OBSTETRICS

Spatiotemporal electrohysterography patterns in normal and arrested labor

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OBJECTIVE: The purpose of this study was to investigate the spatiotemporal patterns of uterine electrical activity in normal and arrested labors.

STUDY DESIGN: From a database of electrohysterograms, 12 subjects who underwent cesarean delivery for active-phase arrest were each matched with 2 vaginally delivered controls. Using 30-minute segments of the electrohysterogram during the arrest, or the same dilation in controls, the center of uterine electrical activity was derived. The vertical motion of this center of uterine activity was determined for each contraction and the frequencies of movement patterns analyzed.

RESULTS: Predominantly upward movement of the center of uterine activity (longer and/or stronger contraction at the fundus) was more common with normal dilation ($P = .003$). Receiver operating characteristic curve analysis gave an area under the curve of 0.91 for predicting outcome (vaginal vs cesarean delivery).

CONCLUSION: There is a significant correlation between upward movement of the center of uterine activity (fundal dominance) and current labor progress.

Key words: Center of uterine activity, cesarean delivery, dystocia, electrohysterogram, vaginal delivery

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★ EDITORS' CHOICE ★

In 2004, the cesarean delivery rate was 29.1% of all births, a new high for the US[1] and well above the government's Healthy People 2000 goal of 15%. Despite this ongoing national initiative to reduce cesarean deliveries, the rate continues to rise (by 6% in 2003-2004), due to both an increase in the primary cesarean rate and a decrease in the rate of vaginal birth after cesarean (VBAC). Failure to progress in labor (dystocia) is the leading cause of nonelective cesarean delivery. Taken together with the declining VBAC rate, dystocia may directly or indirectly account for 50-60% of all cesarean deliveries.[2] Diagnosis of dystocia, however, is a matter of controversy. The traditional "2-hour rule" (2 hours of adequate contractions without cervical dilation) was successfully challenged,[3] and the recommendation dropped from the most recent American College of Obstetricians and Gynecologists (ACOG) Practice Bulletin regarding dystocia.[4]

Dystocia is a labor abnormality resulting in abnormal progression, and may be attributable to power (uterine contractions and maternal expulsive effort), passenger (position or size of the fetus), or passage (shape or size of the birth canal). Active management of labor presumes the significance of power problems, yet intrauterine pressure monitoring does not predict labor dystocia.[3] It has long been recognized that generation of pressure alone is not sufficient to achieve complete cervical dilation. A descending pressure gradient from the fundus to the cervix may also be important.[5] While tocodynamometry and intrauterine pressure monitoring measure overall uterine activity, their use is impractical

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Dr N. R. Euliano is president, and Ms Marossero and Mr Nguyen are employees of Convergent Engineering. Drs T. Y. Euliano and N. R. Euliano, Ms Marossero, and Dr Principe are listed on patents filed for some of the technology described in this paper.

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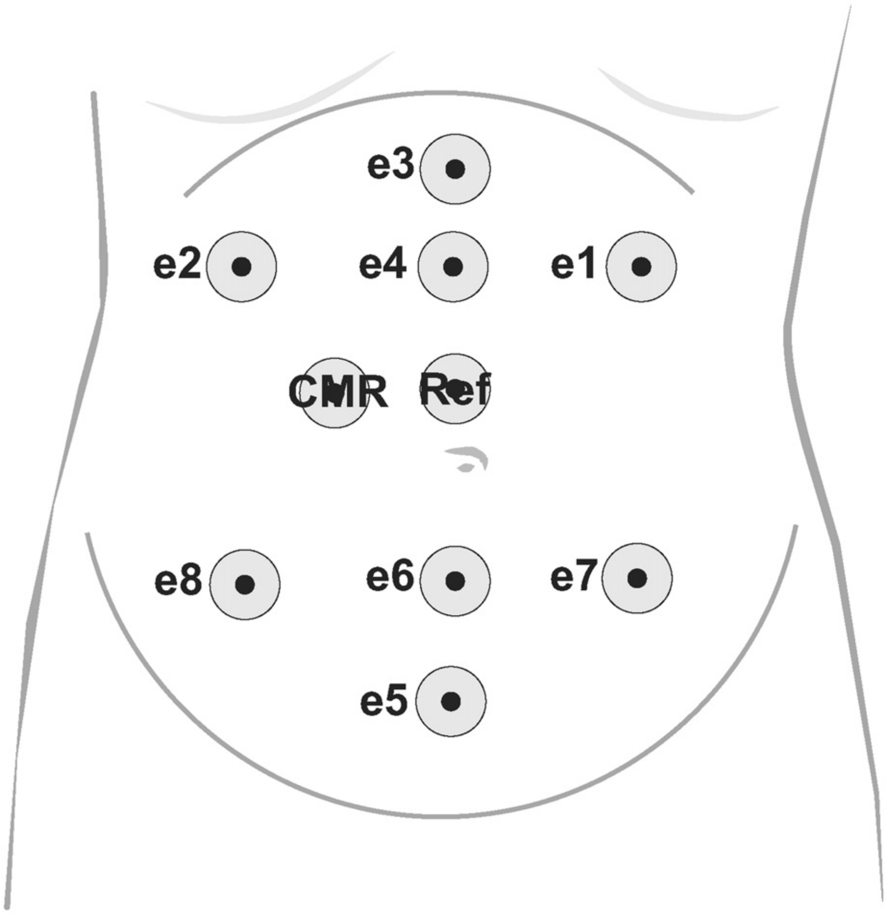
FIGURE 1
Electrode locations



CMR, common mode rejection; *e*, electrode; *Ref*, reference.

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for mapping activity at different locations around the uterus. Transabdominal electrohysterography, noninvasive monitoring of the electrical signal generated as the contraction spreads through the myometrium, provides such an opportunity. This study compared the spatiotemporal patterns of electrical activity during uterine contractions in patients with normal and arrested labor.

MATERIALS AND METHODS

We conducted a case-control study using data derived from a larger study designed to noninvasively collect fetal electrocardiographic (ECG) and uterine electrical activity, represented by the electrohysterogram, or EHG. Following University of Florida College of Medicine Institutional Review Board approval, the protocol was instituted in 2001 at Shands Hospital at the University of Florida. The service consists of resident physicians supervised by faculty and fellows. All patients admitted for expectant labor management with a singleton gestation in cephalic position were eligible for inclusion, but those in active labor were specifically sought. The monitoring period depended on the availability of research personnel, and thus often included only a portion of each subject's labor.

The final experimental setup, settled upon in 2005, was as follows: after written informed consent and skin preparation by gentle rubbing with abrasive gel, 10 3-cm^2 silver/silver chloride (Ag/$AgCl_2$) electrodes (Ambu, Glen Burnie, MD) were positioned on the maternal abdomen (Figure 1). The electrodes were connected to an amplifier in a monopolar fashion with centrally located common reference and common mode rejection leads. Electrode positions were modified slightly for each patient, as required by the location of the tocodynamometer and ultrasound fetal heart rate monitor, but the midline fundal and suprapubic locations were fixed. Impedance of each electrode was measured (as compared with the reference) (General Devices EIM-105 Prep-Check, Ridgefield, NJ). Skin preparation was repeated as needed at each site until the measured impedance was below 10 kΩ where possible. The 8 recorded signals were fed to an 8-channel high resolution, low-noise unipolar amplifier specifically designed for fetal ECG signals. All 8 signals were measured with respect to the reference electrode. The amplifier 3 dB bandwidth was 0.1-100 Hz, with a 60-Hz notch filter. The amplifier had a variable gain, but for our purposes the gain was set to 6500. The data were transferred to a personal computer via a 16-bit resolution A/D card and stored at a 200-Hz sampling frequency. In addition to electrical signals, data from the standard maternal-fetal monitor (Corometrics; GE Medical Systems, Waukesha, WI) were also collected for comparison. The EHG-derived contraction curve was viewed only by the research personnel and was not used for patient care.

For this study, we analyzed those subjects who underwent primary cesarean delivery for labor arrest after achieving at least 5-cm cervical dilation, and had EHG monitoring with the final amplifier design (2 versions) for at least 30 minutes during the period of arrest. Patients were excluded if they had a uterine scar due to the increased rate of repeat cesarean delivery in this population.[6] Each potential subject's chart was reviewed by our maternal-fetal medicine specialist (R.K.E.) to confirm the diagnosis (arrest of dilation at ≥ 5 cm, and no other indication for cesarean delivery). Each of these index subjects was matched with 2 vaginally delivered controls with no prior cesarean delivery and a normal labor curve (active phase dilation > 1 cm/hr). The subjects were matched for gestational age ± 2 weeks, body mass index (BMI) ± 10, parity (nulliparous or parous), induction vs spontaneous labor, and EHG monitoring during dilation within ± 1 cm of the dystocia. These matching criteria were

FIGURE 2
Construction of the uterine contraction map

A, Shows a single contraction in 8 EHG channels, referenced to the umbilicus. Neighboring electrodes were subtracted pairwise to create a geographic map of the uterine activity over different areas of the abdomen. Following subtraction, the resulting 15 signals were low-pass filtered as shown in **B**, Which demonstrates differences in the timing and amplitude of the EHG signals at each location on the abdomen. **C**, Is a single frame from a contraction movie of spatial contraction intensity images, where *black* corresponds to high power and *light gray* to low. This frame corresponds to an instant near the peak of the contraction. These video clips show the Gaussian model used to determine the center of uterine activity (CUA) during a representative contraction in a patient who delivered vaginally (SVD), and 1 who underwent cesarean delivery for labor arrest (dystocia). Relative power intensity ranges from *blue* (low) to *burgundy* (high). Of note, the power cannot be compared between patients. In the SVD clip, the CUA begins mid-uterus, moves first downward, then distinctly upward during the latter half of the contraction. This upward movement represents higher contraction power in the fundus than the lower uterine segment, pushing the fetal presenting part toward the cervix. In contrast, the dystocia clip shows the CUA beginning in the lower portion of the uterus, progressing upward, then back downward, signifying a relative relaxation of the uterine fundus during the second half of the contraction. This lack of fundal dominance commonly occurred in arrested patients.

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selected by R.K.E. based on factors likely to affect labor outcome. Parity, maternal size, and induction status are supported by Hin et al.[7]

Sixteen cesarean delivery patients met the inclusion criteria; 2 were excluded for unusable data (amplifier saturation during collection and low signal-to-noise ratio), and 2 for lack of matching controls. The remaining 12 index subjects were successfully matched with the nearest 2 vaginally delivered controls that met the criteria above. Upon reviewing the EHG data for the controls, some had noise in the signal at the dilation of interest (determined by assuming a linear dilation rate between surrounding cervical examinations); thus, the dilation at the segment used occasionally varied by more than ± 1 cm of the dystocia, but never more than ± 2 cm.

EHG

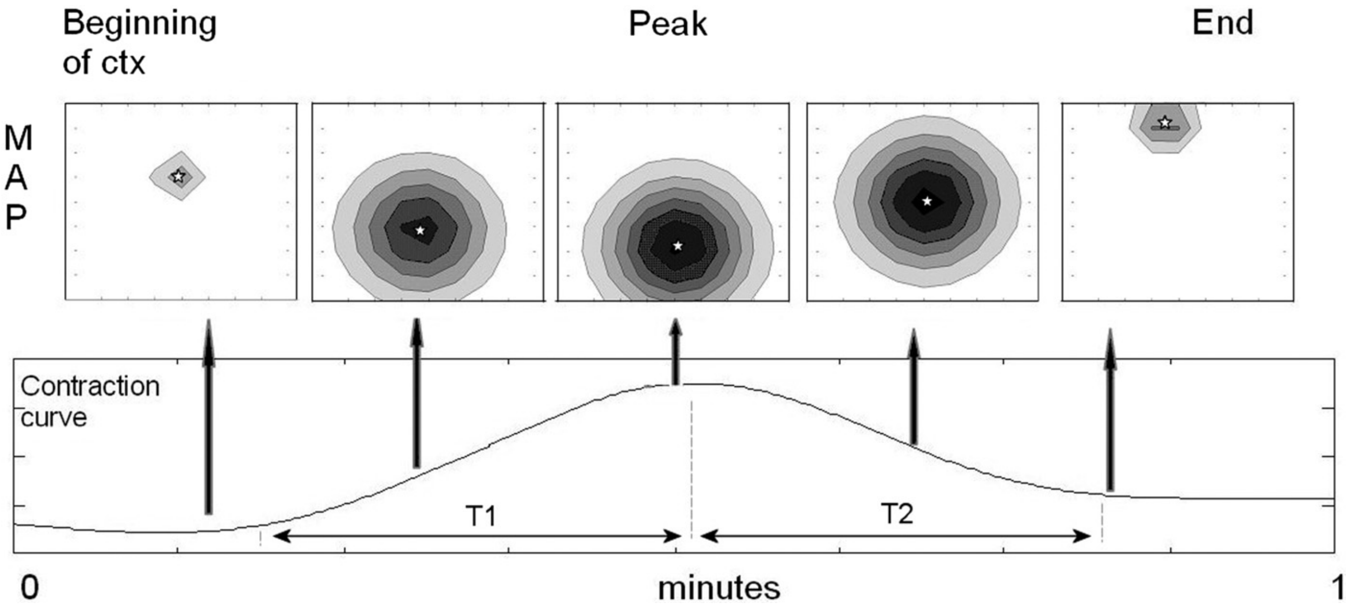
From the 8 individual electrode signals (Figure 2, A; videos), pairwise subtraction between neighbors removed common signal characteristics and provided local information about the uterine electrical activity pattern. After channel normalization, rectification, and filtering (Butterworth low-pass filter with a cutoff at 0.02 Hz), these signals represented the local contraction strength at 17 locations over the abdomen, displayed as a 5×5 grid (Figure 2, B). This grid was calculated 10 times per second and the data interpolated over the abdomen and over time, generating a real-time movie of the relative intensity of the uterine muscle activity over the abdomen (Figure 2, C). From this uterine contraction map, a Gaussian model was used to determine the center of uterine activity (CUA). Figure 3 demonstrates the evolution of the electrical map during a sample contraction, with the intrauterine pressure shown in the curve at the bottom and the white star indicating the CUA. The vertical motion of the CUA was determined by its location at the beginning, peak, and end of the contraction.

Using a 30-minute window positioned during the labor arrest, or near the same dilation in the controls, the vertical direction of CUA movement during each half of each contraction was calculated: T1 = onset to peak; T2 = peak back to baseline. The precise anatomic location of the CUA was patient dependent, varying with the exact location of the electrodes; therefore, only the direction of the CUA was analyzed.

When the contraction begins (Figure 3, *left*), energy builds and spreads throughout the uterus. By the peak of the contraction (*end* of T1; Figure 3, *center*), the vast majority of the uterus is contracting. Therefore, the direction of the CUA during T1 depends primarily on where the contraction began. During T2, the contraction begins to subside. If the lower portion of the uterus begins to relax earlier than the upper portion, the CUA moves upward (Figure 3, *right*).

Finally, contraction patterns were classified as moving downward (toward the lower uterine segment [LUS]) or upward (toward the fundus) for each half of

FIGURE 3
Determination of center of uterine activity movement



A simplified representation of the uterine activity. The center of uterine activity is denoted by the star in each figure, and its vertical motion over time can be tracked.

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each contraction, resulting in 4 contraction patterns: LUS-fundal, LUS-LUS, Fundal-LUS, and fundal-fundal. The percentage of each pattern in a 30-minute segment of data from each patient was calculated.

Statistics

Regression diagnostics, focused on residual analysis, led to the conclusion that the assumption of Gaussian errors was appropriate. For each arrest patient, the prevalence of each of the 4 contraction patterns was evaluated by calculating the average prevalence for the vaginal deliveries in each of the matched clusters and subtracting the prevalence of the associated cesarean delivery. We used the continuous percentage of the 4 contraction patterns because categorizing that variable would lose power for hypothesis testing and reduce the precision of the estimated odds. This difference was then tested using a 2-tailed Student *t* test. Canonical discriminant (multivariate) analysis was used to gain statistical power for the small sample size. This established the relative significance of each labor pattern for predicting the outcome of cesarean delivery for dystocia. Logistic regressions compared the prediction of outcome based solely on the pairing variables versus with the addition of the contraction pattern information. This regression allowed adjustment for the pairing covariates and produced receiver operating characteristic (ROC) curves. A chi-square statistic was calculated to summarize this comparison. Data were analyzed using the SAS system for personal computers (SAS Institute, Cary, NC).

TABLE
Pairing variables and patient demographics (mean ± standard deviation)

	Delivery		
Patient variable	Cesarean N = 12	Vaginal N = 24	*P* value
Gestational age (wk)	39.0 ± 1.7	38.5 ± 1.1	.43
Body mass index	34.2 ± 6.3	30.4 ± 4.9	.12
Dilation at monitoring (cm)	7.0 ± 1.7	7.4 ± 1.2	.51
Newborn weight (g)	3479 ± 512	3131 ± 372	.07
Maternal age (y)	24.1 ± 4.8	23.4 ± 5.2	.73
Duration of arrest (h)	6.1 ± 3.1		
Montevideo unit maximum (mmHg)	255 ± 70		
Oxytocin augmentation	100%	71%	
Epidural use	100%	96%	

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RESULTS

The average duration of arrest in the cesarean delivery cohort was 6 ± 3 hours. All arrest patients and 17/24 vaginally delivered patients received oxytocin augmentation. All patients had a sustained contraction frequency of every 1-3 minutes, and of the 11 cesarean patients who had intrauterine pressure (IUP) monitoring, all achieved Montevideo units (MVU) > 150 mmHg. The groups were not significantly different with regard to the pairing variables (gestational age, BMI, dilation at monitoring), or in newborn weight or maternal age (Table). No patient experienced any adverse events related to skin preparation or the study protocol in general.

Predominantly fundal movement of the CUA was more common in those dilating normally (Figure 4). During T1, 12/24 vaginally delivered patients vs 1/12 cesarean delivery patients had a predominantly fundal CUA direction. Similarly, during T2, 17/24 vaginally delivered vs 3/12 cesarean delivery patients had the same pattern. Overall, 23/24 vaginally delivered patients had a predominantly fundal CUA direction during T1 and/or T2, compared with 4/12 for the cesarean delivery cohort. Comparing each pattern, 2 differed significantly between the groups: LUS-LUS was more common in cesarean delivery patients (P = .015), while fundal-fundal was more common with vaginal deliveries (P = .003).

Logistic regression analysis using only the pairing variables—gestational age, BMI, parity, spontaneous vs induced labor, and dilation at the time of study—to predict outcome (cesarean for arrest vs vaginal delivery), resulted in an area under the ROC curve (AUC) of 0.79. Upon adding 3 of the 4 dilation patterns (because the fourth would be ipsative), the AUC increased to 0.91 (Figure 5). Calculating a chi-square value of 13.090 for the difference between 2 models' log likelihood score gives a P value = .004, indicating the addition of the dilation patterns is a significant predictor of delivery type.

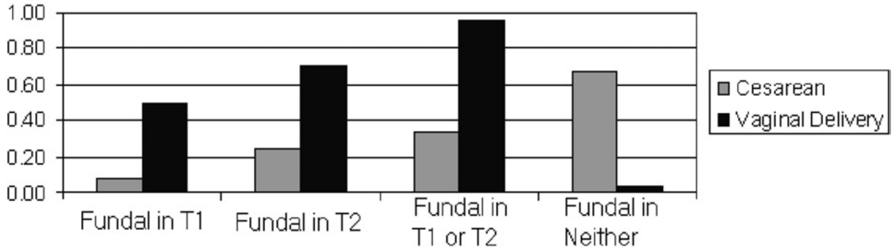
COMMENT

Intrapartum assessment of uterine activity is routinely employed to guide active management of labor and delivery. The goal of such management is 2-fold: (1) progress in labor resulting in vaginal delivery, and (2) identification of unsuccessful labor that requires cesarean delivery. While the gold standard for assessing labor progress is serial cervical examinations, the risk of infection coupled with the inherent inaccuracy of the measure limits its use for assessment at intervals of less than 2-3 hours.[8,9] Though sufficient for normal labors, in the slowly dilating patient, these inaccuracies can complicate the diagnosis of labor arrest. The recent introduction of continuous cervical dilation and fetal head station monitoring (Computerized Labor Monitor; Barnev Ltd, Netanya, Israel) may improve labor monitoring[10]; however, its invasive nature (fetal scalp and cervical clips) may limit adoption.

Neither tocodynamometry nor IUP monitoring is predictive of successful dilation, and use of an IUP catheter does not improve outcome.[11,12] Montevideo units (MVUs) do not differ between labor outcomes (cesarean for dystocia vs vaginal delivery) in patients with abnormally progressing labor undergoing augmentation.[3]

While generation of intrauterine pressure is necessary, since at least 1950, the

FIGURE 4
Predominant patterns of center of uterine activity movement



Fundal indicates movement of the CUA toward the fundus; T1 indicates the time from contraction onset to contraction peak, and T2 indicates the time from contraction peak to return to baseline.

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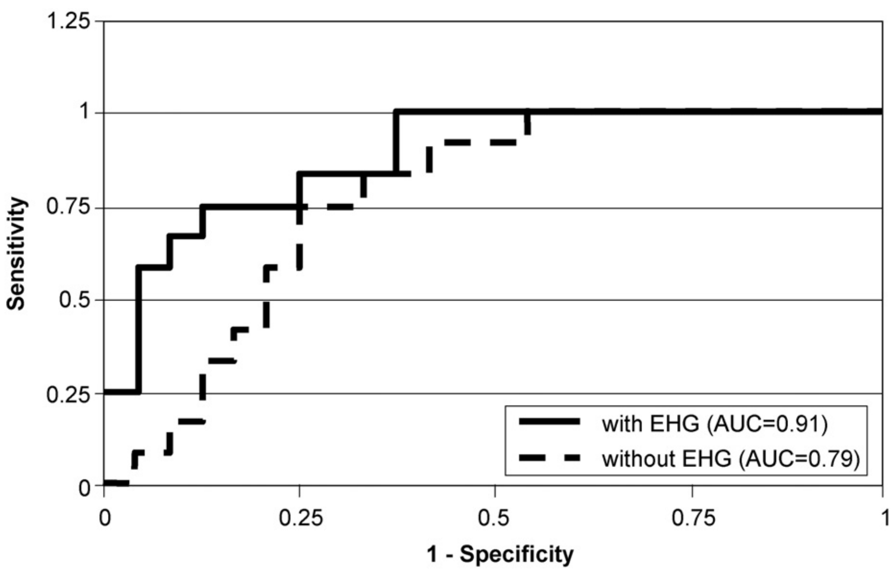
FIGURE 5
Receiver operating characteristic causes for labor arrest



Receiver operating characteristics curves for likelihood of labor arrest and cesarean delivery using matching criteria (gestational age, BMI, parity, spontaneous vs induced labor, and dilation at time of study) with or without the addition of EHG data.

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need for fundal dominance and a descendent gradient has been recognized as essential for normal labor.[5] This gradient should cause the fetal presenting part to exert force on the cervix, and there is evidence this 'head-to-cervix' force better predicts the rate of cervical dilation and mode of delivery.[13] Head-to-cervix force, however, is technically challenging to measure, and its dynamically changing characteristics are difficult to quantify. Magnetomyography, investigation of the minute magnetic fields generated by the electrical activity, has been preliminarily investigated for spatialtemporal mapping of the uterus prior to labor.[14] Due to the equipment, patient positioning issues, and requirement for a shielded room, this technology is not yet ready for clinical application.

Using electrohysterography, we investigated and compared a single spatial characteristic of uterine contractions during normal and arrested labors: vertical movement of the CUA. This movement describes the changing ratio of fundal-to-LUS contraction strength. Women who were dilating normally demonstrated more fundal direction of the CUA than those with labor arrest. This upward movement implies either further increasing contraction strength higher in the uterus or decreasing contraction strength in the lower portion. We submit that this upward movement of the CUA indicates fundal dominance.

We found that a fundal direction in general, and particularly during the second half of the contraction, correlated with labor progress. Our results are consistent with those of Caldeyro et al,[15] who used both an internal sensor and 7 external uterine activity monitors to evaluate contractions in 18 women in 'normal, prolonged, and false labors.' They reported the most important factors in prolonged labor were absolute intensity of contractions and absence of fundal dominance.

More recently, using IUP catheters placed in both the upper and lower uterine segments of laboring women, Margono et al[16] studied 15 patients with active phase labor arrest requiring augmentation, and compared these with 7 patients with normal (nonaugmented) labor. Mean active pressure was calculated for 12 contractions preceding oxytocin administration and, in the augmented group, for 12 contractions during the maximal oxytocic effect. In every patient who delivered vaginally (either spontaneously [n = 7] or with augmentation [n = 9]), the fundal mean active pressure exceeded that of the lower segment. The opposite was true for the abdominally delivered women (n = 6). Interestingly, oxytocin augmentation caused no significant change in the mean active pressure in either segment for either group. The authors note this fundal dominance 'might be used to gauge the likelihood of success of oxytocin augmentation.'

Finally, Spatling et al[17] performed 4-channel tocography on 54 laboring patients ($\geq$ 2 cm dilation) for 30 minutes. Using visual analysis of the 4 toco signals plotted in parallel, they evaluated contraction propagation through the 4 quadrants of the uterus. Overall, they found no correlation between the propagation pattern and mode of delivery, but did report that a right fundal onset of the contraction correlated with subsequent vaginal delivery. While this differs from our results, comparison is complicated by the heterogeneity of their operative delivery group, and the inclusion of patients in the latent phase of labor.

There are several limitations of our study. Placement of electrodes on the maternal abdomen was based on anatomic reference points (the umbilicus, fundus, and pubis), but absolute distance between electrodes was not recorded and varied somewhat by the size of the patient and the location of the toco and ultrasound monitors. For this analysis, we used the fundal and suprapubic electrodes for the fundus and lower portions of the uterus, respectively, but it was not possible to analyze the actual distance of movement of the CUA; thus, we focused only on direction.

Interpretation of case-control studies is limited by their retrospective nature and concerns regarding the appropriateness of the control group. We chose to match for factors with a well-known relationship to the a priori risk of cesarean delivery: gestational age, induction, parity, and BMI.[18-20] Although the BMI range is large, the resulting average 10% higher BMI in the arrest patients seems acceptable. The wide range was necessary to find reasonable matches for this important parameter.

Finally, as noted above, the diagnosis of dystocia is controversial and practitioner-dependent. For this reason, we had a single maternal-fetal medicine specialist (R.K.E.) review each chart to ensure there were no other confounding reasons (such as a worrisome fetal heart rate tracing) that may have encouraged the obstetrician of record to opt for cesarean delivery. Still, this cannot rule out cephalopelvic disproportion (CPD) as the reason for labor arrest. In fact, a change in the shape of uterine contractions has been reported to occur in the presence of CPD,[21] though this study included patients with a diagnosis of labor arrest as well. The investigators identified a prolongation of T2 (time from peak of a contraction back to baseline) relative to T1 (time from onset to peak) in 100 women who underwent cesarean delivery for CPD or arrest of labor, as compared to 100 women with spontaneous vaginal delivery. They attribute this to uterine behavior that "appears to be responding and adapting to the lack of forward motion of the fetus." The current, much smaller study, failed to replicate this finding: fall to rise ratio 1.00 $\pm$ 0.25 vs 1.00 $\pm$ 0.29 for cesarean and vaginal deliveries, respectively, but instead identifies a difference in the electrical activity of the uterus in patients with the same diagnosis. However, whether the abnormal uterine function causes the arrest, or the arrest causes abnormal uterine function, deserves further consideration.

The goal of this investigation was to identify specific characteristics of the electrohysterogram spatial map that differed between normally progressing labor and the opposite extreme, arrested dilation. To our knowledge, this approach is novel. Others have focused on characteristics of the electrohysterogram including the power spectrum in term and preterm labor,[22-24] and the burst duration[25] and intensity[26] in preterm labor. Each of these studies employed 1 or 2 sets of bipolar electrodes located near the umbilicus and did not investigate spatial patterns.

Providing the clinician information regarding the efficiency of uterine contractions has potential benefits. Recognition of an ineffective pattern may encourage more rapid initiation or acceleration of oxytocin infusion. The additional data may help with decisions whether to continue a slow but effective labor vs halting a labor attempt. While CUA direction in progressing labor is not likely to differ in the 2 groups, it would be instructive to prospectively investigate at what point in labor the CUA changes direction in those that eventually arrest. Further investigation of the features of the electrohysterogram during labor, as well as the effect of oxytocin, is warranted. If large prospective studies confirm the presence of a significantly different pattern in progressing vs nonprogressing labor, a practical system for intrapartum electrohysterography may be a helpful addition for monitoring in the labor ward. Meanwhile, the potential for enhancing the prediction of labor induction success, and distinguishing real from false term and preterm labor also deserve investigation. ■

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