Oxygen Saturation Resolution Influences Regularity Measurements

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***Abstract*— The measurement of regularity in the oxygen saturation (SpO_2) signal has been suggested for use in identifying subjects with sleep disordered breathing (SDB). Previous work has shown that children with SDB have lower SpO_2 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 SpO_2 at various resolutions and the effect of this resolution difference on SpO_2 regularity, has not been studied. To investigate this effect, we used the SpO_2 signal of children with and without SDB, recorded from the Phone Oximeter (0.1% resolution) and the same SpO_2 signal rounded to the nearest integer (artificial 1% resolution). To further validate the effect of rounding, we also used the SpO_2 signal (1% resolution) recorded simultaneously from polysomnography (PSG), as a control signal. We estimated SpO_2 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% SpO_2 resolution provided no significant differences between SDB and NonSDB. However, the artificial 1% resolution SpO_2 provided significant differences between SDB and NonSDB, showing a more random SpO_2 pattern (lower SpO_2 regularity) in SDB children, as suggested in the past. Similar results were obtained with the SpO_2 recorded from PSG (1% resolution), which further validated that this SpO_2 regularity change was due to the rounding effect. Therefore, the SpO_2 resolution has a great influence in regularity measurements like ApEn, SamEn and LZ complexity that should be considered when studying the SpO_2 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 (SpO_2). SpO_2 fluctuations caused by episodes of apnea modulate the SpO_2 signal (see Figure 1.a). Thus, the regularity of SpO_2 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 SpO_2 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 SpO_2 resolution, typically ranging from 0.1% to 1%. However, it remains unclear how this difference in SpO_2 resolution might influence regularity measurements.

Our aim was to include information about SpO_2 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 SpO_2 up to 0.1% resolution and the blood volume changes in tissue (photoplethysmography (PPG)).With the hypothesis that SpO_2 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 SpO_2 regularity obtained with the same device with different SpO_2 resolutions (0.1% and 1%), and further validated these results with a control signal (1% resolution SpO_2 simultaneoulsy 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

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performed. The measurement of electrocardiogram (ECG), electroencephalogram (EEG), SpO_2 (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 SpO_2 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)

	SDB	*NonSDB*
Children (Male/Female)	56 (18/38)	90 (41/49)
Age	8.8 ± 4.6	9.3 ± 4
BMI	23.2 ± 8.3	18.3 ± 4.9
AHI	19.7 ± 19.5	1.4 ± 1.1

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 SpO_2 resolutions (0.1% and 1%), we rounded the Phone Oximeter's SpO_2 (0.1% resolution) to the nearest integer providing an artificial 1% resolution SpO_2. To further validate our analysis, we used the SpO_2 recorded from PSG (1% resolution), as a control signal. The same regularity analysis was applied to these three SpO_2 signals. The mean overnight ApEn, SamEn and LZ applied to SpO_2 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 SpO_2 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 SpO_2 signal.

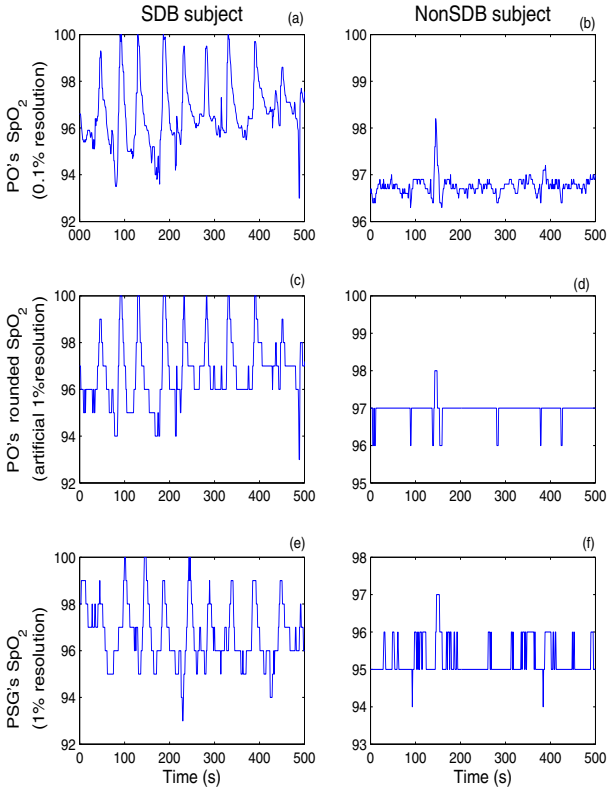

Fig. 1. Original SpO_2 signal segment (0.1% resolution) recorded using the Phone Oximeter (PO) for (a) a child with SDB and (b) a child without SDB, the same SpO_2 signal rounded to nearest integer (artificial 1% resolution) for the same (c) SDB and (d) NonSBD children, and the corresponding SpO_2 signal recorded simultaneously with the PSG's pulse oximeter for the same SDB (e) and NonSDB (f) children.

Lempel-Ziv complexity (LZ): Provides information about the complexity of the signal, where larger values correspond to higher complexity or randomness [9]. To calculate LZ, the signal, SpO_2 in this case, is transformed into a binary sequence ("0" and "1") using the median SpO_2 value as a threshold. Then the number of distinct patterns contained in the extracted sequence is calculated by increasing the complexity counter ($c(n)$) whenever a new subsequence of consecutive characters is found. Once the number of different patterns has been computed, the LZ

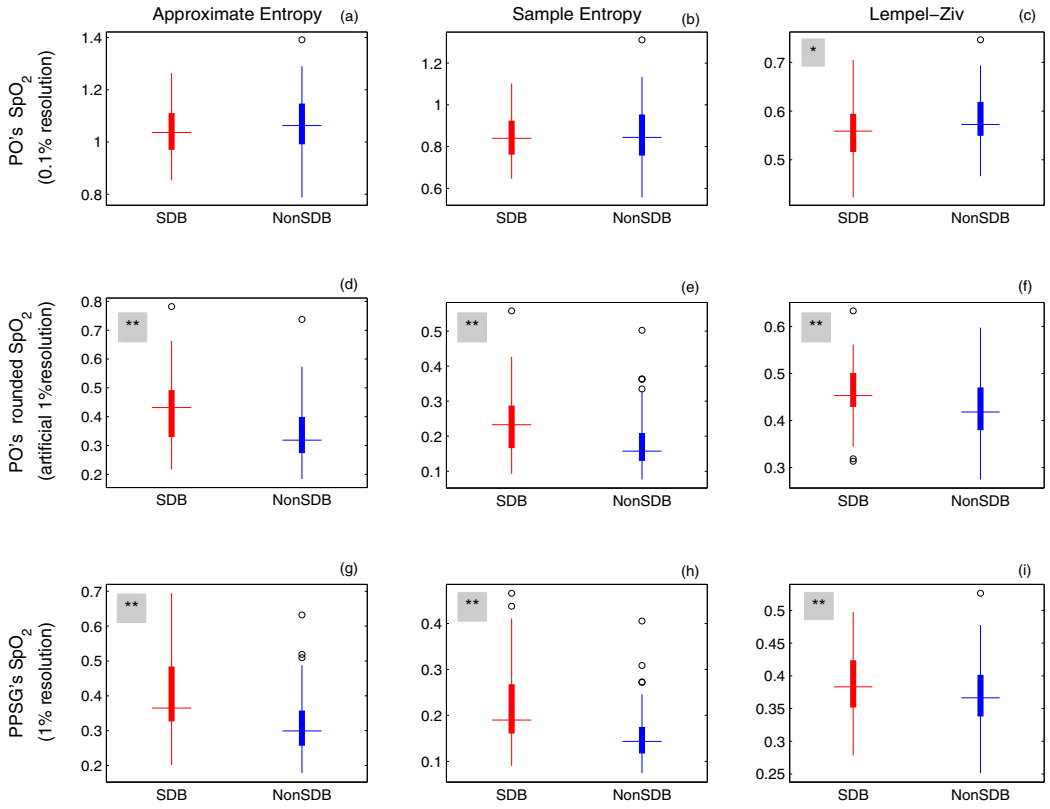

Fig. 2. Boxplot of the mean value of the approximate entropy, sample entropy and Lempel-Ziv complexity calculated from each of the three overnight SpO_2 signals; original Phone Oximeter's (PO's) SpO_2 (0.1% resolution), rounded PO's SpO_2 (artificial 1% resolution) and SpO_2 recorded from PSG (1% resolution). Significant differences between SDB and NonSDB children are represented by one star (*) when p-value < 0.01 and by two stars (**) when p-value < 0.0001. Quartile values are displayed as bottom, middle and top horizontal line of the boxes. Whiskers are used to represent the most extreme values within 1.5 times the interquartile range from the median. Outliers (data with values beyond the ends of the whiskers) are displayed as circles.

complexity value ($LZ = \frac{c(n)}{b(n)}$) of the SpO_2 signal can be obtained by normalizing it by a function ($b(n) = \frac{n}{log_2(n)}$) of the length of the analyzed sequence.

III. RESULTS

From Figures 2.a and 2.b, it can be observed that the ApEn and SamEn of 0.1% SpO_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 SpO_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% SpO_2 resolution seemed to be more regular in children with SDB than in NonSDB.

Looking at the ApEn, SamEn and LZ values obtained with the rounded SpO_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 SpO_2 than the NonSDB children. These results coincide with the analysis applied to the 1% resolution SpO_2 extracted from PSG study, and confirm that the differences found in SpO_2 regularity are due to the rounding effect. Figures 2.g, 2.h and 2.i, illustrate that the 1% resolution SpO_2 from PSG provided the same significant results as the rounded SpO_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 SpO_2 resolution on non-linear measurements like ApEn, SamEn and LZ complexity. We showed that in terms of regularity measurements, different results were obtained with the devices providing 0.1% SpO_2 resolution as compared to 1% SpO_2 resolution. We also showed that this difference was due to the rounding effect caused by the SpO_2 resolution. Considering these results we cannot assume that the SpO_2 pattern is more random in children with SDB than in NonSDB children, because this difference is no longer significant with a higher SpO_2 resolution. The lower resolution provided by the PSG's pulse oximeter (Figure 1) might bias the SpO_2 regularity values. The SpO_2 randomness shown for NonDSB children using 0.1% SpO_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 SpO_2 changes due to the desaturations provoked by sleep

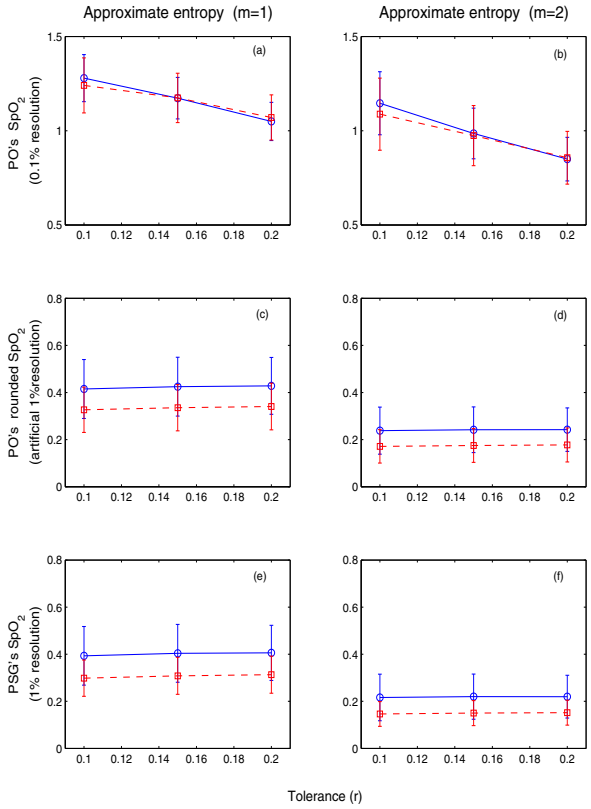

Fig. 3. The approximate entropy and sample entropy of the SpO_2 was evaluated with tolerance values ranging from 0.10 to 0.20 and $m = 1$ (1^{st} column) and $m = 2$ (2^{nd} column). Each row represents the regularity measurements calculated using the different SpO_2 signals (1^{st} row: original Phone oximeters (PO's) SpO_2, 2^{nd} row: rounded PO's SpO_2 and 3^{rd} row: SpO_2 recorded from PSG. The mean value and standard deviation of these values are represented for children with SDB in red dotted line with square markers and in blue solid line with circle markers for NonSDB children.

apnea, as illustrated in Figure 1.a. Therefore, to study the regularity or randomness of the SpO_2 pattern we should consider the device's resolution.

Recent studies based on the analysis of 0.1% resolution SpO_2 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 SpO_2 signal, coincided with that of prior works. DelCampo et al. [6], [10] illustrated that the analysis of SpO_2 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 SpO_2 resolution influence on the regularity measurements studied, it remains unclear how SDB affects the SpO_2 regularity.

V. CONCLUSION

The aim of this study was to show the influence of the pulse oximeter's oximetry resolution when studying SpO_2 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 SpO_2 pattern in children with SDB.

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