

PERIOD DOMAIN ANALYSIS IN FETAL PULSE OXIMETRY

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Abstract—The photoplethysmographic signals acquired during pulse oximetry can be compromised in many ways. Intrapartum fetal pulse oximetry in particular presents challenges to signal processing. Period domain analysis can overcome the low pulsatile amplitudes, noise, and maternal modulation found in these signals. The efficiency of an incremental algorithm reduces the processing requirements for period domain analysis, facilitating use in low-power and portable devices.

Keywords - Fetal pulse oximetry, spectral analysis, period domain analysis, ensemble averaging

I. INTRODUCTION

Pulse oximetry is the non-invasive measurement of oxygen saturation (SpO₂) based upon the relative absorbance of multiple light wavelengths by different species of hemoglobin. The last decade has seen a renewed interest in overcoming the limitations of low perfusion and motion in pulse oximetry, and extending its use into new areas such as intrapartum fetal monitoring [1].

In fetal pulse oximetry (FPO), the sensor is placed through the birth canal onto a part of the fetus. Fetal physiology normally operates at a much broader and lower oxygen saturation range, typically SpO₂ = 40%-75%, with clinically significant desaturations occurring below 30% [2]. Stability of tissue conditions at the monitoring site, such as blood volume, become more critical at low saturations, and calibration of these devices is a challenge [3].

Commercially available devices operate in reflectance (backscattering) mode, and are placed trans-cervically upon the fetal body in utero [4]. The pulsatility of the photoplethysmographic (PPG) signals is small compared to adults or neonates. The intrauterine placement makes ambient light interference unlikely, but introduces the possibility of maternal modulation of the fetal signals. The intimate proximity of the fetus to maternally vascularized tissue can result in a strong modulation at the maternal pulse rate.

Traditional time domain techniques employed to process PPG signals include peak detection and fiducial point determination for cardiac period calculation, and peak-valley measurement for the pulsatile amplitude measurement used in SpO₂ calculation. Recently, frequency domain analysis has been used into algorithms for determination of the fundamental cardiac frequency and, to some extent, selective removal of noise components based upon frequency content [5]. These algorithms work in conjunction with time domain techniques, rather than replacing them.

We propose processing the PPG signals in the period domain, i.e., determining the relative contributions of different periods to the signal content [6]. The advantages of this method are improved resolution for low frequency biomedical signals, and compatibility with time domain algorithms.

II. ALGORITHM IMPLEMENTATION

The Discrete Fourier Transform (DFT) and incremental or “sliding” DFT are fundamental algorithms [7]. For sampling frequency f_s the frequency “bin” k of the N -point DFT corresponds to frequency $f_k = k \cdot f_s / N$ Hz, and

$$X^i(k) = \sum_{n=0}^{N-1} x(i+n) e^{-j2\pi k n / N} \quad k = 0, 1, \dots, N-1 \quad (1)$$

is the expression for spectrum of the k th frequency “bin” of for the sample sequence $x_i \dots x_{i+N-1}$. At $i+1$, the “sliding” or incremental DFT is calculated as

$$X^{i+1}(k) = e^{j2\pi k / N} [X^i(k) + x(i+N) - x(i)] \quad (2)$$

To derive the Discrete Period Transform (DPT), let $s = 1, 2, \dots, N-1$ samples be the range of periods possible in the sequence $x_i \dots x_{i+N-1}$. Frequency f_k corresponds to period $s_k = 1/f_k = N / (k \cdot f_s)$ seconds = N/k samples, so $k = N/s_k$. Substituting into (1) and (2), for the period s ,

$$T^i(s) = \sum_{n=0}^{N-1} x(i+n) e^{-j2\pi n / s} \quad s = 1, 2, \dots, N-1 \quad (3)$$

and

$$T^{i+1}(s) = e^{j2\pi / s} [T^i(s) + x(i+N) - x(i)] \quad (4)$$

The DPT calculates the period spectrum at a resolution $1/f_s$. Over the relatively small frequency range of PPG signals (approx. 0.1-10Hz), this resolution is achieved with modest processing power and memory. No conversion from frequency is necessary for compatibility with time domain algorithms, an advantage where period measurements are interchanged between power spectrum and time domains.

Ensemble averaging has been applied to PPG signals, usually employing an external cardiac “trigger” obtained from an ECG source [8]. This has also been attempted in fetal pulse oximetry, although obtaining a reliable fetal ECG signal generally requires use of a fetal-invasive scalp electrode. By deriving a reliable cardiac period estimate from period domain analysis, ensemble averaging may proceed without an external trigger source.

III. METHODOLOGY

A fetal signal database was collected to investigate pulse oximetry algorithms in a personal-computer-based Fetal Oximetry Platform (FOP). The OB Scientific™ OBS-900 Fetal Oxygen Sensor was placed through the birth canal onto the fetal torso. Red, infrared, and dark signals from the sensor, digitized at a rate of 120 samples/second and 21 bit resolution, were transmitted from the OBS-500 Fetal Pulse

Oximeter to a portable computer for storage. The FOP system incorporates the oximeter's algorithms as well as a user interface for graphical and textual display and analysis of the oximeter operation. FOP permits a signal record to be re-run with alterations to the algorithms and subsequent pulse-to-pulse comparison of the results.

IV. RESULTS

A. Pulse Rate Determination

Fig. 1 illustrates an example of weak signal data (red and infrared (IR)) in the time domain (a-c), and the corresponding period domain spectrum (d). The peak in (d) is the cardiac period (fetal heart rate 137 beats/minute).

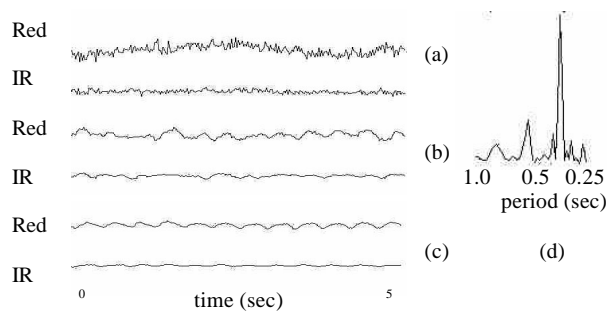


Fig. 1. Weak photoplethysmographic signals: (a) unprocessed, (b) band-passed, (c) ensemble averaged, (d) period domain

Fig. 1 (a) is the unfiltered signal data from the sensor. The result of simple band-pass filtering to obtain the pulsatile portion of each signal is shown in (b). Reliable determination of the pulse rate from (b) would be difficult. The cardiac period is apparent in (d). The fetal signal components extracted using ensemble averaging with the cardiac period estimate of (d) are shown in (c). The period domain spectrum yields a useful cardiac period for rate calculation that can be tracked through all but extreme, prolonged noise.

B. Maternal modulation

Fig. 2 illustrates a case of significant maternal modulation in the time domain (a-c) and the period domain (d). The right peak in (d) is the cardiac period (fetal heart rate 126 beats/minute), whereas the left peak is the maternal cardiac period (97 beats/minute heart rate).

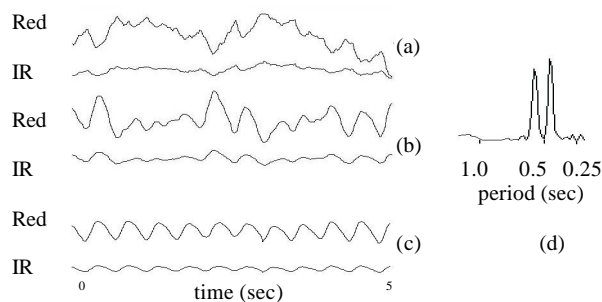


Fig. 2. Maternal modulation in PPG signals: (a) unprocessed, (b) band-passed, (c) ensemble averaged, (d) period domain

The result of simple band-pass filtering to obtain the pulsatile portion of each signal is shown in Fig. 2 (b). Ensemble averaging utilizing the cardiac period derived from period domain analysis can better extract the fetal signal components, as illustrated in (c). Errors in pulse rate and oxygen saturation calculations could result from processing the signals in (b). Applying ensemble averaging results in a much cleaner signal (c) for further time domain analysis.

V. DISCUSSION

Biomedical signals are notorious for lacking statistical stationarity. The PPG period domain spectrum obtained with the incremental DPT algorithm tracks relatively fast heart rate changes (such as heart rate accelerations and decelerations), but may not produce useful results in the presence of arrhythmias. Because it is used in conjunction with time domain pulse detection, the period domain algorithm may be disabled automatically in such circumstances.

In the case of fetal pulse oximetry, highly irregular rhythms are relatively uncommon. When bigeminy is present with regularity of pulse spacing, period tracking may "lock on" and track the normal (hemodynamically strong) pulses at half the actual pulse rate. Ensemble averaging at the halved rate will still be effective, if the temporal relationship of normal and PVC beats is consistent.

VI. CONCLUSION

Period domain analysis utilizing an incremental DPT algorithm is an effective and efficient way to process periodic biomedical signals for spectral content. It provides the capabilities of frequency domain analysis, with certain advantages in implementation. Processing of photoplethysmographic fetal pulse oximeter signals with period domain analysis improves pulse rate availability and accuracy, and permits removal of interference by techniques such as ensemble averaging without an external noise reference.

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