Prediction of labour outcomes using prelabour computerised cardiotocogram and maternal-foetal Doppler indices: A prospective cohort study

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May 11, 2023

Abstract

Objectives: To investigate the association and the potential value of prelabour fetal heart rate short-term variability (STV) determined by computerised cardiotocography (cCTG) and maternal-foetal Dopplers in predicting labour outcomes. **Design:** Prospective cohort study. **Setting:** The Prince of Wales Hospital, a tertiary maternity unit, in Hong Kong SAR. **Population:** Women with a term singleton pregnancy in latent phase of labour or prior to labour induction were recruited during May 2019 – November 2021. **Methods:** Ultrasonographic assessment of foetal growth, Doppler velocimetry and the cCTG monitoring including Dawes-Redman CTG analysis. **Main Outcome Measures:** Umbilical Cord arterial pH, emergency delivery due to pathological CTG during labour and neonatal intensive care unit (NICU)/special care baby unit (SCBU) admission. **Results:** Of the 400 cases, 34 (8.5%) women underwent emergency delivery for pathological CTG during labour. A total of 6 (1.50%) and 148 (37.00%) newborns required NICU and SCBU admission, respectively. Middle cerebral artery pulsatility index (MCA-PI) and MCA-PI z-score were significant lower in pregnancies that required emergency delivery for pathological CTG during labour compared with those who did not [1.23 (1.07-1.40) vs 1.40 (1.22-1.64), p=0.002 and 0.55 (±1.07) vs 0.12 (±1.06), p=0.049,]. Umbilical cord arterial pH was associated with STV (r = 0.107, p = 0.035) and the independent predictors for umbilical cord arterial pH were smoking (p = 0.006) and STV (p = 0.025). **Conclusions:** In pregnant women admitted in latent phase of labour or for induction of labour at term, cCTG STV is associated with umbilical cord arterial pH but not predictive of emergency delivery due to pathological CTG during labour.

Introduction

Cardiotocography (CTG), also referred to as electronic foetal monitoring (EFM), is the most widely used non-invasive foetal heart rate (FHR) monitoring before and during labour [1, 2]. Foetal hypoxia and acidosis could be detected primarily through the recognition of specific patterns on the CTG signal (e.g., decelerations)[3-5]. These CTG patterns, however, are difficult for human visual interpretation to reliably and consistently identify[1, 6, 7]. It is well-established that subjective assessment of the CTG patterns suffers from poor inter-observer and intra-observer reproducibility [1, 8-13] and is associated with increased operative vaginal delivery and Caesarean section rates without improving perinatal outcomes [14, 15]. Computerised cardiotocography (cCTG) has been considered to be superior to conventional CTG as this approach provides more reliable and consistent interpretation of the CTG tracing [1, 2, 16, 17]. Based on specific criteria of Dawes-Redman system, cCTG enables quantitative and objective evaluation of the foetal state[1, 2]. Results from earlier studies comparing human visual analysis and computerised analysis of FHR tracing supported the idea that computerised analysis could overcome the subjectivity of visual interpretation of FHR tracing [18, 19].

Short-term variation (STV) is the measurement of beat-to-beat variation in the FHR over a very short

time scale provided by cCTG[20]. A study demonstrated that the risk of metabolic acidaemia increased as the antepartum cCTG STV decreased; at the optimal cut-off level at 3.0 milliseconds or less, the positive and negative predictive values were 64.6% and 86.6%, respectively[21]. The Dawes-Redman approach has the advantages of enabling objective evaluation of cCTG STV and analyzing the CTG trace with information on foetal movements, presence of sinusoidal patterns, and quality of the electronic tracing [1]. It has been observed that there is increasing use of cCTG for the evaluation of foetal wellbeing especially for high-risk cases, including those with foetal growth restriction (FGR) and preeclampsia [2, 16, 22]. As such, the International Society of Ultrasound in Obstetrics and Gynecology (ISUOG) has integrated the use of cCTG STV in a recent guideline for the monitoring and management of pregnancies with FGR[22].

Doppler velocimetry by examining the uterine artery pulsatility index (UtA-PI), umbilical artery pulsatility index (UA-PI), middle cerebral artery pulsatility index (MCA-PI) and cerebroplacental ratio (CPR) (which is the ratio between MCA-PI and UA-PI), can evaluate uteroplacental function and allow for the detection of uteroplacental insufficiency [23-26]. These Doppler indices are important in the diagnosis, monitoring, and management of high-risk pregnancies especially for those with FGR [22, 27-29]. In addition, evidence shows that monitoring and delivery timing according to a specific protocol including Doppler indices and cCTG provide better-than-expected outcomes for fetuses diagnosed with FGR[30].

Despite solid evidence supporting the use of cCTG and Doppler velocimetry in the management of pregnancies complicated with FGR, there is a scarcity of data on the clinical utility of cCTG and Doppler velocimetry in pregnancies in other clinical scenarios, such as during latent phase of labour or before induction of labour. This study aimed to investigate the relationship and the potential value of prelabour maternal-foetal Dopplers and cCTG STV in predicting labour outcomes including umbilical cord arterial pH, emergency delivery due to pathological CTG during labour and neonatal intensive care unit (NICU)/special care baby unit (SCBU) admission.

Methods

This is a prospective cohort study in pregnant women with a term singleton pregnancy in latent phase of labour or prior to labour induction at the Prince of Wales Hospital, Hong Kong SAR. This series is an expansion from the initial study of 218 cases who delivered at our hospital between May 2019 and December 2019 [16]. The gestational age was calculated using the first date of the last menstrual period and confirmed by the measurement of foetal crown-rump length in the first trimester or head circumference in the second trimester [31]. The entry criteria were a live fetus in cephalic presentation between 37 complete weeks and 41 weeks 6 days of gestation, either in the latent phase of labour or due to undergo induction of labour. Women who were unconscious or severely ill, women with learning disabilities or serious mental illnesses, women in labour with cervical dilatation of 3 cm or more or when the estimated foetal weight (EFW) was greater than 4.2 Kg where elective Caesarean delivery is offered in our institute were excluded. The women who agreed to participate in the study provided written informed consent, which was approved by the Institutional Review Board (Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee, Reference Numbers CRE-2017.608).

The ultrasonographic assessment of foetal growth, amniotic fluid volume, placental location and Doppler velocimetry was performed transabdominally using convex 2D 1-5 MHz probe of Voluson E6 (GE Healthcare, Austria) or convex 2D 2-6 MHz probe Affiniti 50W (Philips Healthcare, Amsterdam, Netherlands) by one of the five obstetricians with at least three years of expertise in obstetric ultrasound (MSNL, SM, AHWK, STKW, AWTT). The Hadlock model 3 was used to estimate foetal size based on measurements of head circumference, abdominal circumference, and femur length [32]. The UA-PI was measured from a free-floating section of the umbilical cord, while the MCA-PI was measured from the proximal third of the vessel, taking care not to compress the foetal head with the transducer. The UtA-PI was measured within 1 cm of the crossing of the uterine artery with the external iliac artery adopting a similar technique as previously described for measuring the UtA-PI by the transabdominal approach during the second trimester of pregnancy [33, 34]. The pulsatility indices from the right and left uterine arteries were measured and the mean UtA-PI was calculated. During foetal quiescence, all foetal parameters including biometry and Doppler indices were

measured in triplicate, with averages recorded. The CPR was calculated as the ratio of MCA-PI to the UA-PI.

After the ultrasound evaluation, the participants had cCTG monitoring for at least 60 minutes using the Sonicaid Team 3 Foetal Monitor, which includes Dawes-Redman CTG analysis, together with the Sonicaid Centrale Huntleigh software (Huntleigh Healthcare Ltd, Wales, United Kingdom). The Dawes-Redman CTG analysis is a software that interprets the CTG trace numerically based on the Dawes-Redman criteria. If all the criteria are met, the software will perform the first analysis after 10 minutes of CTG tracing. If all the criteria are not met, the recording and analysis continue to evaluate every 2 minutes until all criteria are met, or until a maximum of 60 minutes. "Dawes-Redman criteria not met" will be used to describe the CTG tracing only after 60 minutes of monitoring. The participants were instructed to use an event marker button to record foetal movements. If there were unsatisfactory CTG findings based on conventional visual assessment during the tracing, on-call obstetricians were notified, and the participant was managed in accordance with our internally published and agreed-upon departmental protocol. Participants with CTG tracing duration of less than 60 minutes were not included in the statistical analysis.

During labour, the attending midwives and obstetricians were blinded to the ultrasonographic Doppler and cCTG findings, except when absent/reversed end diastolic flow in the UA was detected. The research team as well as midwives and obstetricians were also blinded to the cCTG findings to reduce bias. Induction of labour and intrapartum care were both carried out in accordance with hospital departmental protocol and practice. An experienced obstetrician determined the Bishop score. If the cervix was favourable (Bishop score [?]6), labour was induced with amniotomy followed by oxytocin. If the cervix was unfavourable (Bishop score <6), 10 mg Dinoprostone slow-release vaginal pessary (Propess?, Ferring Pharmaceuticals, Saint-Prex, Switzerland) was used to induce labour. Women with an unfavourable cervix were reassessed 24 hours later; if the cervix remained unfavourable, another Propess? was administered, and if the cervix was favourable, an amniotomy was performed. If the woman remained in the latent phase after 12 hours of oxytocin infusion, or if the cervix failed to dilate at a rate [?]1 cm/hour for [?]2 hours when the cervix was >4 cm dilated, a Caesarean delivery was indicated due to lack of labour progress. The attending obstetricians will interpret the CTG during active labour, and further management, including instrumental or Caesarean delivery, would be carried out in accordance with the department protocol based on their clinical assessment and evaluation. The presence of recurrent variable or late decelerations and/or reduced variability was used to identify pathological CTG [3, 35].

Data on maternal and pregnancy characteristics, including age, weight, height, racial origin, smoking, parity and gestational age, indications for induction, pregnancy, and labour outcomes, such as mode of delivery, birth weight, umbilical cord arterial pH and base excess, Apgar scores at 1 and 5 minutes, and NICU/SCBU admission, were obtained from computerised medical records and entered the secure research database.

Patient involvement

A total of 400 consecutive women with a singleton pregnancy who delivered at the Prince of Wales Hospital maternity unit, Hong Kong SAR between May 2019, and November 2021 were enrolled to the study. They provided informed consent before undergoing ultrasonographic and cCTG assessment.

Statistical analysis

Logarithmic$_{10}$ transformation of variables was performed prior to statistical analysis, when necessary, then the Kolmogorov-Smirnov test was used to determine whether the data were parametric. Parametric continuous variables were presented in mean and standard deviation (SD) while nonparametric continuous variables were presented in median and interquartile range (IQR). Count and percentage were used to present categorical variables. The following variables were reported as z-scores corrected for gestational age: EFW, birth weight, UA-PI, MCA-PI, CPR, and UtA-PI. Relationship between EFW z-score, UA-PI z-score, MCA-PI z-score, CPR z-score, UtA-PI z-score, $\log_{10}$ cCTG STV, and umbilical cord arterial pH was determined using Pearson correlation analysis. To determine which of the maternal characteristics, labour onset, indications of induction of labour, EFW z-score, maternal-foetal Doppler indices, $\log_{10}$ cCTG STV,

and Dawes-Redman criteria were significant predictors of umbilical cord arterial pH, univariate linear regression analysis was used. To identify the variables that were independent predictors of umbilical cord arterial pH, predictors with a p value of < 0.1 were included in a multivariate linear regression analysis with forward selection. Univariate and multivariate logistic regression analyses were used to determine whether which of the study factors mentioned above were significant predictors of umbilical cord arterial pH < 7.1 and NICU/SCBU admission. The statistical software package SPSS 20.0 (IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp) was used for data analyses.

Results

Amongst the 400 consecutive pregnant women, 103 (25.75%) were enrolled during the latent phase of labour and 297 (74.25%) were enrolled prior to induction of labour. The most common indication for labour induction was spontaneous ruptured of membranes (31.99%). Median (IQR) of gestational age at enrollment was 39.57 (38.43–40.57) weeks and 63.25% of women were nulliparous. There were no cases with absent/reversed end diastolic flow in the umbilical artery. A total of 6 (1.50%) and 148 (37.00%) newborns required NICU and SCBU admission, respectively. Characteristics of the study population regarding NICU/SCBU admission of the newborns are summarised in *Table S1* .

Of these participants, 34 (8.5%) women had emergency delivery due to pathological CTG during labour, 12 (3.0%) and 22 (5.5%) women were delivered by emergency Caesarean section and emergency operative vaginal delivery, respectively. The maternal demographic and pregnancy characteristics between cases requiring emergency delivery due to pathological CTG during labour and those that did not are summarised in**Table 1** . Women who required emergency delivery due to pathological CTG during labour, compared to those that did not, had significantly lower MCA-PI, MCA-PI z-score, Apgar scores at 1 and 5 minutes as well as umbilical cord arterial pH and base excess. On the other hand, there were higher rates of umbilical cord arterial pH < 7.1 and NICU admission. There were no differences in other parameters among maternal and labour characteristics, maternal-foetal Doppler indices, cCTG parameters and birth outcomes observed between these two groups.

Umbilical cord arterial pH was associated with $\log_{10}$cCTG STV (r = 0.107, p = 0.035) but not EFW z-score and maternal-foetal Doppler velocimetry. Whereas there was no correlation between these prelabour parameters (EFW z-score, maternal-foetal Doppler velocimetry and $\log_{10}$ cCTG STV) and umbilical cord arterial base excess as presented in *Table S2* and *Table S3* . Multivariate regression analysis demonstrated that significant independent predictors for umbilical cord arterial pH were $\log_{10}$ cCTG STV (p = 0.025) and smoking (p = 0.006) with$R^2 = 0.031$ (***Table 2***) . Logistic regression analysis demonstrated that none of these prelabour parameters were predictive for emergency delivery due to pathological CTG during labour and umbilical cord arterial pH < 7.1(***Table 4*** and *Table S5*) . Nonetheless, nulliparity, maternal diabetes (pre-existing or gestational diabetes mellitus) and EFW z-score were associated with an increased risk of NICU/SCBU admission (***Table 3***) .

Discussion

Main findings

The study has demonstrated that; firstly, MCA-PI and MCA-PI z-score are significant lower in pregnancies that require emergency delivery for pathological CTG during labour compared with those who do not; secondly, the umbilical cord arterial pH significantly correlates with $\log_{10}$ cCTG STV, whilst none of the study parameters correlates with umbilical arterial cord base excess; thirdly, smoking and $\log_{10}$ cCTG STV are independent predictors of umbilical cord arterial pH; fourthly, nulliparity, maternal diabetes and EFW z-score are independent predictors of NICU/SCBU admission; and lastly, none of the factors amongst maternal characteristics, labour onset, indications of labour induction, EFW z-score, maternal-foetal Doppler indices, $\log_{10}$ cCTG STV and Dawes-Redman criteria by cCTG is predictive of emergency delivery due to pathological CTG during labour and umbilical cord arterial pH <7.1.

Strengths

Currently there is a limited number of prospective studies examining the relation between umbilical cord arterial pH and labour outcome in a cohort of women with term pregnancy and prelabour maternal-foetal Dopplers, cCTG STV, and Dawes-Redman criteria. The strengths of this study are the extensive evaluation of various maternal and labour characteristics, maternal-foetal Doppler velocimetry and FHR parameters to predict birth outcomes and the demonstration of the correlation between cCTG STV and umbilical cord arterial pH. Another strength is the ability to blind clinicians, midwives, and researchers to the results of the Doppler indices and the cCTG, thus the findings of the Doppler and cCTG assessment did not influence the management of labour.

Limitations

This is a small single centre study with a relatively small number of emergency deliveries due to pathological CTG during labour. Furthermore, despite a high rate of SCBU/NICU admission, the majority of these newborns were admitted to SCBU and the total number of NICU admission was low. Further randomised controlled trial to investigate the benefits of prelabour and intrapartum cCTG parameters in predicting labour outcome in both high-risk and low-risk pregnancy are needed but large prospective multicentre studies would be required.

Interpretation

Despite the association between abnormal conventional CTG and poor perinatal outcomes, the use of CTG has not been shown to improve perinatal outcomes [1, 16]. In an attempt to overcome the disadvantages of traditional CTG monitoring, the cCTG, which is an advanced electronic assessment of FHR, has been introduced. The clinical usefulness of the cCTG as a routine prelabour screening technique for foetal well-being remains debatable. Our initial study demonstrated that admission maternal-foetal Doppler indices, cCTG STV and Dawes-Redman criteria were not predictive of composite neonatal morbidity. However, we demonstrated a significant correlation between mean UtA-PI and umbilical cord arterial base excess but not pH, suggesting the former might be a better reflection of placental reserve/function during labour. Further, it was observed that there was a trend toward a reduction in composite neonatal morbidities (arterial cord blood pH $<$ 7.1, base excess [?] -12 mmol/L, Apgar score [?] 5 at 5 min and/or NICU admission) with increasing $\log_{10}$ cCTG STV (odds ratio, 0.074; 95%CI, 0.005–1.128, p = 0.061)[16].

In the current study, the finding that there was a significant positive correlation between $\log_{10}$ cCTG STV and umbilical cord arterial pH agrees with a previous study by Bellver *et al* .[36]. There was no association between $\log_{10}$ cCTG STV and emergency delivery due to pathological CTG during labour (n = 34) and between $\log_{10}$ cCTG STV and umbilical cord arterial pH $<$ 7.1 (n = 10) which could be attributed to the low rates of these two outcomes. Women who required emergency delivery due to pathological CTG during labour, compared to those that did not, had significantly lower MCA-PI and MCA-PI z-score. These findings may represent foetal cerebral vasodilatation, a haemodynamic response to foetal hypoxaemia to increase blood supply to the brain (known as the brain sparing effect). As expected, neonatal outcomes were poorer in newborns that required emergency delivery due to pathological CTG during labour. In this study, 40% and 83% of emergency deliveries due to pathological CTG during labour had umbilical cord arterial pH $<$7.1 and required NICU admission, respectively. There was also a significant negative correlation between umbilical cord arterial pH and smoking; however, direct effect of smoking on umbilical cord arterial pH has not been previously demonstrated. Oncken et al. reported no difference between umbilical cord arterial pH between smokers and non-smokers. Whilst Tarasi et al. reported that smoking appeared to be a protective factor for umbilical cord arterial pH $<$ 7.1[37]. Chronic or acute hypoxia and the presence of carbon monoxide in the maternal circulation from smoking could result in altered oxygen delivery and be harmful to the fetus[38]. Nonetheless, the correlation between smoking and umbilical cord arterial pH needs further exploration.

The predictors for NICU/SCBU admission were nulliparity, maternal diabetes and EFW z-score; with the latter two being related to neonatal hypoglycemia in pregnancies complicated by maternal diabetes. Increased maternal BMI also demonstrated a tendency toward increasing the risk of NICU/SCBU admission, although it was not statistically significant. This finding may emphasise the importance of adequate glycemic control

during pregnancy. While nulliparous women are more likely to have a longer labour and labour complications compared to parous women[39], as a result, their infants have an increased risk of NICU/SCBU admission.

Our findings are comparable to that of a study by Fratelli et al. which demonstrated no predictive value of pre-induction maternal-foetal Doppler indices (z-scores of UtA-PI, UA-PI, and MCA-PI) for operative delivery for intrapartum foetal compromise or umbilical cord arterial pH < 7 in a cohort of appropriately grown fetuses undergoing induction of labour in an unselected population [40]. Pre- or early labour assessment of maternal-foetal Dopplers, $\log_{10}$ cCTG STV, and Dawes-Redman criteria may not be reliable tools to either predict or exclude intrapartum acidosis and ensure a favourable labour outcome. These findings could be explained by the fact that labour outcome is influenced by several intrapartum events and variable foetal response to intrauterine stress.

Conclusions: In consecutive women with singleton pregnancy admitted during latent phase of labour or for induction of labour at term, MCA-PI, and MCA-PI z-score are significant lower in pregnancies that require emergency delivery for pathological CTG during labour compared with those who do not. cCTG STV is associated with umbilical cord arterial pH but not predictive of emergency delivery due to pathological CTG during labour. None of the factors amongst maternal characteristics, labour onset, indications of labour induction, EFW, maternal-foetal Doppler indices, cCTG STV and Dawes-Redman criteria by cCTG is predictive for umbilical cord arterial pH < 7.1 and emergency delivery due to pathological CTG during labour. This study has demonstrated that unfavourable labour outcomes cannot be anticipated by routine prelabour maternal-foetal Doppler velocimetry and cCTG assessment, thus further research is necessary to identify potential predictors of labour outcomes.

Table 1. Characteristics of the study population regarding emergency delivery due to pathological CTG during labour status

Characteristics	**No emergency delivery due to pathological CTG during labour (n= 366)**	**Emergency delivery due to pathological CTG during labour (n=34)**	**p value**	**p value**
Maternal age (years)	32.44 (±4.89)	32.50 (±4.38)	0.910	0.910
Maternal weight (Kg)	56.40 (51.20-62.20)	53.70 (50.85-60.50)	0.518	0.518
Log_{10} maternal weight	1.76 (±0.07)	1.75 (±0.07)	0.689	0.689
Maternal height (cm)	159.00 (156.00-163.00)	158.00 (154.50-162.00)	0.181	0.181
Log_{10} maternal height	2.20 (±0.02)	2.19 (±0.01)	0.158	0.158
Maternal BMI (Kg/m^2)	22.29 (20.29-24.72)	21.75 (20.54-24.06)	0.745	0.745
Log_{10} BMI	1.35 (±0.06)	1.35 (±0.07)	0.781	0.781
Gestational age (weeks)	39.48 (±1.17)	39.79 (±2.11)	0.165	0.165
Smoking	7 (1.92; 0.51-3.34)	2 (5.88; -2.45-14.22)	0.138	0.138
Chinese Asian	357 (97.54; 95.95-99.14)	33 (97.06; 91.08-103.04)	0.863	0.863
Nulliparous	227 (62.02; 57.03-67.02)	26 (76.47; 61.45-91.49)	0.095	0.095

Characteristics	No emergency delivery due to pathological CTG during labour (n= 366)	Emergency delivery due to pathological CTG during labour (n=34)	p value	p value
Induction of labour	271 (74.04; 69.53-78.56)	26 (76.47; 61.45-91.49)	0.757	0.757
Indications for labour induction	**Indications for labour induction**	**Indications for labour induction**	**Indications for labour induction**	
Postdate Diabetes (preexisting or GDM) Hypertension Decrease FM/ Suboptimal CTG Large or small for gestational age SROM	68 (18.60; 14.58-22.58) 23 (6.28;3.79-8.78) 10 (2.73; 1.05-4.41) 30 (8.20; 5.37-11.02) 37 (10.11; 7.01-13.21) 86 (23.50; 19.13-27.86)	9 (26.47; 10.85-42.10) 1 (2.94; -3.24-8.92) 2 (5.88; -2.45-14.22) 6 (17.64; 4.15-31.15) 2 (5.88; -2.45-14.22) 9 (26.47; 10.85-42.10)	0.264 0.432 0.303 0.065 0.427 0.697	0.264 0.432 0.303 0.065 0.427 0.697
Estimated foetal weight (g)	3177 (2923-3379)	3254 (3163-3426)	0.110	0.110
Estimated foetal weight (z-score)	0.12 (±1.33)	0.35 (±1.92)	0.195	0.195
Umbilical artery PI	0.80 (0.68-0.91)	0.72 (0.68-0.84)	0.144	0.144
Umbilical artery PI z-score	0.14 (±0.86)	-0.00 (±0.86)	0.308	0.308
Middle cerebral artery PI	1.40 (1.22-1.64)	1.23 (1.07-1.40)	0.002*	0.002*
Middle cerebral artery PI z-score	0.12 (±1.06)	0.55 (±1.07)	0.049*	0.049*
Cerebroplacental ratio	1.78 (1.51-2.13)	1.64 (1.33-0.90)	0.102	0.102
Cerebroplacental ratio z-score	-0.21 (±0.97)	-0.41 (±1.00)	0.465	0.465
Mean uterine artery PI	0.74 (0.63-0.90)	0.68 (0.58-0.78)	0.060	0.060
Mean uterine artery PI z-score	0.75 (±1.46)	0.27 (±1.34)	0.092	0.092
Short term variability	8.10 (6.50-9.70)	7.75 (6.90-9.30)	0.899	0.899
Log_{10} short term variability (ms)	0.90 (±0.13)	0.89 (±0.13)	0.815	0.815
Dawes-Redman criteria not met	31 (8.49; 5.62-11.37)	4 (11.76; 0.35-23.18)	0.519	0.519
Birth weight (g)	3200 (2990-3440)	3135 (2920-3415)	0.576	0.576
Birth weight z-score	-0.00 (±0.74)	-0.16 (±0.70)	0.218	0.218
Apgar score at one minute	8.77 (±0.67)	7.82 (±1.64)	<0.001*	<0.001*

Characteristics	**No emergency delivery due to pathological CTG during labour (n= 366)**	**Emergency delivery due to pathological CTG during labour (n=34)**	**p value**	**p value**
Apgar score at five minutes	9.81 (±0.44)	9.35 (±1.30)	<0.001*	<0.001*
Umbilical cord arterial parameters				
Umbilical cord arterial pH	7.25 (7.20-7.30)	7.21 (7.15-7.29)	0.017	0.017
Umbilical cord arterial pH < 7.1	6 (1.68; 0.34-3.01)	4 (12.5; 0.39-24.61)	<0.001*	<0.001*
Arterial base excess [**?**] -12 mmol/L	14 (3.91; 1.89-5.93)	6 (18.75; 4.45-33.05)	<0.001*	<0.001*
NICU admission	1 (0.27; -0.26-0.81)	5 (14.71; 2.16-27.25)	<0.001*	<0.001*
SCBU admission	133 (36.34; 31.34-41.29)	15 (44.12; 26.53-61.70)	0.369	0.369

Characteristics	**No emergency delivery due to pathological CTG during labour (n= 366)**	**Emergency delivery due to pathological CTG during labour (n=34)**	**p value**	**p value**
Statistically significant at p<0.05; NICU, neonatal intensive care unit, SCBU; special care baby unit; Kg, kilogram; cm, centimeter; BMI, body mass index; GDM, gestational diabetes mellitus; FM, foetal movement; CTG, cardiotocography; SROM, spontaneous rupture of membranes; g, gram; PI, pulsatility index; ms, millisecond; mmol/L, millimoles per liter. Numerical variables presented in median (interquartile range) or mean (standard deviation). Categorical variables presented in n (%: 95% confidence interval)	* Statistically significant at p<0.05; NICU, neonatal intensive care unit, SCBU; special care baby unit; Kg, kilogram; cm, centimeter; BMI, body mass index; GDM, gestational diabetes mellitus; FM, foetal movement; CTG, cardiotocography; SROM, spontaneous rupture of membranes; g, gram; PI, pulsatility index; ms, millisecond; mmol/L, millimoles per liter. Numerical variables presented in median (interquartile range) or mean (standard deviation). Categorical variables presented in n (%: 95% confidence interval)	* Statistically significant at p<0.05; NICU, neonatal intensive care unit, SCBU; special care baby unit; Kg, kilogram; cm, centimeter; BMI, body mass index; GDM, gestational diabetes mellitus; FM, foetal movement; CTG, cardiotocography; SROM, spontaneous rupture of membranes; g, gram; PI, pulsatility index; ms, millisecond; mmol/L, millimoles per liter. Numerical variables presented in median (interquartile range) or mean (standard deviation). Categorical variables presented in n (%: 95% confidence interval)	* Statistically significant at p<0.05; NICU, neonatal intensive care unit, SCBU; special care baby unit; Kg, kilogram; cm, centimeter; BMI, body mass index; GDM, gestational diabetes mellitus; FM, foetal movement; CTG, cardiotocography; SROM, spontaneous rupture of membranes; g, gram; PI, pulsatility index; ms, millisecond; mmol/L, millimoles per liter. Numerical variables presented in median (interquartile range) or mean (standard deviation). Categorical variables presented in n (%: 95% confidence interval)	

Table 2. Linear regression analysis for the prediction of umbilical cord arterial pH

Independent variable	**Univariate Correlation coefficient (95% CI)**	*p* **value**	**Multivariate Correlation coefficient (95% CI)**	*p* **value**
Maternal age	0.001 (-0.001 to 0.003)	0.185		
Log_{10} maternal weight	0.092 (-0.021 to 0.205)	0.109		
Log_{10} maternal height	0.167 (-0.324 to 0.658)	0.504		
Log_{10} maternal body mass index	0.079 (-0.039 to 0.197)	0.190		
Smoking	-0.067 (-0.117 to -0.018)	0.008	-0.070 (-0.120 to -0.021)	0.006*
Nulliparity	-0.014 (-0.030 to 0.001)	0.073		
Near-postdate	-0.022 (-0.041 to -0.003)	0.025		
Diabetes	0.034 (0.002 to 0.065)	0.035	0.030 (-0.001 to 0.061)	0.054
Hypertension	0.022 (-0.027 to 0.071)	0.378		
Large or small for gestational age	0.013 (-0.012 to 0.039)	0.304		
Decrease FM/ Suboptimal CTG	0.010 (-0.017 to 0.037)	0.466		
Estimated foetal weight z-score	0.003 (-0.002 to 0.008)	0.284		
Umbilical artery PI z-score	4.746E-5 (-0.009 to 0.009)	0.992		
Middle cerebral artery PI z-score	-0.001 (-0.008 to 0.006)	0.774		
Cerebroplacental ratio z-score	0.001 (-0.007 to 0.008)	0.871		
Mean uterine artery PI z-score	0.003 (-0.003 to 0.008)	0.335		
Log_{10} short term variability	0.063 (0.005 to 0.121)	0.035	0.066 (0.008 to 0.124)	0.025*
Dawes-Redman criteria not met	-0.002 (-0.028 to 0.024)	0.876		

* Statistically significant at p<0.05; FM, foetal movement; CTG, cardiotocography; PI, pulsatility index

Table 3. Logistic regression analysis for the prediction of NICU/SCBU admission

Independent variable	**Univariate**	*p* **value**	**Multivariate**	*p* **value**
	Odd ratio (95% CI)		**Adjusted Odd ratio (95% CI)**	
Maternal age	1.022 (0.980 - 1.067)	0.304		

Independent variable	**Univariate**	***p* value**	**Multivariate**	***p* value**
Log_{10} maternal weight	6.821 (0.326 - 142.890)	0.216		
Log_{10} maternal height	0.000 (0.000 - 35.983)	0.152		
Log_{10} maternal body mass index	23.257 (0.943 - 583.582)	0.054	9.593 (0.354 - 259.648)	0.179
Smoking	2.035 (0.538 - 7.701)	0.295		
Nulliparity	2.842 (1.807- 4.469)	<0.001	3.212 (2.009 - 5.136)	<0.001*
Postdate	1.024 (0.615 -1.706)	0.926		
Diabetes	2.842 (1.212 - 6.665)	0.016	2.707 (1.091 - 6.718)	0.032*
Hypertension	0.793 (0.235 - 2.680)	0.709		
Large or small for gestational age	1.590 (0.819 - 3.087)	0.170		
Decrease FM / Suboptimal CTG	0.782 (0.379 - 1.613)	0.505		
Estimated foetal weight z-score	1.189 (1.024 - 1.380)	0.023	1.227 (1.044 - 1.444)	0.013*
Umbilical artery PI z-score	0.828 (0.661 - 1.061)	0.142		
Middle cerebral artery PI z-score	1.173 (0.967 - 1.424	0.105		
Cerebroplacental ratio z-score	0.955 (0.776 - 1.174)	0.659		
Mean uterine artery PI z-score	0.960 (0.832 - 1.107)	0.573		
Log_{10} short term variability	0.865 (0.180 - 4.151)	0.857		
Dawes-Redman criteria not met	0.935 (0.456 - 1.915)	0.853		

* Statistically significant at p<0.05; FM, foetal movement; CTG, cardiotocography; PI, pulsatility index

Table S1. Characteristics of the study population regarding NICU/SCBU admission of the newborns

Characteristics
Maternal age (years)
Maternal weight (Kg)
Maternal height (cm)
Maternal BMI (Kg/m^2)
Gestational age (weeks)
Smoking
Chinese Asian
Nulliparous
Induction of labour
Indications for labour induction
Postdate Diabetes (preexisting or GDM) Hypertension Decrease FM/ Suboptimal CTG Large or small for gestational age S
Estimated foetal weight (g)
Estimated foetal weight (z-score)

Characteristics
Umbilical artery PI
Middle cerebral artery PI
Cerebroplacental ratio
Mean uterine artery PI
Short term variability (ms)
Dawes-Redman criteria not met
Spontaneous vaginal delivery
Caesarean delivery
Operative vaginal delivery
Birth weight (g)
Birth weight z-score
Apgar score at one minute
Apgar score at five minutes
Umbilical cord arterial pH
Umbilical cord arterial pH < 7.1
Base excess [**?**] -12 mmol/L
Caesarean section for foetal distress
Operative vaginal delivery for foetal distress

* Statistically significant at p<0.05; NICU, neonatal intensive care unit, SCBU; special care baby unit; Kg, kilogram; cm, centimeter; BMI, body mass index; GDM, gestational diabetes mellitus; FM, foetal movement; CTG, cardiotocography; SROM, spontaneous rupture of membranes; g, gram; PI, pulsatility index; ms, millisecond; mmol/L, millimoles per liter. Numerical variables presented in median (interquartile range) or mean (standard deviation). Categorical variables presented in n (%: 95% confidence interval)

Table S2. Pearson correlation between estimated foetal weight, maternal-foetal Doppler velocimetry, computerised cardiotocography short term variability and umbilical cord arterial pH

Umbilical cord arterial pH	**r**	***p* value**
Estimated foetal weight z-score	0.054	0.284
Umbilical artery PI z-score	0.001	0.992
Middle cerebral artery PI z-score	-0.015	0.774
Cerebroplacental ratio z-score	0.008	0.871
Mean uterine artery PI z-score	0.050	0.335
Log_{10} short term variability	0.107	0.035*

* Statistically significant at p<0.05; PI, pulsatility index

Table S3. Pearson correlation between estimated foetal weight, maternal-foetal Doppler velocimetry, computerised cardiotocography short term variability and umbilical cord arterial base excess

Umbilical cord arterial base excess	**r**	***p* value**
Estimated foetal weight z-score	-0.021	0.638
Umbilical artery PI z-score	-0.033	0.521
Middle cerebral artery PI z-score	-0.014	0.792
Cerebroplacental ratio z-score	0.035	0.496
Mean uterine artery PI z-score	0.092	0.081
Log_{10} short term variability	0.059	0.249

* Statistically significant at p<0.05; PI, pulsatility index

Table S4. Logistic regression analysis for the prediction of emergency delivery (Caesarean section and operative vaginal delivery) due to pathological CTG during labour

Independent variable	**Univariate**	*p* **value**	**Multivariate**	*p* **value**
	Odd ratio (95% CI)		**Adjusted Odd ratio (95% CI)**	
Maternal age	1.004 (0.910 -1.004)	0.910		
Log_{10} maternal weight	0.332 (0.002 - 73.150)	0.688		
Log_{10} maternal height	0.000 (0.000 - 616.926)	0.158		
Log_{10} maternal body mass index	2.188 (0.009 - 537.514)	0.780		
Smoking	3.187 (0.636 - 15.987)	0.159		
Nulliparity	1.990 (0.876-4.519)	0.100		
Near-postdate	1.578 (0.705-3.533)	0.268		
Diabetes mellitus	0.452 (0.059 - 3.454)	0.444		
Hypertension	2.225 (0.467 - 10.596)	0.315		
Large or small for gestational age	0.556 (0.128 - 2.34132)	0.433		
Decrease FM / Suboptimal CTG	2.400 (0.921 - 6.253)	0.073	1.593 (0.506 - 5.012)	0.426
Estimated foetal weight z-score	1.175 (0.922 - 1.498)	0.192		
Umbilical artery PI z-score	0.811 (0.542 - 1.213)	0.307		
Middle cerebral artery PI z-score	1.388 (0.999 - 1.927)	0.051	0.291 (0.001 - 84.061)	0.669
Cerebroplacental ratio z-score	0.872 (0.603 - 1.259)	0.464		
Mean uterine artery PI z-score	0.795 (0.608 - 1.038)	0.092	0.798 (0.606 - 1.050)	0.107
Log_{10} short term variability	0.721 (0.047 - 11.101)	0.815		
Dawes-Redman criteria not met	1.437 (0.475 - 4.343)	0.521		

* Statistically significant at p<0.05; FM, foetal movement; CTG, cardiotocography; PI, pulsatility index

Table S5. Logistic regression analysis for the prediction of umbilical cord arterial pH < 7.1

Independent variable	**Univariate**	*p* **value**	**Multivariate**	*p* **value**
	Odd ratio (95% CI)		**Adjusted Odd ratio (95% CI)**	
Maternal age	0.976 (0.931 - 1.023)	0.306		

Independent variable	**Univariate**	***p* value**	**Multivariate**	***p* value**
Log_{10} maternal weight	0.584 (0.019 - 18.130)	0.759		
Log_{10} maternal height	0.019 (0.000 - 51348.946)	0.598		
Log_{10} maternal body mass index	0.934 (0.026 - 33.482)	0.970		
Smoking	3.737 (0.983 - 14.202)	0.053	3.313 (0.858-12.783)	0.082
Nulliparity	1.442 (0.888-2.341)	0.139		
Near postdate	1.771 (1.029-3.051)	0.039	1.678 (0.968-2.909)	0.065
Diabetes	0.396 0.116 - 1.358	0.141		
Hypertension	0.571 0.123 - 2.654	0.475		
Large or small for gestational age	0.727 0.322 – 1.638	0.441		
Decrease FM / Suboptimal CTG	0.733 0.309 - 1.740	0.482		
Estimated foetal weight z-score	0.900 0.765 - 1.058	0.201		
Umbilical artery PI z-score	1.047 0.802- 1.367	0.734		
Middle cerebral artery PI z-score	0.943 0.759 - 1.171	0.593		
Cerebroplacental ratio z-score	1.023 0.809 - 1.294	0.849		
Mean uterine artery PI z-score	1.026 0.873 - 1.206	0.755		
Log_{10} short term variability	0.438 0.075 - 2.562	0.359		
Dawes-Redman criteria not met	1.000 0.452 - 2.215	0.999		

* Statistically significant at $p<0.05$; FM, foetal movement; CTG, cardiotocography; PI, pulsatility index

Acknowledgements

We would like to thank midwives and doctors at the Prince of Wales Hospital in facilitating the performance of this study.

Disclosure of Interests

LCP has received speaker fees and consultancy payments from Roche Diagnostics and Ferring Pharmaceuticals. LCP has received in-kind contributions from Roche Diagnostics, PerkinElmer, Thermo Fisher Scientific, and GE Healthcare. This does not alter our adherence to BJOG policies on sharing data and materials. Other co-authors report no conflicts of interest.

Author contribution

MSNL, AHWK, STKW, AWTT, STAT and SM were responsible for participant recruitment and ultrasonographic examination. SM did data analysis and manuscript preparation under LCP and DSS supervision. The conceptualization of this project, manuscript edition and the project supervision were accomplished by LCP.

Details of Ethics Approval

This study was approved by the Institutional Review Board (Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee, Reference Numbers CRE-2017.608) on 4 January 2018

Funding

Hong Kong Obstetrical and Gynecological Trust Fund (Research project code 6905641), Hong Kong SAR. The study sponsors had no role in the study design, collection, analysis, and interpretation of the data, or in the writing of the article.

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