Nonlinear Analysis of Neonatal Breathing Dynamics – A Case Study

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BACKGROUND

The premature infant is prone to respiratory issues due to poor development of the regulatory system as well as mechanical issues with the lung itself. These problems often lead to apnea, the cessation of breathing. Until the respiratory system develops, the infant must be kept in critical care.

The release from the clinic is dependent upon reduction in the apneas presented by the infant. Methods for the analysis of breathing dynamics provide a quantitative measure of the breathing dynamics and are useful in evaluating the path of respiratory development. Release to home is dependent upon reductions in the number of apneas presented by the infant. While in the clinic the infant's lung volume can be noninvasively monitored via optical or electrical impedance methods [1].

Techniques used to analyze neonatal breathing patterns offer valuable quantitative insight into how the infant's respiratory system develops over time. By examining the structure and variability of the breathing signal, clinicians can assess whether the infant's respiratory control is maturing properly.

Most apnea detection methods essentially identify the loss of tidal volume as detected by chest impedance or actual mouth airflow. This approach reveals the past episodes of apnea. It is preferable to have detection methods that have some predictability of apnea or at least the prevalence of apnea in a particular infant [2]. Additional monitoring of abdominal motion may increase the accuracy of apnea detection [3].

Alternatively, others have chosen to develop algorithms to process breathing time series and attempt to detect apneas [4]. But since the respiratory regulation system processes nonlinear elements, it is suggested that nonlinear data analysis methods may provide better prediction of apnea events than by using simple lung volume time series. Nonlinear analyses have been applied to ECG data in this respect and likewise to asthmatic breathing [5].

In this research, sample data is obtained from normal infant breathing and an infant that presents apneas. The measurements that will be applied are cross-correlation, delay mapping, Fourier analysis, and the fractal dimensions described by Drzewiecki [7].

The results of each of these approaches will be compared for the ability to detect the normal versus apnea patient. Common findings among all measures will be discussed. Lastly, we discuss any physiological significance of these results.

The respiratory patterns of premature infants exhibit considerable variability that ranges from regular respiration to periodic breathing with cyclic distribution of short apneic events, and to prolonged apneas. Using a noninvasive impedance pneumogram, tidal volume was noninvasively monitored in a healthy preterm infant in the intensive care nursery (ICN). The volume time series was then analyzed using different nonlinear methods. The response of each nonlinear method was studied during the observed respiratory patterns, and during normal respiration. The resulting analyses are compared for their relative ability to detect apnea events.

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METHODS

A. Experimental Data

Breathing data was obtained from a male infant in the NICU at Robert Wood Johnson Hospital, New Brunswick, NJ. In the intensive care unit, a male infant, gestational age of 35 weeks, post-conceptional age of 37 weeks, and a body weight of 1990 grams was monitored noninvasively with an electrical impedance pneumogram [2]. (Hewlett Packard, Model 78801), and recorded on FM video tape (Vetter, model 4000A) for processing later. Subject recording sessions were for one hour. The FM recorder data was digitized (Data translation, analog to digital converter) and stored on digital drive disc via a personal computer (PC) system. Five-minute episodes were digitized at a sampling rate of 4 Hz that illustrate either normal or apneic breathing in the single infant. The above procedures were reviewed by the local committee for the protection of Human Subjects in Research and informed consent was obtained from the infant's parent. To correct any electrode drift during the recording, the final records were high pass filtered at 0.6 Hz. Additionally, electrode offset level was corrected by calculating the mean of the entire data series. Then, the mean was subtracted from the data series. Both datasets, normal and apnea breathing, were preprocessed identically using MATLAB.

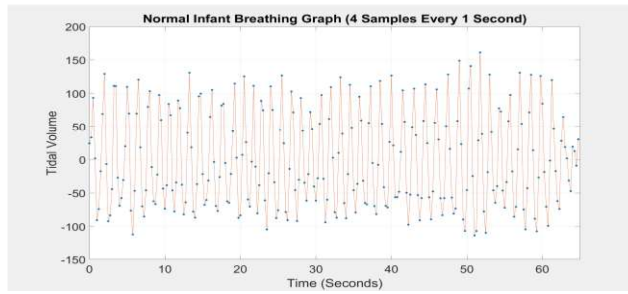

Figure 1. Time segment showing normal respiration for the neonate subject, V(t), obtained by impedance pneumogram

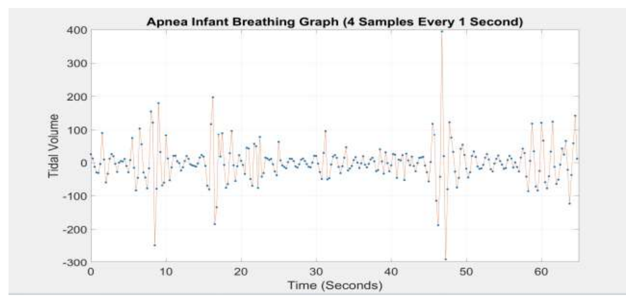

Figure 2. Time segment illustrating periods of apnea breathing. Apnea may be observed as time segments where tidal volume is diminished for 10 to 20 seconds each time

B. Data Analysis

The breathing volume time series was analyzed via autocorrelation, delay mapping, Fourier, and fractal analysis, each during episodes of normal and apnea breathing.

1. Autocorrelation

To initially screen the data for repeated patterns, the autocorrelation function of MATLAB was applied to the data series. This was performed on normal and apnea breathing.

2. Delay mapping

To further examine repeated time patterns for dynamic structure, delay mapping was performed to provide the Poincare plots. Delayed time series was computed in MATLAB by applying the time shift function in Eq. (1).

$$V(r)_{delay} = V(t + r) \quad (1)$$

Then, the impedance pneumograph volumes V(t) are plotted against the shifted volumes V(t+r) where r is the amount of time shift. The value of r was chosen initially using the times of maximum correlation. After viewing the delay plot for this starting value, r was further adjusted to examine the time series for dynamic relationship and structure. Shift times that resulted in a random scatter of points were assumed to possess no dynamic relationship and not examined further. For most plots an ellipse structure is visually evident. For the ellipse structure, an ellipse was statistically fit to the delay plot. This was accomplished by using the MATLAB co-variance function. The eigen vectors were then determined to find the major and minor axis of the ellipse along with its angle of orientation. The calculated ellipse was plotted on each delay plot.

3. Fourier Analysis

Each time series was further analyzed using the MATLAB Fast Fourier Transform, FFT. Results were provided as magnitude – frequency plots.

4. Fractal Dimension

In consideration that the breathing patterns might be self-similar, the fractal dimension of the time series was calculated. The D-value was obtained by finding the log magnitude – log frequency spectrum slope [7].

RESULTS

1. Subject breathing time series.

Figure 1 provides the subject breathing prior to any analysis. This recording illustrates a segment of normal respiration.

Next, a segment of data is shown in figure 2 that illustrates a period of apnea breathing for the same subject.

2. Correlation analysis

The autocorrelation of the normal and apnea breathing time series was computed via MATLAB. Figure 3 and figure 4 provide the autocorrelation for the normal and apnea respectively.

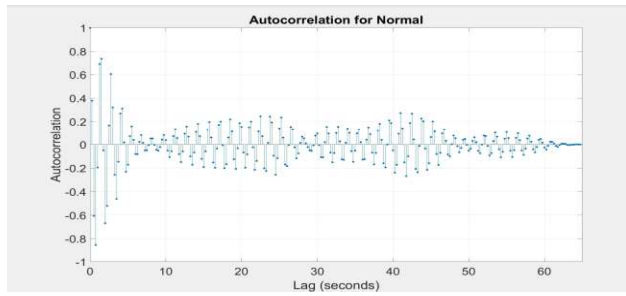

Figure 3. Autocorrelation analysis for normal breathing

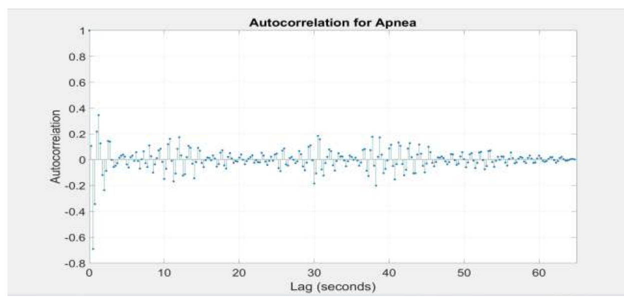

Figure 4. Autocorrelation analysis for apnea breathing

3. Delay mapping

Delay maps were created by applying Eq. (1). The delay time was chosen such that the structure could be observed in the plot. If the plot yielded random points, it was concluded that there is no relationship present.

An initial delay of r = 16 seconds was chosen. For normal breathing this resulted in map of figure 5.

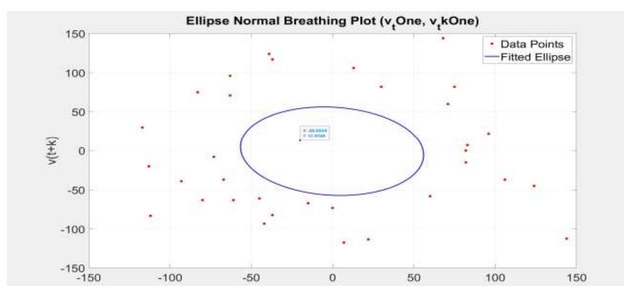

Figure 5. Delay map for normal breathing. Ellipse was placed to indicate points of normal breathing as outside of the ellipse

In the regular breathing map, we find that normal breathing cycles are points that remain outside of the ellipse structure. These points are mostly those of large volumes and large delayed volumes. In comparison, the apnea breathing map is shown in figure 6.

In this case, it can be seen that any volume yields a future volume as much reduced. The ellipse helps to indicate the current breathing volume that yields a much-reduced volume, that is the tendency towards smaller breathing cycles. An additional time delay of r = 4 seconds was chosen. This is shown in figure 7.

Referring to figure 7, it can be seen that the breathing points are scattered throughout the plane of the mapping. In this case, it is more difficult to place an ellipse of normal breathing due to the random pattern of points.

4. Fourier Analysis

The FFT of the normal and apnea data series was computed and displayed as a power versus frequency. The result for normal breathing is shown in figure 8.

The FFT was further applied to the apnea data series that resulted in the power spectrum of figure 9. It is apparent that the secondary peak in power of normal breathing disappears in the apnea data.

5. Fractal Dimension

The FFT power spectrum (Figures 8 and 9) were plotted on a log-log scale for which the slope may be used to find the fractal dimension of data [7].

The dimension values were (between 1 and 2) for normal infant breathing, however, apnea segments still returned values slightly above 2 (ranging from 2 to 2.5).

Discussion

The correlation study revealed large correlations at short time shifts of less than 4 seconds and at larger 16 second shifts.

The short periods correspond breath to breath normal breathing cycles. While the longer intervals correspond with longer processes associated with the regulation of breathing means of metabolic mechanisms.

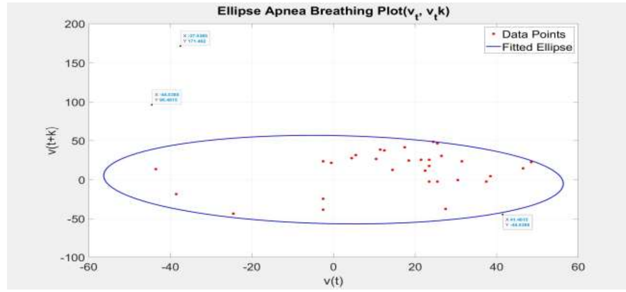

Figure 6. Delay map of an apnea breathing event. The ellipse denotes points of the apnea as inside the ellipse

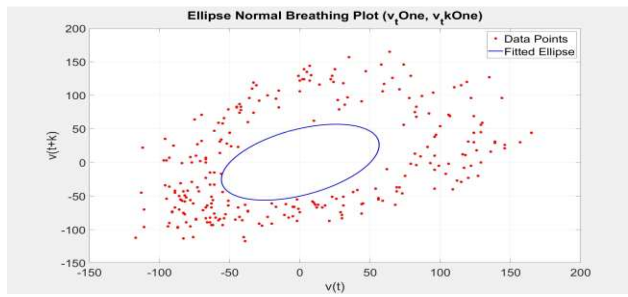

Figure 7. Delay map of normal breathing for 4 second delay

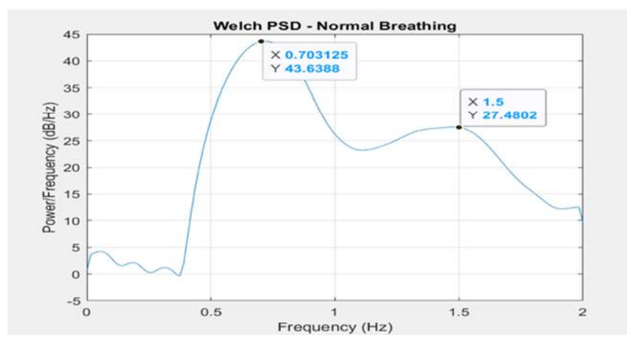

Figure 8. Power spectrum for normal breathing

In the case of an apnea interval, it was found that large correlations disappear. Physiologically this means that the regulatory reflex systems have become inoperative or weak. Of particular concern is that the breath-to-breath correlations have been reduced to less than half of normal breathing. Longer time shift correlations of 10 to 20 seconds are typically low and remain low during an apnea event. Referring to the delay map plots; the results are consistent with the correlation analysis. It is shown that the data points are randomly scattered over the plane for long shifts due to the fact that correlations are very low. In the case of normal breathing, the volumes are mostly large and circulate clockwise around the drawn ellipse. The motion of the points is not shown here and only a fixed time is presented.

Turning to the apnea delay plot, it is evident that most volumes tend towards reduced volume. This is also evident from the flattening of the ellipse. That is all current breath (points move toward diminished tidal volumes). In this case, it can be noted that the breathing points line up within a flattened ellipse as opposed to a random distribution of points. We also see that the normal breathing larger outside elliptical motion of points has mostly disappeared. Generally, it was observed that apnea breathing resulted in more points that lie within the drawn ellipse. Moreover, following the points outside of the ellipse, they begin to move inward provided an early indication of a possible apnea event. This suggests that a method of following the trajectory of points may be developed that indicates a possible apnea.

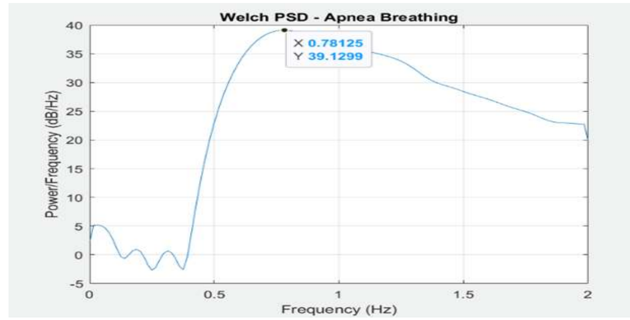

Figure 9. Power spectrum of apnea breathing

The third analysis applied to the breathing data was Fourier analysis. The power spectrum for normal breathing showed two distinct peaks in magnitude, one at 0.7 Hz and a second at 1.5 Hz. During apnea breathing, the 1.5 Hz peak clearly becomes diminished. Instead, there becomes a broad increase in high frequencies. This is consistent with the work of [8] who finds that the high frequency breathing is evident prior to an apnea. It is also consistent with a nonlinear system where frequency doubling is a characteristic. Unfortunately, in the breathing system the period doubling appears to be a path that leads to a stable state that is breathing cessation.

The fractal analysis of the breathing data was accomplished by deriving from the Fourier spectrum as a log-log function. Fractal values increased for the apnea data. This indicates an increase in the self-similarity of the data has occurred. Other studies have also revealed that higher values of fractal dimension coincide with diseased states [6].

Overall, it is encouraging that the nonlinear analysis of the individual patient's data was consistent from method to method. It is then encouraging to pursue these kinds of nonlinear studies in additional patients so to further confirm these results.

CONCLUSION

A single premature infant case breathing time series was studied via different nonlinear analysis methods. Although each method provided different nonlinear information, the results were examined relative to the specific information that the various methods provided.

Delay plot studies were encouraging in that they could potentially offer a more reliable way of detecting and predicting apnea as compared with tidal volume alone. Moreover, the delay mappings provide some insight into the possible modeling of the early infant breathing regulatory system. For example, the delay plots revealed two specific breathing states that are easily observed: the regular breathing and loss of tidal volume. Future use of this method may be used to develop breathing models that represent the early infant breathing patterns.

Lastly, the Fourier analysis results were found to provide a clear signal for the undeveloped respiratory system indicated as a loss of energy within a specific frequency band. The Fourier spectrum as well as the delay maps provide the clearest and most reliable indication of breathing abnormality of this premature infant study. Further application of these approaches should provide a useful path to explore.

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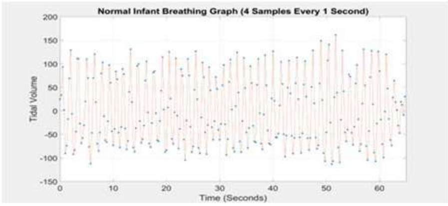
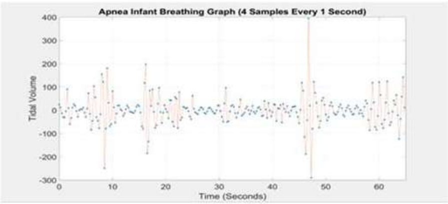
Abstract

- Premature infants experience apnea due to underdeveloped respiratory control.
- This study utilizes nonlinear time-series analysis to differentiate between normal and apnea breathing.
- Impedance pneumogram signals were analyzed using autocorrelation, delay mapping with Poincare plots, Fourier analysis, and fractal dimension methods.
- Each non-linear analysis technique revealed patterns correlating to breathing irregularities.
- Goal: assess whether nonlinear analysis can predict or better characterize apnea events.

Overview of the Analysis Methods

- Noninvasive impedance pneumogram data collected from infant in NICU
- Recorded data digitized using MATLAB
- Preprocessing for normal and apnea breathing
    - High Pass Filter to remove drift (0.6 Hz)
    - Mean Subtraction to remove offset



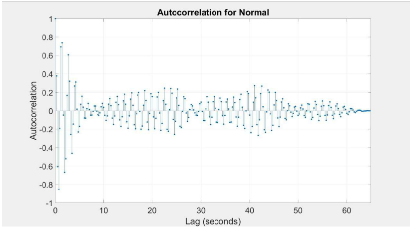


Breathing Signal Data Analysis

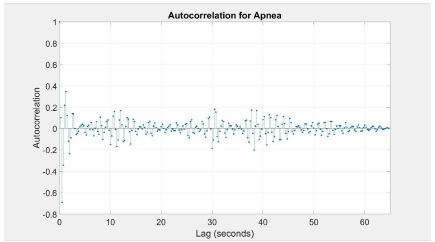
- Autocorrelation: To identify repeating breathing patterns
- Delay Mapping (Poincare Plot): Visualize time delay
- Fourier Transform: Evaluate frequency domain changes
- Fractal Dimension: Quantify similarity between breathing patterns

Autocorrelation

- Autocorrelation collected on the raw data using MATLAB's autocorr function
- Normal breathing shows strong correlations at short lag times and secondary peaks around 16 seconds.

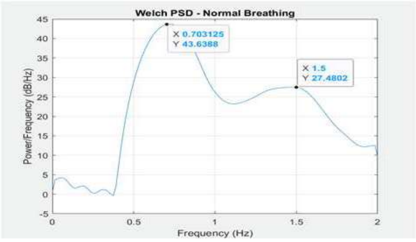


- Apnea breathing experiences a flatter autocorrelation which indicates diminished breathing cycle.

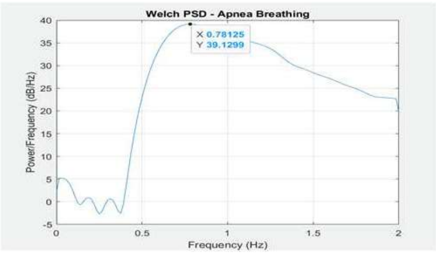


Fourier Transform

- Power spectra of raw data calculated with FFT to show two main peaks for normal breathing (0.7 Hz and 1.5Hz)

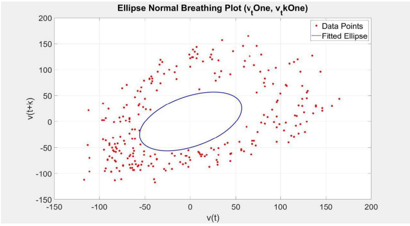


- Apnea breathing plot where secondary peak at 1.5 Hz disappears and energy shifts to higher frequencies.

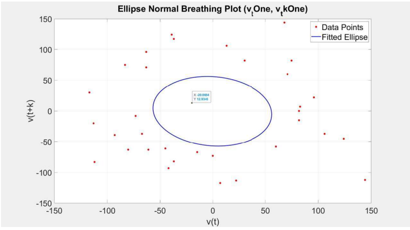


Delay Mapping

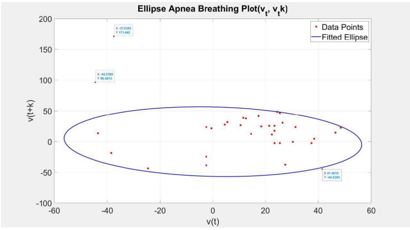
- Delay plots visualize V(t) versus V(t + r), where r is a time shift.
- Normal breathing forms distinct elliptical trajectories to represent stable rhythmic motion.
- Apnea produces ellipses that indicate reduced variability.
- These transitions can be used to potentially spot an approaching apnea
- Delay map for normal breathing. Ellipse was placed to indicate points of normal breathing as outside of the ellipse.



- Delay map of normal breathing for 4 second delay.



- Delay map of an apnea breathing event. The ellipse denotes points of the apnea as inside the ellipse.



Fractal Dimension

- Derived from log-log slope of the power spectrum.
- Normal breathing: D ≈ 1 - 2
- Apnea breathing: D ≈ 2 - 2.5
- Increased fractal dimension correlates to unstable breathing patterns

Discussion

- Normal breathing shows strong short-term correlations and distinct elliptical delay plots
- During apnea, correlations drop, and ellipses flatten.
- FFT reveals disappearance of 1.5 Hz peak in apnea breathing compared to normal breathing.
- Fractal dimension rises for apnea breathing which indicates greater instability and complexity
- Consistent patterns suggest these nonlinear methods can characterize early signs of apnea.

Conclusions

- Nonlinear analysis separates normal breathing from apnea breathing
- Delay mapping has the potential to enable early apnea prediction
- Fourier and Fractal metrics highlight reduced energy and increased complexity.
- Limitation: Analysis was limited to one infant dataset (normal and apnea).
- Future work: Apply these methods to a larger infant sample group to validate predictive apnea indicators.

Summary

- Nonlinear testing analysis can effectively characterize neonatal breathing dynamics.
- Delay mapping and FFT show the clearest separation between normal and apnea states.
- These methods can potentially support noninvasive monitoring and help predict apnea events
- Further testing can be done by including more breathing data from normal and apnea breathing infants.

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