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## Maternal vitamin D status, prolonged labor, and cesarean and instrumental delivery in an era with a low cesarean rate

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### Abstract

**Objective**—To examine the association between maternal 25-hydroxyvitamin D (25(OH)D) and adverse labor and delivery outcomes.

**Study design**—We measured serum 25(OH)D at 26 weeks gestation in a random subsample of vertex, singleton pregnancies in women who labored (n=2798) from the 12 site Collaborative Perinatal Project (1959–66). We used labor and delivery data to classify cases of adverse outcomes.

**Results**—Twenty-four percent of women were vitamin D deficient (25(OH)D <30 nmol/L) and 4.5%, 3.3%, 1.9%, and 7.5% of women had prolonged stage 1 labor, prolonged stage 2 labor, primary cesarean delivery, or indicated instrumental delivery, respectively. After adjustment for prepregnancy BMI, race, and study site, 25(OH)D concentrations were not associated with risk of prolonged stage 1 or 2, cesarean delivery, or instrumental delivery.

**Conclusion**—Maternal vitamin D status at 26 weeks was not associated with risk of prolonged labor or operative delivery in an era with a low cesarean rate.

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#### Conflict of Interest

The authors report no conflicts of interest.

## Keywords

25-hydroxyvitamin D; adverse labor and delivery outcomes; operative delivery; Collaborative Perinatal Project; pregnancy

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## Introduction

Vitamin D deficiency remains a substantial problem in the US, specifically among pregnant women,<sup>1</sup> and prevalence may be increasing.<sup>2</sup> Vitamin D has long been recognized for its importance in calcium homeostasis, while numerous non-skeletal associations including those with muscle function, immune function, and chronic disease have emerged.<sup>3</sup> Maternal vitamin D deficiency has been associated with many adverse pregnancy outcomes, including preeclampsia, gestational diabetes, preterm birth, and small-for-gestational age birth.<sup>4, 5</sup>

Cesarean delivery has risen dramatically in the US over the last few decades with much of the recent increase from primary cesareans.<sup>6</sup> More recently, the rate of cesarean among singleton pregnancies has been constant at 31%.<sup>7</sup> Conversely, instrumental vertex delivery by forceps has decreased over time.<sup>8</sup> Although cesarean and operative vaginal deliveries are usually safe, they are associated with higher maternal morbidity and mortality compared to spontaneous vaginal deliveries.<sup>9, 10</sup> A common cause of operative deliveries is prolonged labor,<sup>11, 12</sup> which also is related to poor maternal and fetal outcomes such as infection and stillbirth.<sup>13, 14</sup> Cesarean delivery, instrumental delivery, and prolonged first or second stage of labor can be related to muscle performance either by myometrial function in the first stage or myometrial function and voluntary bearing-down required to expel the fetus in the second stage of labor.<sup>15</sup>

There is biological plausibility to a relationship between poor maternal vitamin D status and adverse labor and delivery outcomes related to muscle action. The vitamin D receptor has been identified throughout the body, including the uterine smooth muscle<sup>16</sup> and skeletal muscle.<sup>17</sup> Vitamin D deficiency is associated with poor muscle performance in humans<sup>18, 19</sup> and *in vitro*, vitamin D regulates contractile proteins in myometrial cells.<sup>20</sup> Due to the many biological functions of vitamin D, its relationships with labor and delivery outcomes could also be independent of muscle function.<sup>5</sup> Studies of maternal vitamin D status have examined cesarean delivery, and not instrumental delivery or prolonged labor. Findings are mixed, potentially due to varying definitions of cesarean including primary,<sup>20, 21</sup> cause-specific,<sup>21, 22</sup> emergency or elective,<sup>23, 24</sup> and/or all cause.<sup>20, 24, 25</sup> Two US studies found an inverse relationship between maternal vitamin D status and risk of primary cesarean delivery,<sup>21, 25</sup> while other studies observed no associations.

The predominant hypothesis, in our study and in others, is that poor vitamin D status contributes to poor muscle performance in labor; thus we limited our investigation to women who labored. Specifically, our aim was to study these relationships in a time period with lower use of oxytocin augmentation and epidural during labor and very few cesarean deliveries. Our objective was to examine the association between maternal vitamin D status at 26 week gestation and the risk of prolonged labor in stage 1 or 2, primary cesarean delivery, and indicated instrumental delivery in laboring women with singleton pregnancies.

## Subjects and Methods

This was an observational study of maternal vitamin D and adverse pregnancy outcomes using data and blood samples from the Collaborative Perinatal Project (CPP).<sup>26</sup> The CPP enrolled pregnant women from 12 medical centers across the US from 1959–1965 with births occurring through 1966. Non-fasting venous blood was drawn from mothers at the first study visit and approximately every 8 weeks thereafter. Extensive interviews were conducted to collect information on socio-demographics and medical histories. Labor and delivery details were recorded after delivery by the obstetrician responsible for each woman's medical care. We used deidentified data and were therefore granted exemption from ethical approval by the University of Pittsburgh Institutional Review Board.

From CPP pregnancies eligible for the parent vitamin D study (singleton pregnancies of white, black, or Puerto Rican mothers with no preexisting diabetes or hypertension and both entry to the study and a stored serum sample available at 26 weeks gestation; n=27,813), we randomly selected 3074 maternal serum samples for 25-hydroxyvitamin D [25(OH)D] assessment. The sample size was determined for the parent study of preterm birth and preeclampsia.<sup>27, 28</sup> For this investigation, we excluded women without labor and delivery data (n=39). As we were investigating adverse labor and delivery outcomes that could be a result of muscle dysfunction in labor, we excluded those who did not labor (n=119), those who had a cesarean due to previous cesarean section (n=27), and those with breech fetal presentation (n=91) for a final analytic sample of 2798 singleton births to 2749 women (n=48 and n=2 women with 2 or 3 births, respectively). Except for previous cesarean, we included all other indications for cesarean (e.g. for fetal indications).

### Exposure

Circulating 25(OH)D is considered the best biochemical marker of vitamin D status from oral intake and cutaneous production.<sup>29</sup> We used liquid-chromatography-tandem mass spectrometry to measure total serum 25(OH)D [25(OH)D<sub>2</sub> + 25(OH)D<sub>3</sub>]. A DEQAS (Vitamin D External Quality Assessment Scheme)-proficient laboratory performed the assay based on National Institute of Standards and Technology (NIST) standards. This method has a lower detection limit of 1 ng/mL and no upper limit. No total 25(OH)D concentrations fell below the detectable range. The intra-assay coefficient of variation was 8.2% for 25(OH)D<sub>2</sub> and 5.9% for 25(OH)D<sub>3</sub>. Samples had been stored over 40 years at -20°C with no known freeze-thaw cycles. 25(OH)D is not likely to degrade over time or from UV exposure.<sup>30</sup> We additionally conducted a pilot study using CPP samples that demonstrated significant degradation of 25(OH)D was not likely.<sup>31</sup> We used 25(OH)D cutpoints of 30, 50, and 75 nmol/L, since these are cutpoints of interest in defining deficiency, insufficiency, and optimal vitamin D status.<sup>32, 33</sup>

### Labor and delivery outcomes

The obstetrician in charge of the woman's medical care recorded a detailed summary of the labor and delivery events including length of the first and second stages of labor (in hours and minutes); details about use of forceps or vacuum extractor to deliver the baby's head in vaginal vertex births (including indications for use); details about cesarean delivery

(including all applicable indications for cesarean); and a record of either “uterine dysfunction” (first half of CPP) or “arrested progress of labor” (second half of CPP). The CPP instruction manual defined the onset of labor as “the onset of regular uterine contractions which are of increasing intensity and duration, which result in progress as measured by effacement and/or dilation of the cervix or descent of the presenting part.” The best estimate of labor onset was determined retrospectively by the obstetrician from all available information. First stage of labor was defined by CPP as the onset of labor to full cervical dilation and the second stage was defined as the end of the first stage to complete delivery of the infant.

We defined prolonged first stage of labor as > 18 hours<sup>34</sup> and prolonged second stage of labor as > 2 hours.<sup>35</sup> As a secondary analysis, we defined prolonged second stage by parity as > 3 hours for primiparous women and > 2 hours for multiparous women. There were too few cases of primiparous women > 4 hours to use this definition (n=5). We defined primary cesarean delivery as delivery by cesarean for all indications except previous cesarean. “Elective” was never listed as an indication for cesarean deliveries in this sample. We excluded women with no labor to exclude planned cesarean deliveries. We defined instrumental delivery as use of forceps or vacuum extraction in vertex, vaginal deliveries. We further defined *indicated* instrumental delivery by excluding those with “elective” listed as the indication for forceps or vacuum use. Since cesarean or instrumental delivery can alter the length of labor, we additionally excluded these cases from prolonged labor outcomes as a secondary definition.

### Covariates

We examined gestational age at the time of blood draw; season at the time of blood draw (winter/spring vs. summer/fall), maternal prepregnancy body mass index (BMI; reported weight (kg)/measured height(m)<sup>2</sup>), height, race, parity at enrollment, marital status, smoking status, socioeconomic status (by a continuous index developed from education, occupation, and income<sup>36</sup>), and age; sex of the infant; latitude, and study site as covariates.

### Statistical Analysis

Due to missing data in the exposure, outcomes, and covariates, used the Markov chain Monte Carlo technique with a multivariate normal imputation method to create 5 complete datasets with imputed values in place of missing values (*mi impute mvn* in Stata).<sup>37</sup> We assumed data were missing at random. We imputed our exposure: 25(OH)D (missing n = 108); outcomes: length of stage 1 (n = 192), length of stage 2 (n = 186), and instrumental delivery (n = 9); and covariates: maternal pregravid weight (n = 62), height (n = 149), socioeconomic status (n = 57), month of blood draw (n = 34), smoking status (n = 15), and parity (n = 3) based on complete data for gestational age at blood draw, gestational age at delivery, season at delivery, maternal age, race, marital status, delivery route, live birth status, trimester at study entry, infant sex, birth weight, and study site. It is recommended to impute both exposures and outcomes.<sup>37</sup> Results from the imputed datasets are presented based on fitting models separately for each of the 5 datasets and combining results.

We used multivariable log-binomial regression models with robust variance estimation (to account for correlation among repeated pregnancies) to estimate adjusted risk ratios for the association between 25(OH)D and outcomes. 25(OH)D was specified as continuous; as categorical with cutpoints at 30, 50, and 75 nmol/L; and as linear splines with a knot at the cutpoint (one knot per model). Effect measure modification was tested on the multiplicative scale between 25(OH)D and BMI (overweight or not), race/ethnicity, gestational age at blood sample, and parity using the Wald test ( $p < 0.10$ ). We tested if any potential confounders (gestational age at blood sampling, season at blood sampling, prepregnancy BMI, height, race, marital status, smoking, socioeconomic status, age, infant sex, and study site) changed the coefficient of interest by  $>10\%$  after removing them one at a time from full models, an epidemiologic method of selecting covariates.<sup>38</sup> Only study site met our criterion for confounding. We also included maternal race and prepregnancy BMI in adjusted models out of convention. To account for the loss of statistical power from including 11 indicator variables for study site, we additionally ran 1) adjusted log-binomial models with latitude of study site (continuous) in place of site and 2) conditional logistic regression models, conditioned on site and controlling for race and BMI. These models produced similar results, so we only presented the original approach.

We tested the sensitivity of our results to our sample selection by limiting to those who delivered at term, excluding those who had labor induction, and excluding extreme high statistical outliers for 25(OH)D ( $>167$  nmol/L). For all analyses, we used Stata 12 (StataCorp, College Station, TX).

## Results

Most women were white or black, 20–29 years old, of normal weight before pregnancy (BMI 18.5–24.9 kg/m<sup>2</sup>), married, and had delivered a previous child (Table 1). Close to half reported smoking during pregnancy. Mean (SD) 25(OH)D was 50.3 (27.8) nmol/L. The proportions of women with 25(OH)D  $<30$  nmol/L,  $<50$  nmol/L, and  $<75$  nmol/L were 23.9%, 57.0%, and 84.3%, respectively. The proportion of women with prolonged stage 1, prolonged stage 2, cesarean delivery, or indicated instrumental delivery were 4.5%, 3.3%, 1.9%, and 7.5%, respectively. We examined characteristics by adverse labor and delivery outcomes and found a higher proportion of white women among those with prolonged second stage (75%) or operative deliveries (56–63%) compared to the whole cohort (48%; Table 1). We also found higher proportions of nulliparous women and male infants among those adverse labor and delivery outcomes. As well, incidence of outcomes varied by latitude of study site, with more prolonged second stage of labor and indicated instrumental delivery cases in the north.

Maternal 25(OH)D concentrations of 30–49, 50–74, or 75 compared to  $<30$  nmol/L were not associated with risk of prolonged stage 1 in unadjusted models (Table 2). Adjusting for prepregnancy BMI, race, and study site yielded a similar, non-significant association between 25(OH)D and prolonged first stage of labor. In unadjusted models, 25(OH)D of 50–74 and 75 vs.  $<30$  nmol/L were each associated with increased risk of prolonged second stage of labor. However after confounder adjustment, the risk ratios were attenuated to the null. Results were similar when we used a parity specific classification of prolonged second

stage (n=34 cases), and when we excluded women with cesarean or indicated instrumental delivery from the prolonged labor cases (data not shown). 25(OH)D concentrations were not associated with risk of cesarean or instrumental delivery in unadjusted or adjusted models (Table 3).

None of these results were meaningfully different when we expressed 25(OH)D as a continuous variable or with splines, nor after additional adjustment for gestational age at blood sampling, season at blood sampling, height, marital status, smoking, socioeconomic status, age, and infant sex (data not shown). Pregravid BMI, race, parity, and gestational age at blood draw did not modify any of the associations between 25(OH)D and these adverse labor and delivery outcomes. There were no meaningful differences in our results after excluding mothers with induced labor, preterm births, or mothers with extreme high outliers for 25(OH)D >167 nmol/L (data not shown), or after using an alternate classification of prolonged labor (>3 hours for primiparous women, data not shown).

## Discussion

We found no associations between maternal vitamin D status and risk of prolonged first or second stage of labor, cesarean delivery, or indicated instrumental delivery after adjustment for important confounders including BMI, race, and study site. Importantly, our findings were in a cohort of pregnancies from the 1960's, a time with a very low rate of epidural use, oxytocin augmentation of labor, cesarean delivery, and medically indicated preterm birth compared to modern clinical practice.

Whereas other studies have only examined cesarean delivery, our study uniquely took a comprehensive approach to examining labor and delivery outcomes beyond cesarean delivery that may be related to muscle function. We examined prolonged stage 1 of labor, which is commonly related to myometrial function, and prolonged stage 2 of labor and instrumental delivery, each of which could be related to a woman's ability to push and vaginally deliver her baby. Our finding of a lack of an association with cesarean agree with two studies in Europe that examined 25(OH)D in early gestation and risk of elective and emergency cesarean delivery but did not adjust for confounders.<sup>23, 24</sup> The results of a US study of early maternal vitamin D status, however, did not agree with our findings.<sup>21</sup> Scholl et al examined 25(OH)D at a mean of 13.7 weeks gestation among 1153 low-income women and found an increased risk of total and primary cesarean when women had 25(OH)D <30 nmol/L compared with 50–125 nmol/L. Further, they examined risk of cesarean due to prolonged labor and found a 2-fold increased risk for women with <30 nmol/L compared with 50–125 nmol/L after confounder adjustment. In our study, cesarean was rare (<2%) compared to the Scholl study (25%). Yet, we additionally examined instrumental vaginal deliveries, which were more common and similarly found no relationship with vitamin D. Vitamin D might also influence cesarean and operative delivery rate, in principle, by increasing birth weight. We have observed a positive association between maternal 25(OH)D and birth weight in this population.<sup>39</sup> As birth weight is on the causal path between vitamin D status and labor and delivery outcomes, we specifically chose to estimate the total effect of vitamin D on these outcomes, and not the effect through specific pathways like birth weight.

Three small studies examined maternal 25(OH)D concentrations *at delivery* and risk of cesarean.<sup>22, 25, 40</sup> One US study found that vitamin D deficient women (<37.5 vs. 37.5 nmol/L) were 3.8 times more likely to have a primary cesarean;<sup>25</sup> another US study observed no relationship between 25(OH)D and all-cause cesarean; and one study in Pakistan found no association between 25(OH)D and cesarean with cephalopelvic disproportion.<sup>22</sup> These studies cannot be easily compared to ours, since the gestational timing of 25(OH)D assessment was different, however maternal vitamin D status close to the time of delivery – rather than in early pregnancy – may be important.

The vitamin D receptor has been identified in smooth<sup>16</sup> and skeletal muscle tissue,<sup>17, 41</sup> and both animal<sup>38, 39</sup> and human<sup>40, 41</sup> studies have demonstrated the importance of vitamin D in muscle function. Vitamin D status is related to maximal oxygen consumption, muscle strength, and protein synthesis in muscle tissue.<sup>42</sup> Studies of vitamin D and muscle strength or performance have been conducted in non-pregnant populations,<sup>43, 44, 45</sup> but not in pregnant women. The mixed findings in the literature on vitamin D and labor and delivery outcomes suggests that the impact of vitamin D on myometrial function during labor and delivery should be tested in human and animal studies.

Differences in labor and delivery practices between the 1960s and the present allowed us to uniquely examine the relationship between maternal vitamin D status and adverse outcomes at a time when the threshold was high for cesarean delivery. Indeed, the CPP cohort had very low rates of medically indicated preterm births, epidural, and labor induction (7%), and possibly a more natural course of labor onset and progression. Since ultrasound was not available, there were likely inaccuracies in gestational dating. Of note, vaginal birth after cesarean was not in practice at this time, so we expect by including only women that labored (i.e. attempted vaginal birth) and those without previous cesarean as an indication for cesarean, we have effectively limited the sample to primary cesarean deliveries. Although, we cannot be certain some cases were not elective.

We did not control for epidural use or episiotomy, which were rare (~4%) and very common (~68%) at the time of the CPP, respectively.<sup>8</sup> It is unlikely that epidural use could be related to vitamin D status (i.e. not a confounder) and we do not expect the low rate could impact our results. Episiotomy was typically done for forceps and vacuum deliveries, thus controlling for it should not change our instrumental delivery results.<sup>46</sup> To further account for its possible impact, we examined 25(OH)D and length of labor as a continuous outcome, and also found no associations (data not shown). It would have been ideal to examine myometrial dysfunction, but related information was collected inconsistently across CPP, preventing us from evaluating this outcome fully. However, mothers with “uterine dysfunction” or “arrested progress of labor” (as mentioned in the methods) had substantially higher rates of each of the adverse outcomes we examined and this was not associated with 25(OH)D (data not shown). Ideally, studies should measure myometrial dysfunction by contraction frequency or Montevideo units.

Future studies should examine maternal vitamin D status close to the time of delivery in larger cohorts. Maternal vitamin D status has been associated with many aspects of pregnancy health, however, our findings do not support an association of early pregnancy

25(OH)D and risk of prolonged labor or operative delivery. As cesarean rates are very high in the US and worldwide,<sup>9</sup> and length of labor may be longer in modern populations with more medical interventions of labor compared to the 1960s,<sup>8</sup> modifiable risk factors for these adverse labor and delivery outcomes need to be identified.

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**Table 1**  
 Characteristics of women with singleton pregnancies and their newborns by labor and delivery outcomes

	Total (n=2798)	Prolonged stage 1 (n=126)	Prolonged stage 2 (n=93)	Primary cesarean delivery (n=52)	Indicated instrumental delivery (n=211)
	%				
Race					
White	48.0	50.1	75.3	55.8	63.0
Black	44.9	43.4	18.3	38.5	32.7
Puerto Rican	7.1	6.5	6.5	5.8	4.2
Maternal age, years					
<20	24.0	36.6	34.6	15.4	27.5
20-29	60.5	47.8	57.2	67.3	59.7
30	15.5	15.6	8.2	17.3	12.8
Prepregnancy BMI, kg/m <sup>2</sup>					
<18.5	10.6	10.8	13.8	10.8	11.1
18.5-24.9	71.6	72.3	78.3	69.2	74.5
25-29.9	13.7	14.6	5.6	15.8	12.5
30	4.0	2.2	2.4	4.2	2.0
Nulliparous	33.9	65.7	86.7	51.9	54.0
Married	80.4	81.7	82.6	82.7	80.6
Smoking at study entry	47.2	44.2	45.6	42.3	49.3
Trimester at study enrollment					
First (<14 weeks)	27.3	28.3	35.9	28.8	33.2
Second (14-26 weeks)	72.7	71.7	64.1	71.1	66.8
Latitude of study site					
41-45 degrees North	47.8	42.0	73.6	50.0	62.1
38-40 degrees North	43.7	50.6	23.6	48.1	34.6
29-35 degrees North	8.4	7.5	2.8	1.9	3.3
Serum 25(OH)D, nmol/L	50.3 ± 27.8	52.5 ± 26.4	59.6 ± 35.8	47.5 ± 22.1	51.6 ± 27.6
Male infant	50.5	56.1	55.6	55.8	57.3
Gestational age at delivery <sup>a</sup>	38.5 ± 3.0	38.7 ± 2.9	39.0 ± 2.9	38.7 ± 2.1	38.6 ± 3.0
Infant birth weight, g <sup>a</sup>	3091 ± 528	3083 ± 594	3212 ± 471	3261 ± 472	3103 ± 528

Note: All data based on combined results from 5 imputed datasets.  
Abbreviations: BMI, body mass index; 25(OH)D, 25-hydroxyvitamin D.  
<sub>p</sub>Data presented as mean  $\pm$  SD.

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**Table 2**

Maternal serum 25(OH)D at and risk of prolonged labor in 2798 singleton pregnancies.

25(OH)D <sup>a</sup>	Cases	% with outcome	Unadjusted risk ratio	95% CI	Adjusted risk ratio	95% CI
Stage 1 > 18 hours	126	4.5				
<30 nmol/L	27	4.0	Reference		Reference	
30–49 nmol/L	34	3.8	0.94	0.56 – 1.58	0.97	0.57 – 1.66
50–74 nmol/L	42	5.4	1.36	0.81 – 2.26	1.43	0.83 – 2.48
75 nmol/L	23	5.1	1.28	0.73 – 2.27	1.37	0.75 – 2.53
Stage 2 > 2 hours <sup>c</sup>	93	3.3				
<30 nmol/L	13	2.0	Reference		Reference	
30–49 nmol/L	22	2.4	1.19	0.59 – 2.40	0.94	0.46 – 1.93
50–74 nmol/L	36	4.8	2.36	1.23 – 4.52	1.61	0.81 – 3.20
75 nmol/L	22	5.0	2.44	1.19 – 5.03	1.59	0.74 – 3.42

Note: All data based on combined results from 5 imputed datasets.

Abbreviation: 25(OH)D, 25-hydroxyvitamin D.

<sup>a</sup> 25(OH)D measured at 26 weeks gestation.

<sup>b</sup> Adjusted for prepregnancy BMI, race/ethnicity, and study site. Conditional logistic regression models conditioned on study site and adjusted for prepregnancy BMI and race/ethnicity yielded similar results.

<sup>c</sup> n=2759 women who entered stage 2 labor.

**Table 3**

Maternal serum 25(OH)D at and risk of operative delivery in 2798 singleton pregnancies.

25(OH)D <sup>a</sup>	Cases	% with outcome	Unadjusted risk ratio	95% CI	Adjusted <sup>b</sup> risk ratio	95% CI
Primary cesarean delivery	52	1.9				
<30 nmol/L	13	1.9	Reference		Reference	
30–49 nmol/L	14	1.5	0.78	0.37 – 1.64	0.76	0.38 – 1.55
50–74 nmol/L	19	2.5	1.28	0.64 – 2.57	1.22	0.61 – 2.44
75 nmol/L	6	1.4	0.70	0.27 – 1.84	0.65	0.24 – 1.81
Indicated instrumental delivery <sup>c, d</sup>	211	7.6				
<30 nmol/L	50	7.6	Reference		Reference	
30–49 nmol/L	63	6.9	0.91	0.63 – 1.31	0.84	0.57 – 1.22
50–74 nmol/L	61	8.1	1.07	0.74 – 1.54	0.92	0.63 – 1.35
75 nmol/L	36	8.4	1.10	0.72 – 1.68	0.88	0.56 – 1.39
Primary cesarean or indicated instrumental delivery <sup>c</sup>	262	9.4				
<30 nmol/L	63	9.5	Reference		Reference	
30–49 nmol/L	77	8.3	0.88	0.64 – 1.22	0.83	0.60 – 1.16
50–74 nmol/L	80	10.5	1.11	0.81 – 1.52	1.00	0.72 – 1.39
75 nmol/L	42	9.7	1.02	0.70 – 1.50	0.87	0.58 – 1.30

Note: All data based on combined results from 5 imputed datasets.

Abbreviation: 25(OH)D, 25-hydroxyvitamin D.

<sup>a</sup> 25(OH)D measured at 26 weeks gestation.

<sup>b</sup> Adjusted for pregnancy BMI, race/ethnicity, and study site (except cesarean models adjusted for latitude instead of study site). Conditional logistic regression models conditioned on study site and adjusted for pregnancy BMI and race/ethnicity yielded similar results.

<sup>c</sup> Vaginal delivery by forceps or vacuum excluding those with “elective” listed as indication.

<sup>d</sup> n=2759 women who entered stage 2 labor.