Oxygen Saturation Resolution Influences Regularity Measurements

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Abstract—The measurement of regularity in the oxygen saturation (SpO2) signal has been suggested for use in identifying subjects with sleep disordered breathing (SDB). Previous work has shown that children with SDB have lower SpO2 regularity than subjects without SDB (NonSDB). Regularity was measured using non-linear methods like approximate entropy (ApEn), sample entropy (SamEn) and Lempel-Ziv (LZ) complexity. Different manufacturer’s pulse oximeters provide SpO2 at various resolutions and the effect of this resolution difference on SpO2 regularity, has not been studied. To investigate this effect, we used the SpO2 signal of children with and without SDB, recorded from the Phone Oximeter (0.1% resolution) and the same SpO2 signal rounded to the nearest integer (artificial 1% resolution). To further validate the effect of rounding, we also used the SpO2 signal (1% resolution) recorded simultaneously from polysomnography (PSG), as a control signal. We estimated SpO2 regularity by computing the ApEn, SamEn and LZ complexity, using a 5-min sliding window and showed that different resolutions provided significantly different results. The regularity calculated using 0.1% SpO2 resolution provided no significant differences between SDB and NonSDB. However, the artificial 1% resolution SpO2 provided significant differences between SDB and NonSDB, showing a more random SpO2 pattern (lower SpO2 regularity) in SDB children, as suggested in the past. Similar results were obtained with the SpO2 recorded from PSG (1% resolution), which further validated that this SpO2 regularity change was due to the rounding effect. Therefore, the SpO2 resolution has a great influence in regularity measurements like ApEn, SamEn and LZ complexity that should be considered when studying the SpO2 pattern in children with SDB.

I. INTRODUCTION

Obstructive sleep apnea (OSA) is a sleep breathing disordered (SBD) characterized by prolonged partial or complete upper airway obstruction that disrupts normal ventilation during sleep. It is a common condition in childhood and can result in severe complications if left untreated. The high prevalence of OSA (about 2% among children [1], [2] and about 2.5%-6% among adolescents [3]) poses serious threat to the healthy growth and development of many children. Lack of oxygen during sleep can lead to sleep disruption, daytime sleepiness, growth and heart failure, behavioral problems and developmental delay [4], [5].

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Pulse oximetry is a simple non-invasive method to measure blood oxygen saturation (SpO2). SpO2 fluctuations caused by episodes of apnea modulate the SpO2 signal (see Figure 1.a). Thus, the regularity of SpO2 has been proposed as a potential diagnostic test to identify OSA in patients with signs of sleep disordered breathing (SDB) [6]. Approximate entropy (ApEn), Sample entropy (SamEn) and Lempel-Ziv (LZ) complexity are well-known non-linear methods to measure regularity or complexity. ApEn and SamEn measure the repeatability or predictability within the data [7], [8] and LZ evaluates the randomness of a sequence by calculating the number of distinct subsequences and the rate of their occurrence [9]. Patients with OSA showed higher approximate entropy (ApEn) and Lempel-Ziv (LZ) complexity than subjects without OSA [6], [10]. These results suggested that nonlinear analysis of nocturnal SpO2 could yield useful information to improve in OSA diagnosis using pulse oximetry as a standalone OSA screening tool [11]. Different pulse oximeter manufactures provide different SpO2 resolution, typically ranging from 0.1% to 1%. However, it remains unclear how this difference in SpO2 resolution might influence regularity measurements.

Our aim was to include information about SpO2 regularity in a predictive score to improve the performance of the Phone Oximeter as a SDB screening tool in children [12], [13]. The Phone Oximeter is a mobile device that integrates a commercially available and Federal Drug Administration (FDA) approved pulse oximeter with a mobile phone [14]. It provides SpO2 up to 0.1% resolution and the blood volume changes in tissue (photoplethysmography (PPG)). With the hypothesis that SpO2 resolution affects regularity measurements, in this study, we have evaluated the influence of oximetry resolution on the following non-linear methods: ApEn, SamEn and LZ complexity. We have compared the SpO2 regularity obtained with the same device with different SpO2 resolutions (0.1% and 1%), and further validated these results with a control signal (1% resolution SpO2 simultaneously recorded from a different device).

II. MATERIAL AND METHODS

A. Dataset

Following ethics approval and informed consent, 146 children from 3 months to 17 years of age exhibiting signs or symptoms of SDB were studied. The data acquisition was carried out in the Sleep Unit (a dedicated facility attached to the Medical Day Unit) at British Columbia Children’s Hospital where formal polysomnography (PSG) studies are
performed. The measurement of electrocardiogram (ECG), electroencephalogram (EEG), SpO2 (1% resolution, sample frequency of 1 Hz), chest movement, nasal airflow and video recording was acquired using the Embla Sandman S4500. A sleep technician scored the PSG recordings and provided the apnea hypopnea index (AHI), which is the average number of apnea/hypopnea events per hour (Table 1). An AHI greater or equal to 5 events per hour was considered as a positive SDB diagnosis.

A second pulse oximeter sensor was applied to the finger adjacent to the one used during standard PSG. This sensor was attached to the Phone Oximeter and recorded SpO2 simultaneously at a sample frequency of 1 Hz with a resolution of 0.1%.

### TABLE I

**Demographic and Clinical Information of Children with and without SDB (SDB and NonSDB)**

<table>
<thead>
<tr>
<th></th>
<th>SDB</th>
<th>NonSDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children (Male/Female)</td>
<td>56 (18/38)</td>
<td>90 (41/49)</td>
</tr>
<tr>
<td>Age</td>
<td>8.8 ± 4.6</td>
<td>9.3 ± 4</td>
</tr>
<tr>
<td>BMI</td>
<td>23.2 ± 8.3</td>
<td>18.3 ± 4.9</td>
</tr>
<tr>
<td>AHI</td>
<td>19.7 ± 19.5</td>
<td>1.4 ± 1.1</td>
</tr>
</tbody>
</table>

### B. Experimental setup

Different pulse oximeters have many varying characteristics apart from resolution such as sampling frequency, averaging, internal processing, electro-optical sensor, etc. Therefore, to avoid confounding factors when comparing the regularity measurements obtained with different SpO2 resolutions (0.1% and 1%), we rounded the Phone Oximeter’s SpO2 (0.1% resolution) to the nearest integer providing an artificial 1% resolution SpO2. To further validate our analysis, we used the SpO2 recorded from PSG (1% resolution), as a control signal. The same regularity analysis was applied to these three SpO2 signals. The mean overnight ApEn, SamEn and LZ applied to SpO2 was analyzed for children with and without SDB. The Lilliefors test was applied to evaluate the normality of the data and Mann-Whitney U test to evaluate the statistical differences between these 2 groups, considering the data distribution of the regularity measurements.

### C. Regularity measurements

After data collection, the regularity analysis of the SpO2 included the following steps: preprocessing, segmenting overnight oximetry in 5-min (300 samples) signal segments with 50% overlap and calculating the regularity (ApEn, SamEn and LZ) for each segment. The regularity measurements are described below:

**Approximate entropy (ApEn) and Sample entropy (SamEn):** Provide quantitative information about the regularity of the signals, where larger values correspond to higher irregularity or randomness of the signal. ApEn is defined as "the likelihood that runs of patterns that are close remain close on next incremental comparisons" [7]. It has been defined as the negative average natural logarithm of the conditional probability that two sequences that are similar for \(m\) points remain similar, that is, within a tolerance \(r\), at the next point. In order to avoid the occurrence of \(\ln(0)\) in the calculations, the ApEn algorithm counts each sequence as matching itself. ApEn is therefore heavily dependent on the record length and lacks relative consistency. SampEn has been defined as the negative natural logarithm of the conditional probability that two sequences similar for \(m\) points remain similar at the next point. It differs from ApEn in that it eliminates the counting of self-matches and that it takes the logarithm of the sum of conditional probabilities, rather than the logarithm of each individual conditional property [7], [8]. Both ApEn and SampEn were studied for \(m = 1\) and \(m = 2\) and tolerance values of 0.10, 0.15, 0.20 times the standard deviation (recommended values by Pincus [7]) of the SpO2 signal.
In fact, children with SDB showed more regular or periodic SpO\textsubscript{2} changes due to the desaturations provoked by sleep.

**III. RESULTS**

From Figures 2.a and 2.b, it can be observed that the ApEn and SampEn of 0.1% \textit{SpO\textsubscript{2}} resolution provided no significant differences between SDB and NonSDB. However, LZ complexity (Figure 2.c) showed significant differences between these two groups where the \textit{SpO\textsubscript{2}} pattern of SDB children appeared to be more regular. This result can be also observed in Figure 1.a and Figure 1.b, where the 0.1% \textit{SpO\textsubscript{2}} resolution seemed to be more regular in children with SDB than in NonSDB.

Looking at the ApEn, SampEn and LZ values obtained with the rounded \textit{SpO\textsubscript{2}}, artificial 1% resolution (Figures 2.d, 2.e and 2.f), we found significant differences showing that SDB children presented a more irregular or random \textit{SpO\textsubscript{2}} than the NonSDB children. These results coincide with the analysis applied to the 1% resolution \textit{SpO\textsubscript{2}} extracted from PSG study, and confirm that the differences found in \textit{SpO\textsubscript{2}} regularity are due to the rounding effect. Figures 2.g, 2.h and 2.i, illustrate that the 1% resolution \textit{SpO\textsubscript{2}} from PSG provided the same significant results as the rounded \textit{SpO\textsubscript{2}} (artificial 1\% resolution). This rounding effect was also observed with different \(m\) and \(r\) values in ApEn and SampEn (see Figure 3).

**IV. DISCUSSION**

In this study, we evaluated the influence of \textit{SpO\textsubscript{2}} resolution on non-linear measurements like ApEn, SampEn and LZ complexity. We showed that in terms of regularity measurements, different results were obtained with the devices providing 0.1% \textit{SpO\textsubscript{2}} resolution as compared to 1% \textit{SpO\textsubscript{2}} resolution. We also showed that this difference was due to the rounding effect caused by the \textit{SpO\textsubscript{2}} resolution. Considering these results we cannot assume that the \textit{SpO\textsubscript{2}} pattern is more random in children with SDB than in NonSDB children, because this difference is no longer significant with a higher \textit{SpO\textsubscript{2}} resolution. The lower resolution provided by the PSG’s pulse oximeter (Figure 1) might bias the \textit{SpO\textsubscript{2}} regularity values. The \textit{SpO\textsubscript{2}} randomness shown for NonDSB children using 0.1% \textit{SpO\textsubscript{2}} resolution (Figure 1.b) is not demonstrated using the PSG pulse oximeter because of the lower resolution (Figure 1.f) due to the rounding effect (Figure 1.d). This resolution difference might be the reason why children with SDB showed higher randomness than NonSDB children with the PSG’s pulse oximeter in a number of studies [6], [10]. In fact, children with SDB showed more regular or periodic \textit{SpO\textsubscript{2}} changes due to the desaturations provoked by sleep.
apnea, as illustrated in Figure 1.a. Therefore, to study the regularity or randomness of the SpO₂ pattern we should consider the device’s resolution.

Recent studies based on the analysis of 0.1% resolution SpO₂ have shown more accurate characterization and successful results identifying subjects with SDB [12], [15]. The results obtained with the features extrated from time-frequency characterization of the 0.1% resolution SpO₂ signal, coincided with that of prior works. DelCampo et al. [6], [10] illustrated that the analysis of SpO₂ regularity could yield useful information to improve SBD diagnosis. This could enhance the Phone Oximeter’s performance as a SDB screening tool. However, considering the SpO₂ resolution influence on the regularity measurements studied, it remains unclear how SDB affects the SpO₂ regularity.

V. CONCLUSION

The aim of this study was to show the influence of the pulse oximeter’s oximetry resolution when studying SpO₂ regularity in children with SDB. Higher and lower resolution devices provided different results, due to the rounding effect. Thus, we should carefully consider the device’s resolution when dealing with non-linear measurements to characterize the SpO₂ pattern in children with SDB.

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REFERENCES


