# *Sleep State Analysis through HRV in Full-Term Neonates*


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***Abstract*—The supervision of the Autonomic Nervous System within the first year of life is essential for neonate health monitoring. For this purpose, evaluation of different HRV indexes has been performed both through time domain, frequency domain, and non-linear analysis to determine the relationship between Sympathetic and Parasympathetic systems during neonates' active and quiet sleep.**


## I. INTRODUCTION

During the first year of life, infants spend most of their time sleeping. They present two distinct sleep states: active sleep (AS) and quiet sleep (QS) [1]. In full-term neonates, AS is associated with rapid eye movements (REM), an increase of cardiorespiratory rates variability, and general body movements. On the other hand, QS lacks these characteristics.

Sleeping promotes the maturation of the Central Nervous System (CNS) and the Autonomic Nervous System (ANS), which are not yet modeled at the time of birth. Particularly, the ANS belongs to the peripheral nervous system and it is divided into sympathetic and parasympathetic systems, which act synergically to maintain homeostasis and dynamic equilibrium of the physiological functions. They develop at different stages: the sympathetic system early in the pregnancy, while the parasympathetic one emerges later in the perinatal period [2]. Since the complexity of the autonomic balance is related to the Heart Rate Variability (HRV) [3] [4], our purpose is to highlight the ANS role during both AS and QS. The approach used includes multiple indices belonging to time domain, frequency domain, and non-linear methods [4] [5].

## II. MATERIALS AND METHODS

The dataset applied for our study consists of five ECG signals recorded on full-term neonates. These signals were all acquired with a sampling frequency of $500Hz$ but presented mismatching time lengths. As the ECG signals were previously segmented in three minutes sections and labeled as AS or QS, the final dataset is composed of eleven ECG frames, six of which belong to the QS and five to the AS. Same-length frames grant the analysis greater reliability as seen in [6] and allow the comparison between ANS activity in AS and QS. The study is based on both time domain analysis and frequency domain analysis, respectively Section II-B and II-C.

### *A. Signal Processing*

Before the application of any filter, the spectrum of each signal has been analyzed. It was observed that the signal was already filtered at $0Hz$ and $60Hz$. Then a third-order Butterworth low-pass filter was applied at the frequency of $50Hz$. In this way, R-peaks information was maintained and better performance of the peak detection algorithm was achieved. Both MATLAB *findpeaks* algorithm and *Pan-Tompkin* algorithm have been tested. Eventually, the first one has been chosen as it assured better results on our dataset except for a single frame which was processed with Pan-Tompkin. To resolve the presence of ectopic beats, R-peaks were visually checked and manually corrected as suggested in literature [6]. Once this process ended, the final time series of RR intervals had been saved.

### *B. Time domain Analysis*

Time domain analysis was first based on the observation of tachogram, histogram, and scatterplot[1].

Then we focused on both linear and non-linear parameters reported in Table I, which are considered the most representative for HRV studies on short-term signals.

TABLE I: Statistical parameters for time domain analysis.

| Variable | Statistical Measures | |
|---|---|---|
| | Units | Decription |
| avgHRV | ms | Mean duration of the RR intervals. |
| RR-range | ms | Difference between longest and shortest RR interval. |
| RMSSD | ms | Square root of the mean of the sum of the squares of differences between adjacent RR interval. |
| SDNN | ms | Standard deviation of all RR intervals. |
| ApEn | - | Quantifier of regularity, defined as presence of repetitive patterns within a certain tolerance and at different lags. |
| SampEn | - | Estimator of regularity, which, compared to ApEn, reduces the bias given by the length of the signal. |

### *C. Frequency domain Analysis*

The HRV study proceeded with the computation of the Power Spectrum Density (PSD) starting from the previously

[1]Graphs were not reported because of space limitation, but they can be generated with the MATLAB code: https://tinyurl.com/HRV-in-neonates.

built tachogram for the time domain analysis. But first it was necessary to process the 3 min intervals of the RR series. Both the mean value and the trend of the signals were removed. Then the time series were resampled at a $6Hz$ frequency and submitted to spline interpolation. Before proceeding with the spectral analysis, the stationarity of the signals was checked using the *Augmented Dickey-Fuller* test and accepted for $p\ value < 0.05$. The PSD was analyzed both with a non-parametric and a parametric method. For the first one, *Welch method* was chosen. In order to maintain a desired resolution of $0.025Hz$, Hamming window of $M$ samples with a 50% overlap [7] was used and calculated as:

$$M = 1.3631 \cdot \frac{F_{resample}}{desired\, resolution} \tag{1}$$

where 1.3631 is the ENBW for the Hamming window. For *Yule-Walker method* we set $Order_{AR} = 16$ to obtain a precise estimation avoiding spectral smearing or peak splitting [8]. We calculated PSD absolute value in $ms^2/Hz$ for Low Frequencies (LF $0.05 - 0.2Hz$) and High Frequencies (HF $0.5 - 1.5Hz$), as well as the ratio $\frac{LF}{HF}$ [2].

## III. Results

Each parameter has been tested via Lilliefors test to check if it comes from a distribution in the normal family. Based on it, parameters will be presented as $mean\ (std)$ for normal distribution and $median\ (IQR)$ for non-normal distribution. All the values were computed for AS and QS separately, and supported by *Student's t-test* (*t-test*) for normal distribution or *Mann–Whitney U test* (*MW-test*) for non normal distributions[2].

### A. Time domain results

As it can be seen in Table II, AS highlights a wider RR range and a higher variability both within adjacent peaks (RMSSD) and all along the signal (SDNN), while average HRV (avgHRV) does not show exceptional differences. However, all these parameters show insufficient evidence (*t-test* p-Value $> 0.1$) to discriminate between AS and QS.

Whereas approximate Entropy (ApEn) performs a remarkable role in sleep state discrimination, with a p-Value $< 0.05$. Higher values of ApEn are associated with QS due to less repetitive patterns in respect to AS. Another significant index is the Sample Entropy (SampEn) which measures the complexity of a signal. SampEn shows, according to the results of ApEn, lower complexity during AS. Nevertheless, it has an inferior capability for AS/QS discrimination (p-Value $< 0.1$).

### B. Frequency domain results

As reported in Table III, the absolute value of AS spectral density is greater than the QS one for both LF and HF, while the LF contribution is always the highest. This proves a larger activity of the ANS during AS, in particular of the sympathetic system, which is associated with LF. Moreover the $\frac{LF}{HF}$ ratio is more significant for the AS state, evincing a greater balance capacity between sympathetic and parasympathetic systems. However, none of the frequency domain parameters shows a statistical ability to distinguish AS from QS.

[2]Due to space limitations, more detailed information about statistical tests are shown in the files generated by the MATLAB code.

TABLE II: Time domain results

| | QS | | AS | | |
|---|---|---|---|---|---|
| | Mean | STD | Mean | STD | t-test |
| avgHRV $[ms]$ | 513.55 | 38.72 | 512.31 | 50.96 | $\geq 0.1$ |
| RR range $[ms]$ | 263.00 | 142.13 | 296.20 | 193.01 | $\geq 0.1$ |
| RMSSD $[ms]$ | 28.29 | 24.60 | 31.60 | 26.12 | $\geq 0.1$ |
| SDNN $[ms]$ | 38.82 | 21.65 | 46.98 | 22.24 | $\geq 0.1$ |
| ApEn | 1.12 | 0.04 | 1.00 | 0.10 | $< 0.05$ |
| SampEn | 1.42 | 0.25 | 1.11 | 0.26 | $< 0.1$ |

TABLE III: Frequency domain results.

| | QS | | AS | | |
|---|---|---|---|---|---|
| | Median | IQR | Median | IQR | MW test |
| LF (W) $[ms^2/Hz]$ | 71641 | 74742 | 107606 | 222154 | $\geq 0.1$ |
| HF (W) $[ms^2/Hz]$ | 9345 | 20572 | 9042 | 97902 | $\geq 0.1$ |
| LF (YW) $[ms^2/Hz]$ | 62284 | 79264 | 122667 | 182075 | $\geq 0.1$ |
| HF (YW) $[ms^2/Hz]$ | 14066 | 20532 | 8271 | 105444 | $\geq 0.1$ |
| LF/HF (W) | 7.65 | 7.35 | 5.75 | 21.67 | $\geq 0.1$ |
| LF/HF (YW) | 6.18 | 4.41 | 3.81 | 12.42 | $\geq 0.1$ |

## IV. Conclusion

Newborns have extremely high sympathetic activity during AS. This condition represents a potential risk state, which needs to be kept controlled because the sympathetic nervous system triggers emergency responses only if necessary, while the parasympathetic nervous system conserves the biological system's energy and restores tissues for ordinary functions.

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