# Impacts of First and Second Labour Stages on Hurst Parameter based Intrapartum Fetal Heart Rate Analysis

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## Abstract

*Intrapartum fetal heart rate (FHR), routinely monitored in daily obstetrical practice, enables early detection of fetal asphyxia and thus prevention of labour adverse outcomes. FHR variability (FHRV) constitutes an essential characterization of fetal well-being; fetuses with large FHRV are unlikely to be at risk of brain injury. This study investigates the impacts of labour first and second stages on the characterization of FHR temporal dynamics as well as on the discrimination of healthy from acidotic fetuses. FHR temporal dynamics are quantified using Hurst parameter, $H$, practically estimated within a wavelet framework. Analyses are performed on first and second stages, over a large (3049 records) and well documented database, collected at Hôpital Femme-Mère-Enfant, in Lyon, France. It is observed that $\hat{H}$, for healthy fetuses, remains constant along first stage and then significantly increases during second stage ; while, for acidotic fetuses, $\hat{H}$ increases to larger values earlier within first stage. This may indicate that the defense mechanism classically at work during second stage as a reaction to excessive stress, is already in use during first stage for acidotic fetuses. Detection performance curves (ROC) also show that second stage $\hat{H}$ permits slightly better discrimination of healthy from acidotic fetuses, compared to first stage $\hat{H}$.*

## 1. Introduction

**Intrapartum fetal heart rate (FHR)** provides information about fetal behaviour and is commonly monitored during intrapartum period. The purpose is to timely detect acute fetal acidosis and act to prevent severe long term sequels for neonate and its healthy development. FHR monitoring constitutes the main method for continuous fetal surveillance. One of the key characteristics of FHR is variability (FHRV) [1]. Decrease or absence of variability is a sign of fetal hypoxia and developing acidemia. In clinical practice, however, variability remains mostly estimated by the visual inspection. Furthermore, the evolution of variability along labour progression is not fully understood, notably with respect to the different labour stages.

**Characterization of first and second stage.** The first stage of labour begins with progressive cervical dilatation and occurrence of regular contractions. The second stage starts with fully dilated cervix and expulsive contractions associated with higher stress for fetus. In contrast to studies on FHR during first stage, the analysis and interpretation of FHR during second stage is less documented for several reasons: i) FHR has lower quality because of increased maternal activity, ii) interpretation might be different from first stage of labour [2] and iii) second stage is usually short and timely intervention might be infeasible.

**Analysis of second stage.** Due to short duration and lower signal quality, only a couple of studies examined second stage and reported relationship between FHR patterns and fetal acidemia. Gilstrap et al. [3] showed that abnormalities of FHR baseline and variability are weakly associated with fetal acidemia. General practice in FHR signal analysis however, is to consider FHR until delivery without division into stages, cf. e.g. [4–6]. There are several reasons for that: i) an attempt to describe FHR progression in general, ii) missing information about the start of second stage, and/or simply unawareness of possible complication for interpretation. Correct approach is to directly separate the two stages and evaluate only the first or second stage, cf. [7]. This stems from observations [8] that minutes preceding the delivery exhibit different properties and characteristics in comparison to FHR at initial phase.

**Goals and contributions.** The proposed contribution goes beyond already achieved works and investigates differences in the temporal dynamics of first and second stages. It analyzes FHRV using Hurst parameter, $H$, estimated from a wavelet decomposition framework (cf. Section 2) on large and well document database collected at French hospital, Femme-Mère-Enfant, in Lyon. The current study extends on earlier works in several aspects: i) it explicitly maps the change of FHRV from first to second stages of

labour, ii) it shows that change in variability is different between healthy and acidotic fetuses, iii) it examines how not distinguishing the analysis between the two stages leads to a bias in evaluation of performance classification.

## 2. Methodology and database

**Scale invariance, wavelet analysis, and Hurst parameter.** It is now well document that FHR variability time series can be characterized by robust fractal (or scale invariance) properties. One thus considers that Fourier Spectrum, $\Gamma_X$, of FHR decreases as a power-law over a large range of frequencies:

$$\Gamma_X(f) \simeq C|f|^{-(2H-1)}, \tag{1}$$

with a constant $C$ and the power law exponent controlled by the Hurst parameter $H$. Numerous methods were proposed for $H$ estimation, though a modern and robust way is based on the use of wavelet transform [9]. The wavelet coefficients, $d_X(a,k)$, naturally capture oscillations of a time series at scale $a$ and discrete time $k$. They are computed for a range of scales $a$ by means of inner product between the time series $X$ and a collection of dilated and translated templates $\psi_{a,k}(t) = \psi_0((t-k)/a)/\sqrt{(a)}$ of a reference pattern, called the mother wavelet $\psi_0$. The wavelet spectrum $S(a)$, that constitutes the wavelet counterpart of the Fourier spectrum $\Gamma_X$, is defined as (cf. [9]):

$$S(a) = \frac{1}{n_a}\sum_k d_X^2(a,k), \tag{2}$$

where $n_a$ is the number of wavelet coefficients at scale $a$. For fractal time series, with Fourier Spectrum as in eq. (1), the wavelet spectrum $S(a)$ behaves as a power law with respect to analysis scales $a$, with a power law exponent proportional to the Hurst parameter:

$$S(a) \simeq C_{\psi_0,H}\ \ a^{2H-1}, \tag{3}$$

across a wide range of scales $a$. The estimation of parameter $H$ is then performed as a linear regression in a $\log S(a)$ vs. $\log a$ across an empirically assessed range of scales $a$.

**Database.** The database, collected at the public academic French Hospital Femme-Mère-Enfant, in Bron, between 2000 and 2010, consists of 3049 intrapartum cardiotocogram (CTG) signals. CTG signals were acquired using scalp electrode by STAN S21 or S31 system (STAN, Neoventa Medical, Sweden). Clinical information for each woman and neonate were systematically collected by obstetricians in charge, cf. [10]. FHR signals 60 minutes long in the first stage and longer than 15 minutes in the second stage with less than 15% of missing data were used for the current study. 796 subjects satisfied the criteria, amongst which 26 fetuses were defined as having neonatal acidosis (umbilical artery pH $\leq$ 7.05). We refer the later group as *acidotic*, as opposed to *healthy* in the sequel. The median length of second stage was 26 $\pm$ 10 minutes. An example of healthy FHR with marked stages is shown in Fig. 1. Database clinical criteria were detailed in [10].

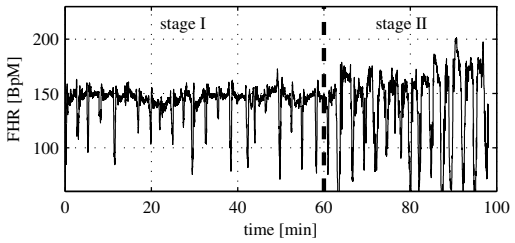


Figure 1. Fetal heart rate: first and second stages.

First and second stages are hereafter referred to as $s_I$ and $s_{II}$. Analysis was systematically performed using 20 minute-long sliding window, with 5 minute overlap: Nine segments were analyzed in first stage ($s_I^1, s_I^2, \ldots, s_I^9$) and 11 segments in second stage ($s_{II}^1, s_{II}^2, \ldots, s_{II}^{11}$). Because most records ended within fifth segment of $s_{II}$, results are systematically presented up to this segment. For the statistical evaluation, non-overlapping windows were used: $s_I^5$ (20 minutes before last 20 minutes of $s_I$), $s_I^9$ (last 20 minutes of $s_I$), and $s_{II}^1$ (first 20 minutes of $s_{II}$).

## 3. Results

**Temporal dynamics**. The evolution of Hurst parameter was analyzed using sliding windows, where each stage was analyzed separately (windows non-overlapping between stages) though for convenience, results are presented by concatenation of the two stages. Fig. 2 clearly shows the difference in temporal dynamics between the two stages. At the transition between $s_I$ and $s_{II}$, FHRV rapidly change resulting in a statistically significant increase (for healthy fetuses) of $\hat{H}$ from 0.45 to 0.50. Considering the two non-overlapping windows of $s_I$ ($s_I^{5,9}$) and first window of $s_{II}^1$, the signed rank test confirms the significance of this change as labour progresses. Table 1 shows a larger change from $s_I^9$ to $s_{II}^1$ compared to change from $s_I^5$ to $s_I^9$.

**Temporal dynamics for healthy and acidotic fetuses.** Closer examination of Fig. 2 reveals that $\hat{H}$, for acidotic cases, is systematically above healthy cases and deviates as labour progresses. For acidotic fetuses, the change in dynamics between $s_I$ and $s_{II}$ is found less significant (cf. p-values in Table 1) than for healthy fetuses though the comparison is limited by power of the statistical test in the acidotic case, due to unbalanced sample size. However, Fig. 3 evidences that the difference exists by showing that wavelet spectra of $s_I^9$ and $s_{II}^1$ are more similar (closer to each other) for acidotic cases (Fig. 3b)) than for healthy

Table 1. **Statistical properties of $\hat{H}$.** Presented as mean (standard deviation) for segments $s_I^5$, $s_I^9$, and $s_{II}^1$. All segments are compared by Friedman test. The difference between segments is tested using the Wilcoxon signed rank test.

| | $\hat{H}$ | | | Friedman test | signed rank test | |
|---|---|---|---|---|---|---|
| | $s_I^5$ | $s_I^9$ | $s_{II}^1$ | $(s_I^5, s_I^9, s_{II}^1)$ | $s_I^5 - s_I^9$ | $s_I^9 - s_{II}^1$ |
| normal | 0.45 (0.13) | 0.45 (0.13) | 0.50 (0.14) | 1.00e-6 | 0.14 | 5.02e-9 |
| acidotic | 0.50 (0.12) | 0.51 (0.11) | 0.56 (0.12) | 0.61 | 0.59 | 0.17 |

cases (Fig. 3a)). For the healthy cases, the wavelet spectra of $s_I^9$ and $s_{II}^1$ deviate one from the other as early as scale $a = 2^3$, that corresponds to 1.25 Hz, whereas for acidotic cases a much smaller deviation can be observed starting only at scale $a = 2^6$ corresponding to 0.15 Hz.

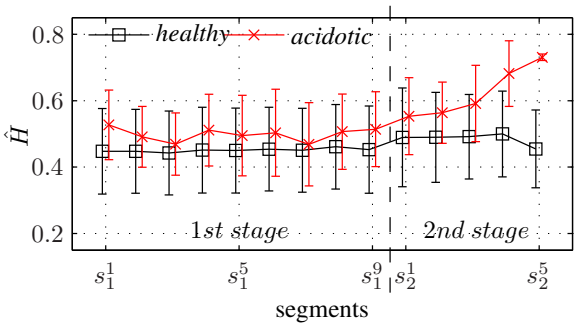


Figure 2. **Time evolution of $\hat{H}$** throughout $s_I$ and $s_{II}$ for healthy and acidotic cases.

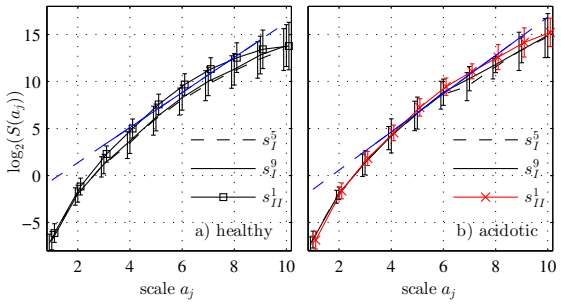


Figure 3. **Wavelet spectra** – for healthy (a) and acidotic (b) fetuses for segments $s_I^5$, $s_I^9$, and $s_{II}^1$.

Because most fetuses were delivered within the first 30 minutes in $s_{II}$, it might be argued that greater portion of short $s_{II}$ is behind the significant change from $s_I$ to $s_{II}$. To investigate the issue, $\hat{H}$ is depicted as function of time with respect to length of $s_{II}$, in Fig. 4, where the number of FHR records ending within a given segment is marked with a terminal bullet (•): Most of FHR records ended in $s_{II}^1$ (463 healthy, 16 acidotic), and in $s_{II}^2$ (101 healthy, none-acidotic), etc. Because all acidotic records ended before or within $s_{II}^5$, the healthy records continuing past this segment are marked with an arrow ($\rightarrow$ 30). Fig. 4 clearly shows changes in temporal dynamics that hold irrespective of $s_{II}$ length. Furthermore, it highlights that acidotic $\hat{H}$ is systematically above healthy $\hat{H}$ and that both healthy and acidotic $\hat{H}$ deviates as time progresses.

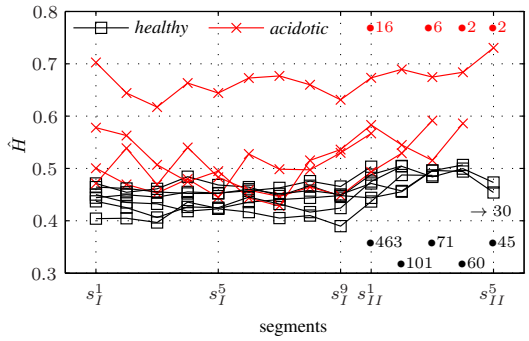


Figure 4. **Time evolution of $\hat{H}$ with respect to length of** $s_{II}$. Number of records ending within particular segment is marked with a bullet (•).

**Acidosis detection.** So far, it has been shown that there is a significant difference between $s_I$ and $s_{II}$. It is further investigated here how not distinguishing analysis between these stages could bias acidosis detection performance evaluation. Classically, the inter-individual differences of FHR between healthy and acidotic fetuses are analyzed just before delivery. This aims at describing the changes of FHR by using information as close as possible (in time) to the pH value (measured directly after delivery). However, there is a significant difference between the two stages and a correct approach to discriminate healthy and acidotic fetuses is to compare only first stages or second stages. Two possible worst case scenario are presented when the stages are mixed. First, an optimistic bias would occur when acidotic records from $s_{II}$ would be compared to healthy records from $s_I$. Such bias is presented in Table 2 using area under ROC curve (AUC) (see AUC marked with $*$) and shows that mixing of $s_I$ and $s_{II}$ leads to better separation (higher AUC) of healthy and acidotic fetuses. Second, a pessimistic bias is considered when acidotic records from $s_I$ and healthy records from $s_{II}$ are compared (AUC marked with † in Table 2). Table 2 also shows AUC for correct comparison (marked ‡) between $s_I$ or $s_{II}$. The corresponding ROC curves for AUC values are shown in Fig. 5 and highlights that optimistic ROC ($*$) and pessimistic ROC (†) are systematically above and below the ROC curves obtained from the correct comparison within $s_I$ or within $s_{II}$.

Table 2. **Area under ROC curve (AUC)** for acidosis detection. Correct performance estimation is marked with (‡), biased with (∗,†).

| | | healthy | |
|---|---|---|---|
| | stage | $s_I$ | $s_{II}$ |
| acidotic | $s_I$ | 0.62 (0.04)$^{\ddagger}$ | 0.53 (0.05)$^{\dagger}$ |
| | $s_{II}$ | 0.70 (0.07)$^{*}$ | 0.63 (0.06)$^{\ddagger}$ |

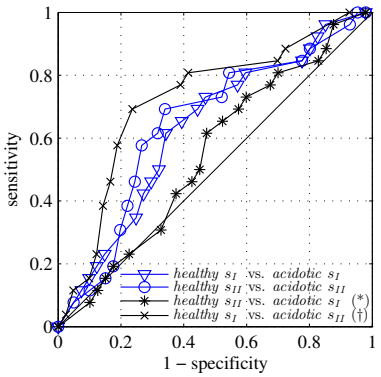


Figure 5. **ROC curves** for pair-wise comparison of healthy and acidotic FHR from $s_I$ and $s_{II}$.

## 4. Discussion and conclusions

Results obtained in the present contribution show that transition from first to second stages are accompanied by significant change of FHR variability, as measured by the Hurst parameter. This change is most probably caused by elevated stress for fetus due to more frequent and prolonged contractions as well as increase of an intrauterine pressure and reduction of placental oxygenation [11], all resulting to more profound decelerations, loss of variability, or bradycardia. These findings support and extend work of Gonçalves et al. [8]. The present contribution shows explicitly that dramatic changes occur directly at the boundary between first and second stages. Further, it takes into account the possibly different lengths of second stage and confirms that the change between the stages is consistent irrespective of the length of the second stage.

The difference between labour stages were already interestingly reported by Lim et al. [12] though without tracking the labour progression along time. Fetal heart rate for elective caesarean section (pre-labour stage), emergency caesarean sections (first stage), and vaginal deliveries (second stage) was shown significantly different as measured by approximate and sample entropy.

For acidotic cases, $\hat{H}$ was found systematically higher than for healthy cases, indicating lower variability. Furthermore, the end of first stage was found more similar to the begin of second stage suggesting that the protective mechanism a fetus uses during increased stress in second stage is already in action in acidotic fetuses at the end of first stage. Continuing further to the delivery the change in dynamics between this groups became larger.

Regarding the discrimination between healthy and acidotic fetuses, it was shown that failing to distinguish between the stages leads either to pessimistic or optimistic biases in performance estimation. This calls for two important methodological changes: First, the design of FHR features that would be robust to mixing of the two stages, though this might be impossible to devise since the detection of increased fetal stress is of major importance ; Second, the distinction of the two stages in the evaluation of FHRV.


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