Multi-Detector Heart Rate Extraction Method for Transabdominal Fetal Pulse Oximetry*

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Abstract— Intrapartum fetal well-being assessment relies on fetal heart rate (FHR) monitoring. Studies have shown that FHR monitoring has a high false-positive rate for detecting fetal hypoxia during labor and delivery. A transabdominal fetal pulse oximeter device that measures fetal oxygen saturation non-invasively through NIR light source and photodetectors could increase the accuracy of hypoxia detection. As light travels through both maternal and fetal tissue, photodetectors on the surface of mother's abdomen capture mixed signals comprising fetal and maternal information. The fetal information should be extracted first to enable fetal oxygen saturation calculation. A multi-detector fetal signal extraction method is presented in this paper where adaptive noise cancellation is applied to four mixed signals captured by four separate photodetectors placed at varying distances from the light source. As a result of adaptive noise cancellation, we obtain four separate FHR by peak detection. Weighting, outlier rejection and averaging are applied to these four fetal heart rates and a mean FHR is reported. The method is evaluated in utero on data collected from hypoxic lamb model. Ground truth for FHR is measured through hemodynamics. The results showed that using multi-detector fetal signal extraction gave up to 18.56% lower root-mean-square FHR error, and up to 57.87% lower maximum absolute FHR error compared to single-detector fetal signal extraction.

I. INTRODUCTION

Current antenatal fetal well-being assessment relies on fetal heart rate (FHR) monitoring throughout pregnancy using Doppler ultrasound [1]. It is believed that uterine contraction followed by fetal bradycardia could indicate fetal hypoxia and could require surgical intervention [2]. Although, early detection of hazards to the fetus is expected to reduce fetal mortality, a secondary effect of routine FHR monitoring is the significant increase in number of emergency cesarean deliveries [3]. Studies showed that despite the increased rate in cesarean deliveries, the rates of harm to fetus due to hypoxia stayed the same [4, 5]. The ultrasound Doppler signal used to detect FHR loses accuracy due to disturbance from maternal and fetal breathing [6]. Furthermore, a non-reassuring FHR tracing does not always indicate hazards to the fetus but could simply be caused by normal physiological responses [5]. Therefore, the decision of surgical intervention by obstetricians only based on FHR tracings is not educated enough and yields a high false positive rate [7, 8]. Alternative objective methods to assess fetal well-being is needed.

Garite et al. conducted a multicenter randomized, controlled trial to evaluate transvaginal fetal pulse oximetry and concluded that measuring the fetal oxygen saturation in addition to continuous monitoring of FHR tracings increased the confidence in assessing fetal well-being [8]. Transvaginal fetal pulse oximeter is an invasive device that is inserted through the birth canal after the rupture of uterine membrane. A reflectance pulse oximeter is then placed on fetal head in order to measure fetal oxygen saturation. The results of this study showed a decrease in false positive cesarean deliveries due to non-reassuring FHR tracings, but the overall cesarean delivery rate stayed constant because of increased fetal dystocia in the study group. Nevertheless, knowledge of fetal oxygen saturation did improve obstetricians' confidence in fetal well-being when a non-reassuring FHR tracing was present.

Recently, a transabdominal fetal pulse oximetry (TFO) was developed to measure fetal oxygen saturation in a fully non-invasive manner [9, 10]. The feasibility of in-utero fetal oxygen saturation monitoring using TFO has been demonstrated in a hypoxic lamb model [11, 12]. TFO is a reflectance-based oximeter where photons from two LED light sources in red and near-infrared (NIR) region travel through the maternal abdomen and fetus [13]. Because of how light interacts with tissue, only a small portion of photons are reflected by fetal tissue back to the surface and captured by photodetectors [14]. The detected signal is a mixed signal containing both maternal and fetal information. It is crucial to effectively extract the fetal signal from the measured mixed signal, that mostly contains maternal information, in order to accurately estimate fetal oxygen saturation [15].

In this paper, a methodology to recover weak fetal information captured by TFO is presented. The presented techniques are tested on data collected from a hypoxic fetal lamb in utero.

II. METHODS

A. Transabdominal Fetal Pulse Oximetry

Transabdominal fetal pulse oximetry (TFO) is a non-invasive device designed and built to measure fetal oxygen saturation [16, 17]. Photons emitted into mother's abdomen through near-infrared (NIR) LED light sources scatter through maternal tissue before reaching the fetus. NIR emitters are chosen for higher optical penetration depth since fetal tissue is a few centimeters away from the surface [14, 16]. A portion of the photons that propagate through fetal tissue is reflected back to the mother's abdomen's surface where they are captured by photodetectors [17]. A picture of the optical probe housing the emitters and photodetectors is shown in Fig. 1.
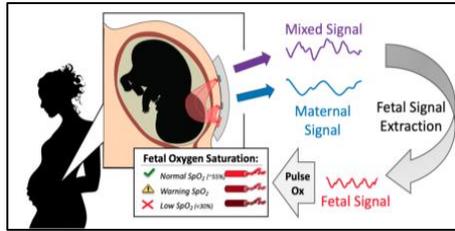
Figure 1. Optical Probe.

Figure 2. High-Level overview of Transabdominal Fetal Pulse Oximetry [16].
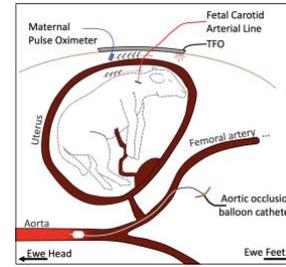

Figure 3. Hypoxic lamb model setup.

Since the detected light intensity at the surface propagates through two different pulsating mediums (maternal and fetal), it carries mixed information from both maternal and fetal layers. Maternal information includes maternal heart rate (MHR), maternal respiration rate (MRR) and Mayer waves [17]. Therefore, the fetal signal should be extracted from this mixed signal in order to estimate fetal oxygen saturation [18]. There are five photodetectors placed at difference distances from the emitters [16]. The number and placement of detectors are based on a previous study on optode design space exploration [16]. As the distance between detector and emitter increases, the light detected travels through a longer distance and therefore penetrates deeper into the tissue [16]. Far detectors contain more fetal information compared to near detectors. But at the same time light gets attenuated more as it travels through a longer distance and therefore, far detectors also capture a weaker signal. The closest detector (D1) to the emitter contains only maternal information and as we move further away from the emitter, the detectors will capture more and more fetal information [14-16]. A high-level overview of fetal signal extraction is shown in Fig. 2.

B. Data Acquisition from Hypoxic Lamb Model

The procedures used to produce a hypoxic lamb model were approved by the UC Davis Institutional Animal Care and Use Committee (IACUC). Fetal hypoxia was induced in an anesthetized pregnant ewe (±140 days of gestation) by the insertion of a balloon catheter into the infrarenal abdominal aorta. The fetal carotid artery was cannulated by inserting an arterial line into the lamb's neck for drawing arterial blood gases and continuously capturing fetal heart rate (FHR) through hemodynamic monitoring. Ewe's maternal heart rate (MHR) was monitored using a pulse oximeter on the abdomen, and the maternal respiratory rate (MRR) was monitored through capnography. The leaked amniotic fluid from the uterus was replaced with warm saline solution. The lamb was placed back in the uterus and the uterus and abdomen were sutured. The monitored vital signs (MHR, FHR, MRR) were logged through BIOPAC. TFO optical probe in Fig. 1 was placed on the ewe's abdomen for continuous measurement. The fetus was measured to be 1.3 cm deep. An overview of the setup is shown in Fig. 3. The aortic balloon catheter was inflated gradually until fetal oxygen saturation measured by blood gas analysis (SaO2) dropped below 15%. The balloon was then fully deflated, the fetus was recuperated, and the experiment was repeated for another round [12].

A. Fetal Signal Extraction

As explained previously, the data captured by the photodetectors is a mixed signal that contains both maternal and fetal information and therefore further processing is necessary in order to extract fetal information to be used in oxygen saturation calculation. Previous studies have shown that adaptive noise cancellation (ANC) techniques perform well in extracting the fetal information [15, 20]. Recursive least squares (RLS) adaptive noise cancellation (ANC) filtering is used in this paper to filter out the fetal signal [19].

The fetal heart rate (FHR) is our desired signal and is contaminated by noise signal. The noise signal includes maternal heart rate (MHR) (1Hz - 1.7Hz or 60-100 bpm), low-frequency physiological signals such as maternal respiration rate (MRR) (~0.2Hz -0.5Hz or 12-20 breaths per minute) and Mayer waves (~0.1Hz), electronic noise from the system and motion artifacts [17]. In this paper, we focus on cancelling the maternal noise sources. Application of ANC requires access to noise-only (maternal-only) signal as reference [19]. This maternal-only signal is captured through a near detector (D1 in Fig. 1) that has 1.5 cm source-detector separation [10]. Other studies have used an additional finger pulse oximeter to measure maternal heart rate only [20]. Our system is superior to the latter approach since both the maternal-only/noise-only and mixed signals are measured through a single device and noise within the mixed signal has higher correlation and higher similarity over time with the reference noise-only measurement which will result in better ANC performance.

We have a multi-detector system where detectors D2 to D5 can capture fetal signal based on the depth of the fetus [16]. Detectors D2 to D5 are placed at 3, 4.5, 7, and 10 cm away from the light emitters respectively [10]. Since the fetal depth was shallow (1.3 cm from surface where TFO is placed) in the acquired data from hypoxic lamb model, all four detectors (D2-D5) captured fetal information. Therefore, we have four different mixed signals to which we can apply ANC to extract the fetal signal. We develop a multi-detector fetal heart rate estimation method that combines the FHRs extracted from four different detectors for a more robust FHR estimation as opposed to existing single-detector FHR estimation method [20].
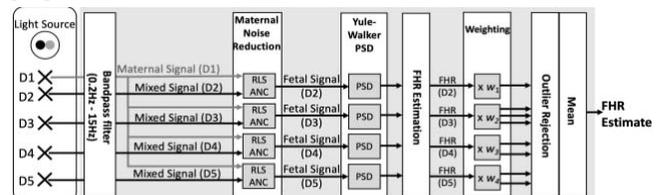

Figure 4. Multi-Detector Fetal Heart Rate Estimation Block Diagram

A high-level diagram of the multi-detector FHR estimator is presented in Fig. 4. The algorithm is implemented in MATLAB. The maternal signal captured by D1 and mixed signals captured by detectors D2 to D5 are bandpass filtered between 0.2 Hz – 15 Hz to remove high frequency and very low frequency noise components before passing through ANC. Strong MRR, MHR contributions are removed from the mixed signal by the RLS adaptive filtering algorithm and the resulting signal contains the extracted fetal information. We set the adaptive filter size to 100 so that it is large enough to gather sufficient information from most recent samples in both the noise signal and the desired signal as we iteratively inspect the data. The resulting signal's power spectral density (PSD) is computed using Yule-Walker autoregressive method of order 100 and passed to FHR estimation block. The FHR estimation block outputs the frequency with highest power density within a pre-defined search span as FHR. The search span of FHR in the PSD is set to 110 bpm – 270 bpm (or 1.83 Hz – 4.5 Hz) based on typical fetal heart rates found in the literature [21]. After an FHR value per detector is estimated, a weight is assigned to each detector. As source-detector distance increases more fetal information is captured since light travels deeper into the tissue before returning to the surface. But on the other hand, as light travels through a deeper and longer path it is also absorbed more and less photons reach the further detectors [16]. Therefore, the weights are assigned based on source-detector distance. The weighting plays an important role in outlier rejection and mean calculation. The FHR estimations that are 3 Median Absolute Deviation (MAD) away from the weighted median are rejected as outliers and finally mean FHR is calculated with remaining weighted FHR estimates.

III. RESULTS AND DISCUSSION

A 49-minutes-long dataset is recorded during round 1 of our hypoxic lamb model and a 31-minutes-long dataset is recorded during round 2. The data is down-sampled by 10 to 80Hz and split into 1-minute long windows with 30 seconds (50%) of overlapping datapoints between windows for analysis. Therefore, a new FHR is computed every 30 seconds and the FHR estimate is an estimate for a 1-minute timeframe. Weighting per detector shown in Fig. 4 is defined as follows: $w_1=1$, $w_2=3$, $w_4=w_5=2$.

Fig. 5a shows an example of time-domain maternal signal captured at detector 1 (D1), mixed-signal captured at detector 3 (D3) and the extracted fetal signal after ANC between minutes 9-10 of round 1. The corresponding yule-walker power-spectral densities (PSD) before and after ANC are shown in Fig. 5b. maternal respiration rate (MRR), maternal heart rate (MHR) and fetal heart rate (FHR) are marked on Fig. 5b. We can see that the extracted fetal signal's PSD after ANC shows significant suppression of MRR and MHR resulting in dominant FHR peak. Fig. 6a shows the FHR estimations of fetal signals extracted from all four detectors D2-D5 during whole duration of round 1. The mean FHR computed as a result of our multi-detector FHR estimation method described previously as well as the reference FHR measured through hemodynamics are also shown in Fig. 6a.
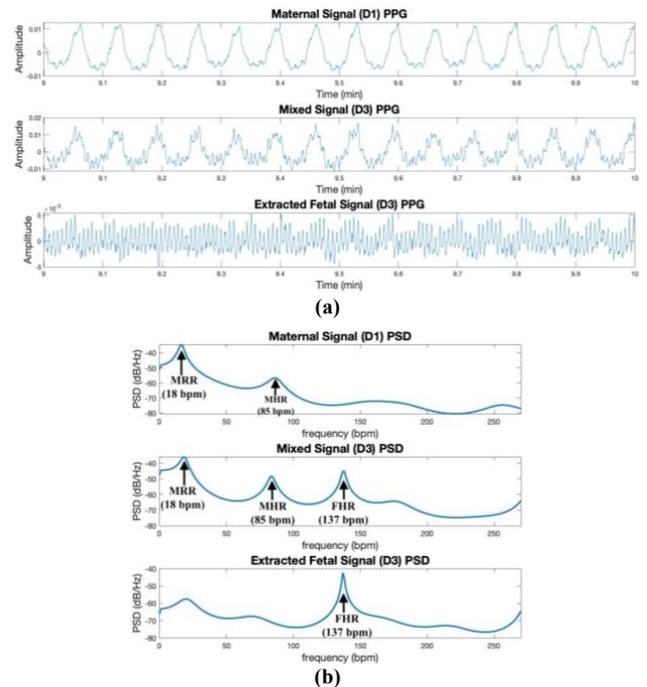

Figure 5. Example dataset from round 1 (a) in time-domain, (b) in frequency domain

Fig. 6b shows the absolute error in estimating FHR via single detectors and multi-detector FHR estimation algorithm. The error is the difference between estimated FHRs and reference FHR measured through hemodynamics. From Fig. 6b, we can infer that the data collected in round 1 was very clean and all detectors, except D5, show accurate FHR estimations with below 5 bpm absolute error over the entire round. We chose root-mean-square error (RMSE) as our accuracy metric since it gives a high weight to large errors which is undesirable in FHR estimation. Table 1 summarizes the performance of single-detector FHR estimations (D2-D5) vs. multi-detector mean FHR estimation. We see that since very clean data was collected in round 1 both multi-detector and single-detector FHR estimates have good performance with around 0.87 bpm RMSE. Comparing multi-detector mean FHR estimation performance with best-performing single-detector (D3) FHR estimation performance in round 1, we see that the difference in RMSE and maximum absolute error are negligible. These results suggest that, multi-detector FHR estimation is not necessary when a very clean fetal signal is collected.
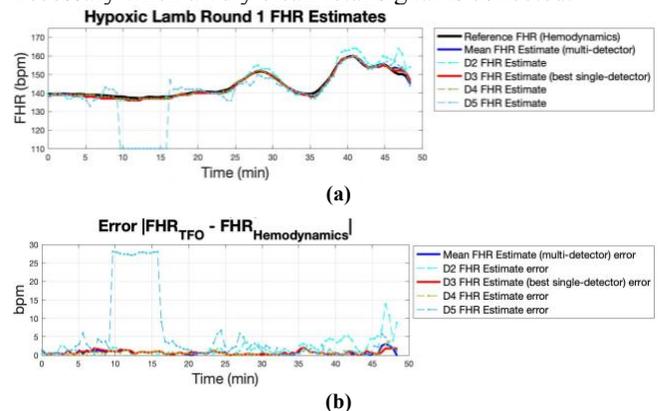

Figure 6. Hypoxic lamb round 1 results. (a) FHR estimates, (b) FHR estimation error over time

	RMSE (bpm)		Maximum Absolute Error (bpm)	
	Round 1	**Round 2**	**Round 1**	**Round 2**
D2 FHR	2.9291	43.4845	13.8543	100.8720
D3 FHR (best single-detector)	**0.8753**	**4.7262**	**2.1356**	**24.2303**
D4 FHR	0.8688	23.5761	3.7721	104.8720
D5 FHR	10.4745	10.2379	28.0960	33.4131
Multi-detector Mean FHR	**0.8879**	**3.8492**	**2.9971**	**10.2075**

Data collected during round 1 is ideal but unfortunately, we cannot always expect the data collected by TFO to be as clean.

Fig. 7a shows the FHR estimations obtained from data collected during hypoxic lamb round 2. The rapid increase in FHR towards the end of the experiment is due to hypoxia induced in fetus. Fig. 7b shows the absolute error in estimating FHR over time. We observe that noisier data was collected during round 2 by individual single-detectors. Comparing multi-detector mean FHR estimation performance with best-performing single-detector (D3) FHR estimation performance in round 2 as shown in Table 1, we get 18.56% lower RMSE, and 57.87% lower maximum absolute error with multi-detector FHR estimation. These better performance metrics are achieved by combining data collected from four detectors which can compensate for data losses and noise occurring in a single detector. This can be visually seen in Fig. 7 where best performing single detector (D3) lost FHR at minutes 6-7 while multi-detector mean FHR was able to compensate for the loss by including FHR information from detectors D4-D5.

These results suggest that multi-detector FHR estimation method presented in this paper offers more robust and more accurate fetal signal information extraction compared to single-detector systems especially when single detector FHR estimates are noisy.
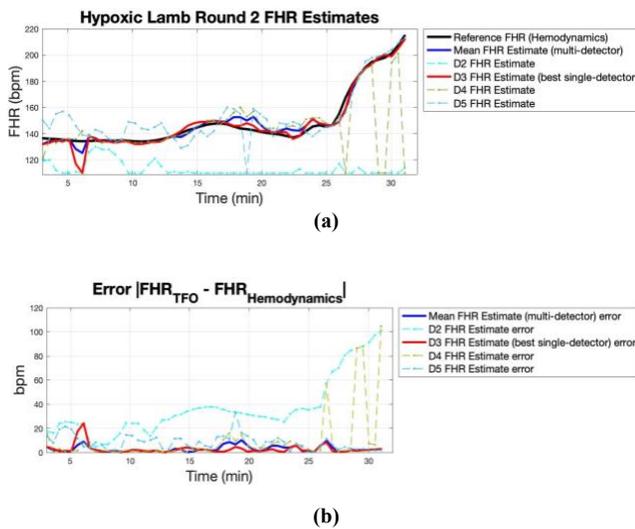

(a)

(b)

Figure 7. Hypoxic lamb round 2 results. (a) FHR estimates, (b) FHR estimation error over time

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