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Linear and non-linear analysis of uterine contraction signals obtained with tocodynamometry in prediction of operative vaginal delivery

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Abstract

Objective: The aim of this study was to explore whether linear and non-linear analysis of uterine contraction (UC) signals obtained with external tocodynamometry can predict operative vaginal delivery (OVD).
Materials and methods: The last 2 h before delivery (H_1 and H_2) of 55 UC recordings acquired with external tocodynamometry in the labour ward of a tertiary care hospital were analysed. Signal processing involved the quantification of UCs/segment (UC_N), and the linear and non-linear indices: Sample Entropy (SampEn) measuring signal irregularity; interval index (II) measuring signal variability, both of which may be associated with uterine muscle fatigue, and high frequency (HF), associated with maternal breathing movements. Thirty-two women had normal deliveries and 23 OVDs. Statistical inference was performed using 95% confidence intervals (95% CIs) for the median, and areas under the receiver operating curves (auROCs), with univariate and bivariate analyses.
Results: A significant association was found between maternal body mass index (BMI) and UC signal quality in H_1, with moderate/poor signal quality being more frequent with higher maternal BMI. There was an overall increase in contraction frequency (UC_N), signal regularity (SampEn), signal variability (II), and maternal breathing (HF) from H_1 to H_2. The OVD group exhibited significantly higher values of signal irregularity and variability (SampEn and II) in H_1, and higher contraction frequency (UC_N) and maternal breathing (HF) in H_2. Modest auROCs were obtained with these indices in the discrimination between normal and OVDs.
Conclusions: The results of this exploratory study suggest that analysis of UC signals obtained with tocodynamometry, using linear and non-linear indices associated with muscle fatigue and maternal breathing, identifies significant changes occurring during labour, and differences between normal and OVDs, but their discriminative capacity between the two types of delivery is modest. Further refinement of this analysis is needed before it may be clinically useful.

Keywords: Cardiotocography; digital signal processing; entropy; operative vaginal delivery (OVD); spectral analysis.

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Introduction

Dystocia is defined as the slow or absent progression of labour, and is the most common indication for operative vaginal deliveries (OVDs) and caesarean section [1]. It is usually caused by abnormal patterns of uterine contractions (UCs) [2], and/or by mechanical obstruction to foetal progress due to the size of the foetus and maternal pelvis, the capacity of the cervix to dilate, or foetal presentation or position [2, 3]. Most situations of dystocia occur during the active phase of labour, which is generally defined as the period between 4 and 6 cm of cervical dilation to complete dilation. In normal labour, UCs during this phase occurs with increasing frequency, rhythm and strength [4, 5]. Monitoring of uterine activity is particularly important, as abnormal UC patterns are a major cause, as well as a consequence, of dystocia [4].

Several methods are available to monitor UCs: tocodynamometry using a mechanical sensor placed on the maternal abdomen, transabdominal electromyography evaluated by electrical sensors also placed on the maternal abdomen, or intrauterine pressure devices. The first is the most frequently used in routine clinical practice, due to its easy availability and non-invasive nature. However, it is associated with lower signal quality, particularly in obese patients [6, 7]. Electromyography is a recent technique that is not widely available in clinical practice [7–10]. Intrauterine pressure sensors are generally considered the most accurate method to monitor UC, but their invasive nature is associated with increased risks, they are more expensive, and there is lack of evidence that they are associated with improved labour outcomes [6, 7, 11].

Some studies report that the frequency and rhythm of UCs are good predictors of the type of delivery [4, 5]. However, in addition to the intrinsic contraction activity of the uterus, the tocodynamometer also captures foetal movements and respiratory movements of the pregnant woman. In this way, the use of linear and non-linear indices, which have proved to be useful in applications such as in foetal heart rate analysis, can also be considered in the analysis of the UC signal [12].

The aim of this exploratory study was to evaluate whether linear and non-linear analysis of UC signals obtained with tocodynamometry can be useful in the prediction of OVDs.

Materials and methods

An observational study was conducted, evaluating 55 UC recordings acquired between December 2008 and January 2013 at the Hospital Dr Nélio Mendonça, in Funchal, Portugal. The recordings were obtained from an equal number of women, during the last hours of labour, and had a median duration of 264 min (range 88–660 min). Participants satisfied the following inclusion criteria: gestational age equal or higher than 37 weeks, singleton pregnancy, cephalic presentation, cervical dilatation of 4–6 cm, spontaneous labour, maximum interval of 5 min between tracing-end and vaginal delivery, and absence of documented malformations. The dataset was divided into two major groups, according to the type of delivery: 32 cases of normal delivery and 23 cases of OVD. The latter were accomplished with vacuum or forceps, according to operator preference. The main maternal and foetal characteristics of the two groups are presented in Table 1.

UC signals were acquired using a conventional external tocodynamometer, placed on the maternal abdomen, linked to a STAN®31 foetal monitor (Neoventa, Gothemburg, Sweden). The UC signal was subsequently exported from the STAN monitor at a sampling rate of 4 Hz, via its RS232 port, to the Omniview-SisPorto® 3.5 system (Speculum, Lisbon, Portugal) for off-line analysis [13]. The hour-before-last (H_1) and the last-hour (H_2) of labour were analysed, and each hour was divided into 10-min segments. Segments that did not display contractions identified by the Omniview-SisPorto® system (due to signal loss), were considered as having poor signal quality and were excluded from further analysis (27 from H_1 and 15 in H_2, out of 330 segments from each hour).

Table 1: Main maternal and foetal characteristics of the normal and operative vaginal delivery (OVD) groups.

	Normal (n=32)	OVD (n=23)	P-value
Maternal data, median (min–max)			
Age (years)	28 (19–36)	28 (16–37)	0.277
Body mass index	26.6 (20.6–34.4)	27.9 (23.1–33.5)	0.500
Parity, n (%)			**0.004**
Nullipara	19 (59.4%)	22 (95.7%)	
Previous vaginal delivery	13 (40.6%)	1 (4.3%)	
Gestational age (weeks)	39.6 (37.0–41.0)	39.9 (37.6–41.3)	0.330
Epidural analgesia, n (%)	31 (96.9%)	22 (95.7%)	1.000
Vacuum/forceps (n)	–	12/11	–
Newborn data, median (min–max)			
Birthweight (g)	3160 (2400–4045)	3205 (2745–3875)	0.627
1 min Apgar	9 (9–10)	9 (7–10)	0.803
5 min Apgar	10 (9–10)	10 (9–10)	0.195
Umbilical artery blood pH	7.26 (7.05–7.37)	7.22 (7.11–7.34)	0.164
Newborn gender, n (%)			0.413
Male	15 (46.9%)	14 (60.9%)	
Female	17 (53.1%)	9 (39.1%)	

P-values <0.05 are presented in bold.

All the UCs identified by the Omniview-SisPorto® 3.5 system were quantified (UC_N), and three linear and non-linear indices were calculated [12]: "sample entropy (SampEn), interval index (II), and high frequency (HF).

SampEn is a non-linear index which quantifies signal irregularity [14], and is computed considering the embedding dimension (m) as 2, and the number of points (N) as 2400. The threshold parameter (r) was automatically computed as defined by Lu et al. [15]. The presence of higher irregularity has been reported in association with muscle fatigue [16].

Interval index, II is a linear index from the time-domain, which assesses short-term UC variability (STV) taking into account long-term variability, and is defined as in the following:

$$\mathrm{II}=\frac{\mathrm{STV}}{\mathrm{STD}[sm(i)]} \tag{1}$$

where

$$\mathrm{STV}=\frac{1}{24\mathrm{M}}\sum_{i=1}^{24\mathrm{M}}\left|sm(i+1)-sm(i)\right| \tag{2}$$

M is the number of minutes in the UC segment (10 in the present study), $sm(i)$ are values of the signal on each period of 2.5 s, and STD represents the standard deviation. Increased variability can also be associated with muscle fatigue.

HF is a linear index from the frequency-domain, which corresponds to the absolute value of the frequency component (area below the spectrum) in the range 0.15–0.40 Hz, and typically corresponds to maternal breathing [12]. The HF index was obtained from nonparametric spectral estimation, using the Welch method, with a Hanning window, applied in each segment over sequences of length 256 points, with 62.5% overlap.

The collected data were coded and analysed using the Statistical Package for the Social Sciences (SPSS Statistics 22.0) and MATLAB (MATLAB R2014b, Mathworks). Statistical inference was based on 95% bootstrap (B=1000) percentile confidence intervals (95% CIs) for the median, and nonparametric Mann-Whitney and Fisher statistical tests, with significance level set at $P<0.05$ [17, 18]. The ability of each index to predict OVD was determined using areas under the receiver operating curve (auROC), with corresponding 95% CIs, accomplished by the sensitivity (Sen) and specificity (Spe) associated with the point of the ROC closest (considering the Euclidean distance) to the optimum. The discrimination between normal and OVD groups in the bivariate analysis was performed using the Fisher linear discriminant analysis, for which Sen and Spe were computed based on whole points, as well as on the leave-one-out method (Sen_{LOO} and Spe_{LOO}) [17].

Results

The groups were matched for maternal and foetal characteristics, with the exception of parity which was lower in the operative delivery group (Table 1).

There were 42 women with a body mass index (BMI)<30 and 13 women with a BMI≥30. In H_1 there were 43 (78%) in which all 10-min segments had good signal quality, and in H_2 this occurred in only two cases (4%). A significant association was found between maternal BMI and UC signal quality in H_1, with moderate/poor signal quality being more frequent in cases with higher maternal BMI.

In both groups, there was an increase in UC_N, II, and HF from H_1 to H_2, denoting increases in UC rhythm, variability, and maternal breathing (Table 2). However, there was a decrease of SampEn from H_1 to H_2, denoting that the signal becomes more regular as delivery approaches. The OVD group exhibited significantly higher values of SampEn and II in H_1, denoting increased signal irregularity and greater variability, and higher values of UC_N and HF in H_2, reflecting increased UC rhythm and maternal breathing. The evolution of UC_N, SampEn, II and HF in each segment of H_1 and H_2 is presented in Figure 1.

The auROC values for predicting OVD, pertaining to the indices UC_N, SampEn, II, and HFn are presented in Figure 2, discriminated for each 10-min segment. The highest auROC achieved in H_1 was 0.641, and in H_2 0.734. The overlapping 95% CI obtained with these results does not allow any comparisons, and suggests a modest discriminative capacity of isolated indices.

With the combination of SampEn and HF, using Fisher linear discriminant analysis, the values of Sen and Spe obtained were respectively 66.7% and 71.0% (Sen_{LOO}=61.9% and Spe_{LOO}=71.0%) in the third segment of H_1, whereas combining UC_N and HF in the sixth segment of H_1, the values of Sen and Spe were respectively 71.4% and 40.0% (Sen_{LOO}=81.0% and Spe_{LOO}=50.0%).

Table 2: UC_N, SampEn, II, and HF in H_1 and H_2 for normal and operative vaginal delivery (OVD) groups.

UC	Normal			OVD			Normal vs. OVD	
Index	H_1	H_2	H_1 vs. H_2	H_1	H_2	H_1 vs. H_2	H_1	H_2
UC_N	3.0–4.0	4.0–4.0	**<0.001**	3.0–4.0	4.0–5.0	**<0.001**	0.171	**0.039**
SampEn	0.32–0.41	0.26–0.34	0.074	0.33–0.48	0.23–0.30	**<0.001**	**0.027**	0.220
II	0.17–0.20	0.21–0.24	**<0.001**	0.18–0.21	0.20–0.26	**0.004**	**0.040**	0.464
HF	2.07–3.16	3.76–6.54	**<0.001**	2.49–3.25	5.31–9.78	**<0.001**	0.371	**0.001**

Data are presented as 95% confidence intervals (95% CIs) for each group/hour. P-values<0.05 are presented in bold.

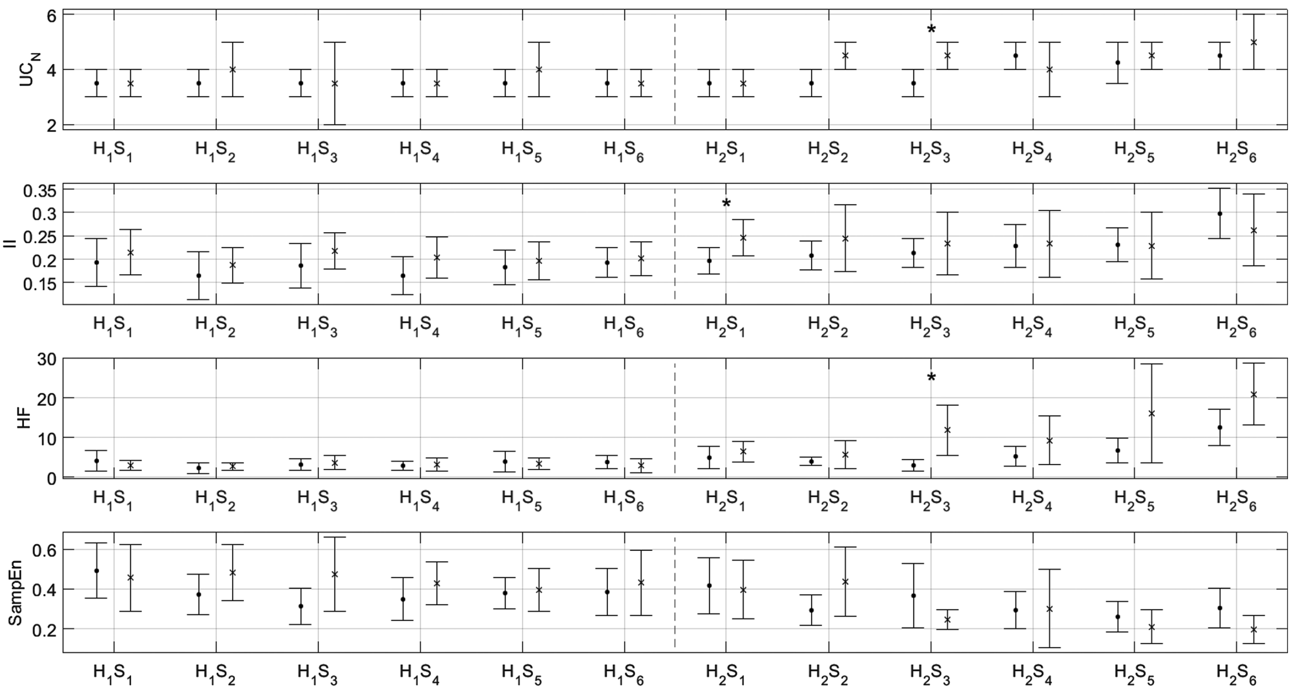

Figure 1: Evolution of the 95% CI pertaining to the indices UC_N, SampEn, II, and HF, throughout the segments S_i (i=1,…,6) of H_1 and H_2, for the normal (·) and OVD (x) groups. The vertical dashed lines correspond to the transition from H_1 to H_2. *P-value<0.05.

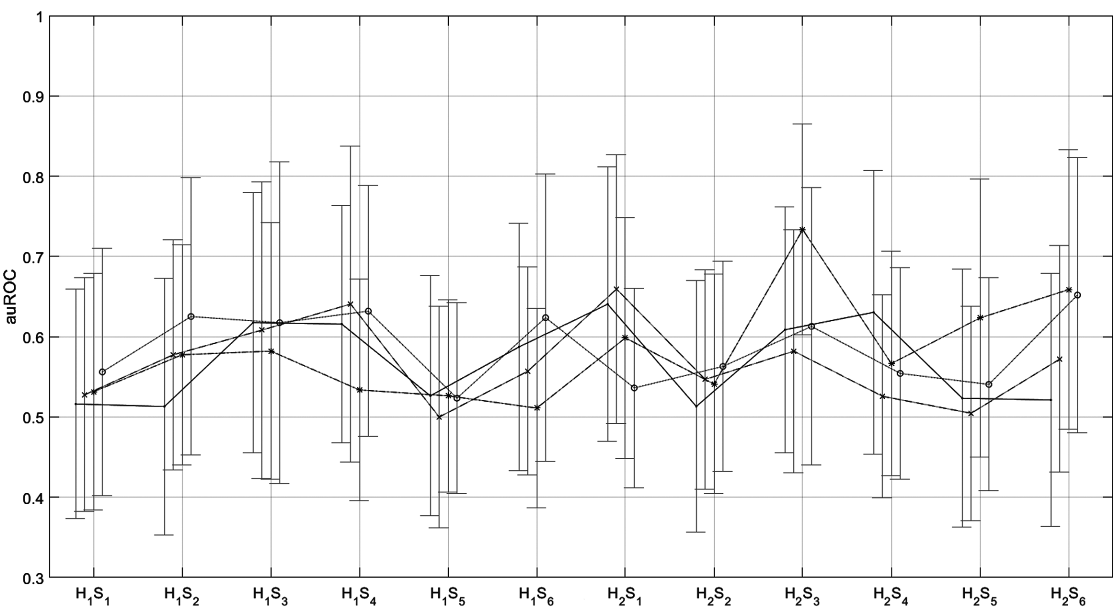

Figure 2: Areas under the ROC curves (auROC) and corresponding 95% CI, pertaining to UC_N (., solid line), SampEn (o, dotted line), II (x, dashed line) and HF (*, dash-dotted line), in the discrimination between normal and OVDs, throughout the 10-min segments S_i (i=1,…,6), in the last 2 h of labour (H_1 and H_2).

Discussion

To the best of our knowledge, this is the first study to evaluate UC signals acquired by external tocography in the prediction of OVD. Tocodynamometry is the main technology used for UC detection in current clinical practice, despite the well-known limitations associated with signal quality. In this study, women with higher BMI had lower signal quality, mostly in H_1. Possible reasons for this not occurring in H_2 are an increased attention of healthcare professionals to signal quality during the second stage of labour, and the greater strength of UCs in this period.

The increased parity seen in the normal delivery group was expected, and is in agreement with the well-known fact that nulliparous women are more frequently diagnosed with obstructed labour and therefore have increased operative delivery rates [3].

Oppenheimer et al. [5] demonstrated that UCs occur with increasing frequency and rhythm during the active phase of labour. These effects are more marked in labours that progress to vaginal delivery and are not clearly seen in caesarean sections. Our study showed an increasing frequency of UCs as delivery approaches, but also increased maternal breathing, greater signal variability, and regularity.

The increased signal irregularity (SampEn) and variability (II) in OVDs observed in H_1 but not H_2, suggests that instrument application and traction during H_2-corrected uterine muscle fatigue. However, increased contraction frequency (UC_N) and maternal breathing (HF) were significantly higher for OVD in H_2, suggesting that instrumentation increases these parameters. An important limitation of this study is the lack of information on the exact timing of application of instrumental delivery.

Another limitation of the present study is the small sample size, which may explain the lack of statistical significance in the auROC comparisons. However, the study was only intended to be exploratory in nature and to evaluate the potential use of such analyses. In the ROC analysis, SampEn and II provided a reasonable discrimination of OVD in H_1, suggesting that normalised STV and signal irregularity may give warning of obstructed labour with some time in advance, and this could be a simpler clinical alternative to lactate measurement in the amniotic fluid [19]. Bivariate analysis of the results, performed with Fisher linear discriminant analysis, suggests that the combination of indices may improve overall accuracy in prediction of OVDs but further refinement is required before this analysis may be clinically useful.

Conclusions

Analysis of UC signals obtained with tocodynamometry, using linear and non-linear indices that are associated with muscle fatigue (SampEn and II) and maternal breathing (HF) showed that significant changes occur during labour, and differences exist between normal and OVDs, but their discriminative capacity between the two types of delivery is modest. Further refinement of this analysis is needed before it may be clinically useful.

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Conflict of interest statement: Diogo Ayres-de-Campos and João Bernardes have been involved in the development of the Omniview-SisPorto® system for FHR analysis (Speculum, Portugal). Royalties are fully converted to institutional research funds.

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