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An investigation of fetal behavioural states during maternal sleep in healthy late gestation pregnancy: an observational study

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Key points

- Fetal behavioural state in healthy late gestation pregnancy is significantly affected by maternal position overnight.
- Maternal left lateral position is the one most frequently adopted at sleep onset.
- The maternal position at sleep onset is maintained the longest overnight.
- Fetal state 1F is more common in maternal supine positions overnight.
- Fetal state 4F is less common in maternal supine sleep positions.
- Fetal state and maternal sleep position are independently associated with fetal heart rate variability.
- Maternal sleep position significantly affects fetal heart rate and heart rate variability and affects circadian fetal heart rate patterns.

Abstract Fetal behavioural states (FBS) are measures of fetal wellbeing. Maternal position affects FBS with supine position being associated with an increased likelihood of fetal quiescence consistent with the human fetus adapting to a lower oxygen consuming state. Several studies have now confirmed the association between sleep position and risk of late intrauterine death. We designed this study to observe the effects of maternal sleep positions overnight in healthy late gestation pregnancy. Twenty-nine healthy women had continuous fetal ECG recordings overnight. Two blinded observers assigned fetal states in 5 min blocks. Measures of fetal heart rate variability (FHRV) were calculated from ECG beat to beat data. Maternal position was determined from infrared video recording. Compared to state 2F (active sleep), 4F (active awake-high activity) occurred almost exclusively when the mother was in a left or right lateral position. State 1F (quiet sleep) was more common when the mother was supine [odds ratio (OR) 1.30, 95% confidence interval (CI) 1.11–1.52] and less common on the maternal right side with the left being the referent position (OR 0.81, 95% CI, 0.70–0.93). State 4F was more common between 21.00 and 01.00 h than between 01.00 and 07.00 h (OR 2.83, 95% CI 2.32–3.47). In each fetal state, maternal position had significant effects on fetal heart rate and measures of FHRV. In healthy late gestation pregnancy, maternal sleep position affects FBS and heart rate variability. These effects are probably fetal adaptations to positions which may produce a mild hypoxic stress.

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Abbreviations aOR, adjusted odds ratio; BMI, body mass index; CI, confidence interval; CTG, cardiotocograph; FBS, fetal behavioural state; FHR, fetal heart rate; FHRV, fetal heart rate variability; IQR, interquartile range; OR, odds ratio; RR interval, interval between R waves on the electrocardiograph; RMSSD, root mean square of successive differences (in the RR interval); SDNN, standard deviation of the RR interval.

Introduction

Maternal sleep position in late pregnancy is now recognised as an important risk factor for stillbirth (Stacey *et al.* 2011; Owusu *et al.* 2013; Gordon *et al.* 2015; McCowan *et al.* 2017). Compared with commencing sleep on the left side, the supine sleep position was found to have an increased risk of stillbirth [adjusted odds ratio (aOR) 2.54, 95% confidence interval (CI) 1.04–6.18] (Stacey *et al.* 2011). The mechanisms by which maternal position could influence fetal outcome were unclear. A hypothetical framework for late pregnancy stillbirth has been proposed (Warland & Mitchell, 2014), in which maternal sleep position acts as a stressor in an already compromised situation with adverse feto-placental and maternal factors. Although the reasons by which maternal position may affect fetal outcome remain unclear, the supine position may reduce maternal cardiac output (Kinsella & Lohmann, 1994) and uteroplacental perfusion (Pirhonen & Errkola, 1990; Jeffreys *et al.* 2006) and result in a hypoxic stress for the fetus.

Recently we reported the results of a study designed to assess the effects of different maternal positions on fetal behavioural states (FBS) in healthy late gestation pregnancies when the mother was awake under controlled conditions (Stone *et al.* 2017). FBS are a marker of fetal wellbeing (Romani & Rizzo, 1995; Martin, 2008) and the development of autonomic nervous control of heart rate (Brandle *et al.* 2015). FBS are patterns of physiological and behavioural variables which are repetitive over time and have clear changes from one state to another. FBS may be defined as combinations of particular physiological variables that are stable over a period of time and recur (Martin, 2008). In the fetus at least three distinct behavioural or activity states have been identified and correspond to the early neonatal behavioural states 1 (quiet sleep – in the fetus termed 1F), 2 (active sleep – fetal 2F), 3 (quiet awake 3F – in the fetus this is very infrequent or not seen) and 4 (active awake 4F – in the fetus a period of considerable fetal activity with rapid heart rate and varying baseline fetal heart rate) (Nijhuis *et al.* 1982). These become stable and consistent by 36 weeks of gestation in healthy fetuses (Nijhuis *et al.* 1982; Nijhuis, 2003). Fetal heart rate (FHR) patterns have been used to deduce the fetal state (Timor-Tritsch *et al.* 1978; Pillai & James, 1990*a*), which is reliably determined by examination of the characteristics of the baseline FHR patterns alone (Pillai & James, 1990*b*).

In our previous study in which the women were awake, clear effects of maternal position on FBS were found, such that compared to state 2F (the most frequently observed state), state 4F (fetal activity with rapid heart rate and varying baseline FHR) was less likely to occur when women were semi-recumbent or supine while state 1F (quiet sleep with stable baseline FHR) was more common (Stone *et al.* 2017). Changes in FHR variability (FHRV) were also seen when maternal position changed.

FHRV is a measure of cardiac autonomic control and in the fetus it is made up of sympathetic and parasympathetic nervous system activity as well as intrinsic pacemaker rhythms of the sino-atrial node (Jensen *et al.* 2009; Papaioannou *et al.* 2013). Sympathetic activity is important in the maintenance of fetal blood pressure, for example in periods of repeated asphyxia (Galinsky *et al.* 2014; Lear *et al.* 2016). FHRV was assessed as the standard deviation of the R-R interval (SDNN) and the root mean square of successive differences (in the R-R interval) (RMSSD). The SDNN is a measure of total HRV, assessing all oscillations within the epoch interrogated. The RMSSD is primarily sensitive to the total magnitude of FHRV, but is sensitive to high-frequency oscillations (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996; Lear *et al.* 2016). In the awake studies, we limited the period of time the women were supine to 30 min. We suggested that the observed changes in FBS and FHRV, in particular in the supine position, reflected appropriate fetal adaptation to adopt a lower oxygen-consuming state in response to a mild change in fetal oxygen tension. In contrast, moderate to severe hypoxia/asphyxia is associated with an autonomic adaptive response and an initial increase in FHRV, which we did not observe (Thaler *et al.* 1985). In overnight sleep studies, which are the subject of this current study, maternal position is determined spontaneously by the woman, and not influenced by the investigator, so there was the opportunity to investigate fetal responses as would occur in maternal sleep in late pregnancy.

In this study, we aimed to assess the effects on fetal behaviour of maternal sleep positions that occur during sleep in late pregnancy. We then determined how both maternal position and fetal state relate together with respect to FHRV.

Method

Ethical approval

This study was approved by the Northern Regional Human Ethics Committee (NTX/11/09/084). All subjects gave

written informed consent. All studies approved by the Northern Regional Human Ethics Committee conform to the *Declaration of Helsinki*. This study was not registered in a database.

Thirty healthy women aged ≥18 years with a normal singleton pregnancy, late in the third trimester (36–38 weeks of gestation), were recruited from low risk midwifery care at the National Women's Hospital, Auckland, New Zealand. The fetal measurements failed in one subject leaving 29 available for analysis.

Maternal exclusion criteria included: current smoking or alcohol use, early pregnancy body mass index (BMI) >30, any medical or obstetric complications (e.g. pre-eclampsia, any known cardiovascular disorder, including hypertension or use of antihypertensive treatments, respiratory or renal disorders, and all forms of diabetes), not regularly attending scheduled obstetric appointments, any orthopaedic or musculoskeletal conditions which would make adopting different maternal positions difficult and inadequate English language to give informed consent. Fetal exclusion criteria included: abnormal biometry for the gestation, reduced amniotic fluid volume, abnormal umbilical arterial Doppler measurements and multiple pregnancy. Birth outcome data were collected to confirm the health status of the mother and neonate.

Procedures

Participants were studied in their homes where researchers set up the recording equipment. Participants were instructed to sleep as normal with regards to bed time and wake time, number of pillows and lighting.

A continuous fetal ECG, electrohysterogram and maternal heart rate were recorded using the Monica AN24 ambulatory transabdominal fetal ECG device (Monica Healthcare, Nottingham, UK). Skin preparation, electrode placement and impedance testing were performed as per the manufacturer's instructions. The device recorded a fetal ECG with true beat to beat intervals being recorded in 1 min epochs without autocorrelation as used in commercial cardiotocography (CTG) machines.

To confirm maternal position, video footage was collected with a camcorder on a tripod (HDR-SR12E Camcorder, Sony, Tokyo, Japan) with an external infrared light (Sony HVL-IRM). Sleep onset was defined as the first 3 min period with no movements, similar to that used previously in an accelerometry study (Wrzus *et al.* 2012). Position changes were therefore counted as positions lasting 3 min or longer, with shorter duration positions considered to be part of a transition between sleep positions. Recording of fetal and maternal data commenced as soon as the equipment was set up and continued overnight until the participants or research assistant removed it the following morning.

Data processing

The data from the Monica device were uploaded to a PC with the Monica (VS) analysis software. The Monica VS software uses beat to beat data to construct a fetal cardiograph, which when combined with the hysterogram produced a printout analogous to a standard CTG suitable for interpreting FBS. The device records from three channels and the interpolated sampling rate is 2.2 kHz (Monica Healthcare).

The Monica has a built in proprietary algorithm to deal with signal loss (any epoch with >30 s signal loss in the 1 min epochs used for the analysis of the raw ECG signal is disregarded and no result is given for that epoch). The manufacturer's analysis program (Monica DK v1.9) was used to calculate FHRV. The mean FHR was assessed for each minute analysed from the time of sleep onset until wakening. Each epoch was quantified by the mean FHR, the SDNN and the RMSSD. Sleep position throughout the night was categorised as left lateral, right lateral or supine and determined from the video recording. The left lateral position was used as the referent to which the other positions were compared.

Fetal state was based on the classic features of the CTG as described by Pillai & James (1990*a*). Briefly, the CTGs were scored independently by two obstetricians (PS, WB), blind to maternal position. Each block was scored for fetal state as either 1F, 2F, 4F, transition or indeterminate using the methods of Pillai and James. Consistent heart rate patterns were defined as a state when the duration was at least 3 min. Our previous study (Stone *et al.* 2017) had shown a high level of agreement between scorers. For this study, the two obstetricians scored the CTGs independently. For observations where there was disagreement, the scorers reviewed the observations together, blind to the original scoring, and where possible reached a consensus view. These observations are those used in the analysis.

To assess the effect of time of night on FHR, we initially assessed the plots of continuous data from the CTG, and were unable to detect any circadian pattern. We then calculated the mean heart rate per hour for each fetus and calculated the difference between this and the average for the whole sleep period from maternal sleep onset until awakening. These were plotted against the time from sleep onset with a smoothed spline curve fitted for each individual as reported in previous studies (Visser *et al.* 1982; Lunshof *et al.* 1998).

Statistical analyses

Univariable analysis of the relationship between maternal position and fetal state was assessed using a chi-square statistic. Odds ratios to estimate the relationships between maternal position and fetal state were assessed and were consistent using simple logistic regression and binary

Table 1. Characteristics of subjects (maternal and fetal)

Subject characteristics	Mean ± SD or median (IQR)
Maternal age (years)	30.8 ± 5.2
Maternal BMI (before pregnancy) (kg m^{-2})	22.8 ± 3.5
Maternal BMI (current) (kg m^{-2})	28.0 ± 4.1
Gestation at testing (weeks)	37 ± 1
Gestation at birth (weeks)	40 ± 1
Birth weight (g)	3410 ± 391
Apgar score 1 min	9 (9–9)
Apgar score 5 min	10 (9–10)

repeated measures analyses taking account of the repeated measures for each subject overnight and the time of night.

Logistic regression was carried out using Proc Logistic and repeated measures using Proc GLIMMIX using a random effect for the intercept and time was fitted with an autoregressive [AR(1)] correlation structure.

Analysis of differences in measures of FHRV were carried out using generalised linear models (Proc GLIMMIX) to test for differences in measures between fetal state and maternal position, and then to test for differences in measures by maternal position stratified by fetal state.

All analyses were carried out in SAS v9.4 (SAS Institute, Cary, NC, USA).

Results

Thirty healthy pregnant women at a median of 37 weeks of gestation (range 36–38 weeks) participated in the study and there were data suitable for analysis from 29 subjects. Characteristics of the subjects and birth outcomes are shown in Table 1. On the night of the study in 14 of the 30 subjects, the bed partners did not participate and slept in a different room.

At the 6 week postnatal check all babies were healthy. There were no recognised congenital anomalies.

Maternal sleep and sleep position data

The time of sleep onset had a median of 22.21 h in the evening [interquartile range (IQR) 22.57, 22.43). The median wake time was 07.01 h (IQR 06.34, 07.15). The median sleep duration was 8 h and 14 min (IQR 7:28, 8:50). The timing of rising to go to the toilet was spread widely throughout the night.

A description of maternal sleep characteristics is shown in Table 2.

The left lateral position was most frequently adopted at sleep onset and most women spent more than half the night in the left lateral position. The position adopted at commencement of sleep was maintained the longest and for 20 of the women was their dominant position. Sleep-onset position was maintained for a median (IQR) of 62 (39–83) min.

Table 2. Maternal sleep characteristics

Sleep description	Video data
Sleep-onset and time in initial position	Median (IQR)
Left ($n = 19$)	65 min
Right ($n = 8$)	60 min
Supine ($n = 2$)	72 min
Overall	62 min (39, 83)
Dominant position	
Left ($n = 20$)	20
Right ($n = 5$)	5
Supine ($n = 4$)	4
Time in each position throughout the night	Median (IQR)
Left	4 h 9 min (3 h 9 min, 4 h 38 min)
Right	2 h 1 min (1 h 7 min, 3 h 41 min)
Supine	1 h 23 min (0 h 11 min, 2 h 25 min)
Number of position changes	9 (8–11)

Data are presented as the number of participants or as median and interquartile range (IQR).

Table 3. Effect of maternal position on fetal state

Maternal position	State 1F Percent of time	State 2F Percent of time	State 4F Percent of time
Left	13.4	82.2	4.4
Right	11.3	83.5	5.2
Supine	14.0	85.2	0.8

Time in each state is shown as a percentage of the total time in that position. Chi square: 81.53 ($P < 0.0001$).

FHR data were analysable for 89.9% of the recording time, with data loss due to poor signal quality 5.4% of the time and fetal state indeterminable in 4.7% of the recording time. Maternal sleep position was coded as being in transition 3.9% of the time.

Fetuses spent most time in state 2F (83.2%), followed by 1F (12.9%), and very little time in 4F (3.9%).

Effect of maternal position on fetal state

The association between fetal behavioural state and maternal position is shown in Table 3. The percentage of time that the fetus spent in each state dependent upon maternal position is shown.

State 4F occurred almost exclusively when the mother was in a left or right lateral position.

Table 4. Effect of being in fetal state 1 and 4 compared to state 2 according to maternal position (left sided sleep position is referent)

Maternal position	State 1 vs. State 2	State 4 vs. State 2
Left	1.00	1.00
Right	0.81 (0.70, 0.93)	1.72 (1.37, 2.18)
Supine	1.30 (1.11, 1.52)	0.33 (0.21, 0.52)

Risks are estimated from a repeated measures analysis with a random effect for subject. Values are odds ratios with 95% confidence intervals.

Taking into account within-subject effects, Table 4 shows the results of repeated measures analyses. These confirmed that 1F was more common when the mother was in the supine position (OR 1.30, 95% CI 1.11–1.52) and less common on the right side (OR 0.81, 95% CI 0.70–0.93), with the left side being the referent position, as shown in Table 4. 4F was increased on the right side and much less common in the supine position.

Effect of time of night on fetal behavioural state

Fetal activity has been reported to be greatest in the evening (Patrick *et al.* 1982*b*; Ehrstrom, 1984), and the effect of time of night on FBS was investigated. Of the time spent in 4F, the majority of it (56.6%) occurred in the time from 21.00 to 01.00 h. When time from sleep onset (as a continuous variable) was added to the above model there was no significant effect, although adding time as a categorical variable showed that compared to 2F, 4F remained more likely in the early part of the night (OR = 2.83, 95% CI 2.32, 3.47). State 1F was slightly less likely to occur in the early part of the night compared to 2F (OR = 0.75, 95% CI 0.67, 0.87).

Effect of fetal state on measures of FHR and heart rate variability

The effects of fetal state and maternal position on measures of FHR and variability in univariable analysis are shown in Table 5. Compared with state 2F (the referent state), FHR was lower in 1F and higher in 4F. SDNN was significantly reduced in 1F (45% decrease) and to a lesser extent in 4F (17%) compared with 2F. RMSSD was also decreased in both 1F (9%) and to a greater extent in 4F (29%) compared to 2F.

When the effect of maternal position was analysed, compared with the left side, supine was associated with a small but statistically significant increase in FHR. Both right and supine were associated with reductions in SDNN and for supine a decrease in RMSSD. In a multivariable model containing both fetal state and maternal position, both remained significant, thus suggesting that they are independently associated with FHRV.

Interactions between maternal position and fetal state were tested for each of the outcomes: FHR ($P = 0.0054$), SDNN ($P = 0.0001$) and RMSSD ($P = 0.06$), suggesting that the effects of fetal state on measures of variability are modified by maternal position.

The results of this analysis of the combined effects of state and position are shown in Table 6.

Table 6 shows that in each state, maternal position had a statistically significant effect on FHR. Compared with the left side (as referent) the supine position was associated with increases in FHR in all states, but these increases were larger in 4F and 1F. The effect on SDNN was particularly seen when the mother was in the right in 1F and supine in 2F. The effects of maternal position on RMSSD show decreases in RMSSD in 1F and 2F when supine, and in 1F on the right. Power was limited to detect differences in 4F due to the small amount of time in this state.

Plots of mean FHR per hour overnight did not show a consistent pattern across subjects. For illustrative purposes, the heart rate overnight from sleep onset, maternal position and FBS are shown together in Fig. 1. This fetus had only a short period in 4F after sleep onset. The woman underwent a number of position changes and spent more time supine than most other women in this study. Most of the 1F occurred when the woman was supine.

Discussion

In this study of healthy late gestation pregnancy, maternal position overnight had a significant effect on fetal behavioural state. In late pregnancy, the women in this study were most likely to commence sleep in a lateral position and maintain this position for the longest time, both initially and throughout the night. This initial period also corresponds to the period of most activity in the fetus. State 4F occurred almost exclusively in maternal lateral positions and also in the early part of the night, which is also the time when sleep position was most stable. After 01.00 h, 4F was infrequent. 4F was rarely observed in the supine position, with 1F being more likely.

Our results have shown that time of night significantly influenced the likelihood of the fetus being in a particular state, with 4F being more likely in the early part of the night and 1F less likely then and more likely later after sleep onset. This may be due in part to the maternal position effects where position change, most often from non-supine to supine sleep, occurred after the period of most stable sleep. We also found that the effects of fetal state on measures of FHRV were modified by maternal position, probably mediated through autonomic nervous system activity. This further supports the concept that maternal position is an important modulator of circadian effects on FHR. It would appear probable that the position effects seen in our previous studies (Stone *et al.* 2017)

Table 5. Differences in measures of FHR and FHRV according to fetal state and maternal position (state 2F and the left lateral position were the referents)

	FHR (bpm)	SDNN	RMSSD
Fetal state	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
1F	**−5 (−6, −4)**	**−7.0 (−7.5, −6.6)**	**−0.5 (−0.7, −0.4)**
2F	Mean = 135 (SEM = 0.94)	Mean = 15.7 (SEM = 0.40)	Mean = 5.8 (SEM = 0.11)
4F	**18 (16, 19)**	**−2.6 (−3.4, −1.8)**	**−1.7 (−1.9, −1.5)**
Maternal position	**$P < 0.0001$**	**$P < 0.0001$**	**$P < 0.0001$**
Left	Mean = 134 (SEM = 1.3)	Mean 14.8 (SEM = 0.43)	Mean = 5.6 (SEM = 0.12)
Right	1 (−0,2)	**−0.7 (−1.1, −0.3)**	0.0 (−0.1, 0.1)
Supine	**2 (1, 4)**	**−1.8 (−2.3, −1.4)**	**−0.4 (−0.5, −0.3)**

Values are odds ratios with 95% confidence intervals.

Table 6. Differences in measures of HRV by position for states 1F and 2F

	FHR (bpm)	SDNN	RMSSD
State 1F ($n = 1513$)			
Maternal position	**$P < 0.0001$**	**$P = 0.0068$**	**$P < 0.0001$**
Left	Mean = 131 (SEM = 0.7)	Mean = 11.1 (SEM = 0.76)	Mean = 5.3 (SEM = 0.2)
Right	**1 (0, 2)**	**−1.6 (−2.6, −0.6)**	**−0.5 (−0.8, −0.2)**
Supine	**5 (4, 6)**	−0.7 (−1.9, 0.4)	**−0.7 (−1.0, −0.3)**
State 2F ($n = 9708$)			
Maternal position	$P = 0.055$	**$P < 0.0001$**	**$P = < 0.0001$**
Left	Mean = 135 (SEM = 0.6)	Mean = 15.6 (SEM = 0.5)	Mean = 5.7 (SEM = 0.1)
Right	1 (0,1)	**−0.7 (−1.1, −0.2)**	0.0 (−0.1, 0.1)
Supine	**1 (0,1)**	**−1.3 (−1.8, −0.8)**	**−0.3 (−0.4, −0.2)**
State 4F ($n = 518$)			
Maternal position	**$P = 0.0258$**	$P = 0.35$	$P = 0.92$
Left	140 (SEM = 4.5)	Mean = 15.3 (SEM = 3.0)	Mean = 5.4 (SEM = 0.7)
Right	2 (−3, 8)	−2.7 (−6.5, 1.0)	−0.1 (−1.0, 0.9)
Supine	**9 (2,17)**	0.6 (−4.1, 5.4)	0.2 (−1.0, 1.4)

Values are odds ratios with 95% confidence intervals.

are also occurring overnight during maternal sleep. We suggest that maternal position change may affect the circadian pattern of FHR overnight.

We initially expected that any changes in FHRV would be mediated by altered behavioural state. However, our multivariate analysis showed that both maternal position and fetal sleep state independently influenced FHRV, and our hypothesis was therefore too simplistic. What this highlights is that FBS are not uniform, but instead that the degree of activity in each state can be influenced by outside influences. Our findings therefore probably reflect that in the supine position, the periods of 1F showed even less fetal activity than observed during 1F in the other positions.

A study of subjective recording of fetal movements in two groups of women, one group recording during daytime and the other at night (Ehrstrom, 1984), described a pattern of nocturnal fetal activity which was consistent with our findings and also showed more variation in hourly frequency during the day, which suggested that maternal activity or exogenous stimuli influenced fetal movements or at least their perception. We would speculate therefore that the maternal position effects we have seen could be considered an exogenous stimulus that may modify endogenous rhythms by creating a mild hypoxia stress secondary to changes in uteroplacental perfusion when the woman is supine.

Our observations in this in-home sleep study are consistent with findings from our experimental laboratory study recently reported (Stone *et al.* 2017) in which maternal position was controlled and randomly allocated between the supine, semi-recumbent, right and left lateral. In that study, whilst the subjects were awake, maternal supine position was associated with an increased time in 1F, almost no time in 4F, and increased likelihood of fetal state change when compared with the referent left lateral position. This overnight study reflects the fetal response to spontaneously adopted maternal position.

With the exception of one fetus, the FHR changes over night did not appear to show a clear circadian pattern. A study of 26 healthy pregnancies from 26 to

38 weeks of gestation under laboratory conditions found that circadian rhythms in basal FHR were present in 73% of fetuses whereas only 30–50% of fetuses showed circadian patterns of FHRV and activity (Lunshof *et al.* 1998). Ultradian rest activity cycles may well dominate an immature fetal suprachiasmatic nucleus (the circadian oscillator) and be the reason why diurnal rhythms in FHR parameters are not seen in all fetuses (Lunshof *et al.* 1998). In a longitudinal study of fetal body movements performed at a consistent time of the day, Ten Hof *et al.* (2002) found that there was intrafetal consistency with fetal behaviours over advancing gestation but very large interfetal differences such that the authors concluded that interpretations of changes needed to be individualised to each fetus.

We do not know whether the effects of maternal position would override circadian effects of maternal physiology including heart rate variability and perhaps temperature on fetal physiology. It is not possible to record fetal circadian rhythms in the absence of maternal influences, but it may be possible to examine the results of maternal sleep behaviours on fetal physiology. Disturbed sleep in late pregnancy with awakening and rising to micturate or due to discomfort may well affect maternal circadian rhythms and those of the fetus (Sadeh, 1997; Seron-Ferre *et al.* 2007). Our data failed to show an overnight reduction in FHR as part of a circadian pattern in heart rate or heart rate variability parameters. The examination of individual FHR patterns revealed no recognisably consistent changes during the night when a nadir in FHR had been reported (Patrick *et al.* 1982*a*; Lunshof *et al.* 1998). In the one fetus in our study which did show a pattern which could be consistent with a circadian one, the magnitude of heart rate changes over the night was similar to that seen by Lunshof *et al.* (1998). A study of 10 healthy near term pregnant women suggested a diurnal variation in FHR with large changes in high pulse variation in the beat to beat heart rate interval in the late evening around midnight (Visser *et al.* 1982). An examination of the FHR patterns from that report would be consistent with the behavioural state patterns that we have seen, although the authors did not define the patterns as fetal states.

There does not appear to be an clear explanation for the differences between those studies and our own, but we speculate that in late pregnancy, women's sleep is disrupted, especially in the early hours of the morning when getting up to pass urine is common. Such non-photic influences are likely to have at least some effect on circadian rhythms in the mother (Mistlberger & Skene, 2004) and possibly also the fetus. All other aspects including normality of the pregnancies, gestational age at assessment, and times of going to sleep and awakening would appear to have been similar to the studies quoted. Whilst we did not measure maternal plasma adrenocorticosteroid or melatonin levels, we have no reason to believe that these would not be normal in our subjects.

Consistent with the ultrasound studies of Patrick *et al.* (1982b), we did find that there was more fetal activity and state 4F during the later evening with little or no 4F from around 01.00 h. In a study including gestations from 28 to 39 weeks, Roberts *et al.* (1979) observed a well-defined circadian variation in fetal activity with FBM peaking

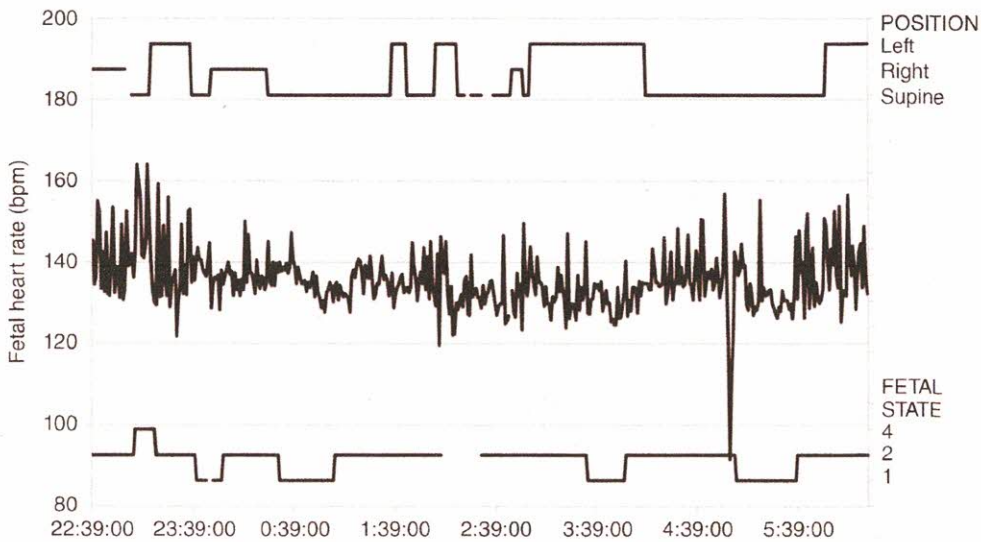

Figure 1. Fetal heart rate from sleep onset to waking
Plot of fetal heart rate over the period from sleep onset to waking with maternal position marked on the right side above and fetal behavioural state below. (Gaps in the behavioural state line or maternal position line indicate periods of transition.) The short deceleration seen around 05.00 h was of 15 s duration and occurred in a period of fetal activity in state 2F.

between 19.00 and 22.00 h, and fetal trunk movements between 22.00 and 01.00 h. This is consistent with the findings of Patrick *et al.* (1982b) and suggest that our study encompassed times where the fetus would have had most gross body movement.

The findings in our study of healthy late gestation pregnancy are consistent with the concept that state changes can occur as an adaptive response and shift the fetus to a lower oxygen-consuming state. Decreased fetal movements are associated with adverse pregnancy outcomes including hypoxia at birth or stillbirth (Heazell & Froen, 2008). It has been further suggested that placentae from pregnancies affected by reduced fetal movements are associated with abnormal placental structure and impaired placental function (Warrander *et al.* 2011). Maternal perception of fetal movements is widely used as a marker of fetal viability and wellbeing. Whilst none of the women in our study reported changes in fetal movements, the FBS was affected by maternal position with fetal quiescence being more likely when the mother was supine. We suggest that this is due to reduced placental perfusion leading to short-term or mild fetal hypoxia, which in a compromised fetus such as in growth restriction (Stacey *et al.* 2012) or in the presence of structural placental abnormality (Man *et al.* 2016) may lead to intrauterine demise. Our observational study of healthy low-risk pregnant women close to term suggests that a healthy fetus appears able to change to 1F to cope with a mildly hypoxic stress.

Given our results and those of case controlled epidemiological studies reporting the effect of sleep position in risk of stillbirth (Stacey *et al.* 2011; Owusu *et al.* 2013; Gordon *et al.* 2015; McCowan *et al.* 2017), we suggest that trials of interventions to reduce supine sleeping in the third trimester of pregnancy are warranted. Our findings suggest that a supine sleep position is disadvantageous even to the healthy late gestation fetus, but whether left or right lateral positions have significantly different effects on fetal behaviour is unclear and is the subject of further research by this group.

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Additional information

Competing interests

The authors declare no competing financial interests.

Author contributions

FBS scoring was performed by PS and WB. Maternal position determined from infrared video, initial analysis of FHRV and conversion of FHR data to conventional CTG was carried out by JM. JT performed all the statistical analyses. AG, LB and CL contributed to analytical design. PS, JT and EM wrote the manuscript with input from all authors. All authors approved the final version of the manuscript. All persons listed as authors qualify for authorship, and all those who qualify for authorship are listed. The Maternal Sleep in Pregnancy Research Group also includes: A. Veale, K. Ellyett, L. McCowan, R. Cronin, A Mirjalilil and S. Woodall. The Group acknowledges C. Ingham for assessment of video data.

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Translational perspective

Late stillbirth is independently related to the position women adopt during sleep. We hypothesised that fetal behavioural state as an indicator of fetal welfare would be affected by maternal position. We studied 29 healthy normal singleton pregnancies overnight between 35 and 38 weeks of gestation and examined the effects of spontaneously adopted maternal positions of fetal behavioural state, which was determined by blinded assessment of fetal heart rate patterns. The results show that in normal healthy third trimester pregnancy, maternal position influences the behavioural state of the fetus. Changes were also seen in measures of fetal heart rate variability, a marker of autonomic responsiveness. Compared with being in state 2F in the left lateral position, there was a 30% increased chance of the fetus being in 1F and over a 60% reduction in 4F during supine sleep. A switch to state 1F or fetal quiescence when the mother is supine suggests the fetus is adopting a low oxygen-consuming state. The results offer insights into fetal activity overnight and the physiological mechanisms that the fetus may utilise to adapt to the effects of maternal sleep position. We speculate that the findings may be due to reduced uterine perfusion and that vulnerable fetuses, which may already be hypoxic, are unable to adapt to the stressor of maternal supine position. We suggest that trials of interventions to reduce supine sleeping in the third trimester of pregnancy are warranted.

Supporting information

The following supporting information is available in the online version of this article.

Video. What is the best sleeping position for mums-to-be?