJ, Southall DP, Harper RM: Dynamic analysis of cardiac R-R interval in normal infants and in infants who subsequently succumbed to the sudden infant death syndrome. Pediatr Res 1992;31:606–612.
12 Stevens V, Wilson AJ, Southall DP, Barber DC, Franks CI: Analysis of the heart rate and breathing patterns of infants destined to suffer sudden infant death syndrome: probability density function analysis. Pediatr Res 1985;19: 1327–1332.
13 Kluge KA, Harper RM, Schechtman VL, Wilson AJ, Hoffman HJ, Southall DP: Spectral analysis assessment of respiratory sinus arrhythmia in normal infants and infants who subsequently died of sudden infant death syndrome. Pediatr Res 1988;24:677–682.
14 Schechtman VL, Harper RM, Kluge KA, Wilson AJ, Hoffman HJ, Southall DP: Heart rate variation in normal infants and victims of the sudden infant death syndrome. Early Hum Dev 1989;19:167–181.
15 Gordon D, Cohen RJ, Kelly D, Akselrod S, Shannon DC: Sudden infant death syndrome: abnormalities in short term fluctuations in heart rate and respiratory activity. Pediatr Res 1984;18:921–926.
16 Schwartz JP, Stramba-Badiale M, Segantini A: Prolongation of the QT interval and the sudden infant death syndrome. N Engl J Med 1998; 338:1709–1714.
17 Chauchemez B, Peirano P, Samson-Dolfus D, Monod M, Coumel P: Decreased vagal tone in SIDS victims. IEEE Engineering in Medicine and Biology Society. 11th Annual International Conference 1989, pp 321–322.
18 Harper RM, Leake B: Polygraphic studies of normal infants and infants at risk for sudden infant death syndrome; heart rate variability as a function of sleep state. Pediatr Res 1978;12: 780–785.
19 Hirsch JA, Bishop B: Respiratory sinus arrhythmia in humans: How breathing pattern modulates heart rate. Am J Physiol 1981,241: H620–H629.
20 Appel ML, Berger RD, Saul JP, Smith JM, Cohen RJ: Beat to beat variability in cardiovascular variables: noise or music? J Am Coll Cardiol 1989;14:1139–1148.
21 Malik M, Camm AJ: Heart rate variability. Clin Cardiol 1990;13:570–576.
22 Dykes F, Ahmann PA, Baldzer K, Carrigan TA, Kitney R, Giddens DP: Breath amplitude modulation of heart rate variability in normal full term neonates. Pediatr Res 1986;20:301–308.
23 Finley JP, Nungent ST: Heart rate variability in infants, children, and young adults. J Auton Nerv Sys 1995;65:2048–2052.
24 Clairambault J: Heart rate variability analysis in normal sleeping full-term and preterm neonates. Early Hum Dev 1992;28:169–183.
25 Eiselt M: Heart rate variability in low risk prematurely born infants reaching the normal term: A comparison with full term newborns. Early Hum Dev 1993;32:183–195.
26 Guiddens DP, Kimey RI: Neonatal heart rate variability and its relation to respiration. J Theor Biol 1985;113:759–780.
27 Hathorn MKS: Respiratory modulation of heart rate in newborn infants. Early Hum Dev 1989;20:81–99.
28 Katona PL: Maturation of cardiac control in full-term and preterm infants during sleep. Early Hum Dev 1980;4:145–159.
29 Spassov L: Heart rate variability during sleep in small-for-gestational age newborns. Pediatr Res 1994;35:500–505.
30 Akselrod S, Gordon D, Ubel FA, Shannon DC, Barger AC, Cohen RJ: Power spectrum analysis of heart rate fluctuation: A quantitative probe of beat-to-beat cardiovascular control. Science 1981;213:220–222.
31 Pomeranz B, Macaulay RJB, Caudill MA, Kutz I, Adam D, Gordon D, Kilborn KM, Barger AC, Shannon DC, Cohen RJ, Benson H: Assessment of autonomic function in humans by heart rate spectral analysis. Am J Physiol 1985; 248:H151–H153.
32 Akselrod S, Gordon D, Madwed JB, Snidman NC, Shannon DC, Cohen RJ: Hemodynamic regulation: Investigated by spectral analysis. Am J Physiol 1985;249:H867–H875.
33 Kochiadakis GE, Kanoupakis EM, Igoumendis NE, Marketou ME, Solomou MC, Vardas PE: Spectral analysis of heart rate variability during tilt-table testing in patients with vasovagal syncope. Int J Cardiol 1998;64:185–194.
34 Pitzalis MV, Mastropasqua F, Massari F, Ciampolillo A, Passantino A, Ognissanti M, Mannarini A, Zanna D, Giorgino R, Rizzon P: Assessment of cardiac vagal activity in patients with hyperthyroidism. Int J Cardiol 1998;64: 145–151.
35 Pitzalis MV, Mastropasqua F, Massari F, Passantino A, Luzzi G, Ligurgo L, Colombo R, Biasco MG, Rizzon P: Different trends of changes in heart rate variability in patients with anterior and inferior myocardial infarction. Pacing Clin Electrophysiol 1998;21: 1230–1238.
36 Kamath MV, Fallen EL: Power spectral analysis of heart rate variability: A noninvasive signature of cardiac autonomic function. Crit Rev Biomed Eng 1993;21:245–311.
37 Gordon D, Herrera VL, McAlpine L, Cohen RJ, Akselrod S, Lang P, Norwood WI: Heart rate spectral analysis: A non-invasive probe of cardiovascular regulation in critically ill children with heart disease. Pediatr Cardiol 1988; 9:69–77.
38 Finley JP, Nungent ST, Hellenbrand W: Heart rate variability in children, spectral analysis of developmental changes between 5 and 25 years. Can J Physiol Pharmacol 1987;65:2048–2052.
39 Nugent ST, Finley JP: Heart rate variability in infants as a function of sleep state. IEEE Engineering in Medicine and Biology Society. 11th Annual Internationl Conference 1989, pp 319–320.
40 Baldzer K, Dykes FD, Jones SA, Brogan M, Carrigan TA, Giddens DP: Heart rate variability analysis in full-term infants: Spectral indices for study of neonatal cardiorespiratory control. Pediatr Res 1989;26:188–195.
41 Chatow U, Davidson S, Reichman BL, Akselrod S: Development and maturation of the autonomic nervous system in premature and full-term infants using spectral analysis of heart rate fluctuation. Pediatr Res 1995;37:294–301.
42 Agata Y, Hiraishi S, Misawa H, Han JH, Oguchi K, Horiguchi Y, Fujino N, Takeda N, Padbury JF: Hemodynamic adaptations at birth and neonates delivered vaginally and Cesarean section. Biol Neonate 1995;68:404–411.
43 Lagercrantz H, Marcus C: Sympathoadrenal mechanisms during development; in Polin R, Fox W (eds): Fetal and Neonatal Physiology. Philadelphia, Saunders, 1992, vol 1, pp 164–165.