ORIGINAL ARTICLE

Estimating time to full uterine cervical dilation using genetic algorithm

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Abstract The objectives of this study were to provide new parameters to better understand labor curves, and to provide a model to predict the time to full cervical dilation (CD). We studied labor curves using the retrospective records of 594 nulliparas, including at term, spontaneous labor onset, and singleton vertex deliveries of normal birth weight infants. We redefined the parameters of Friedman’s labor curve, and applied a three-parameter model to the labor curve with a logistic model using the genetic algorithm and the Newton–Raphson method to predict the time necessary to reach full CD. The genetic algorithm is more effective than the Newton–Raphson method for modeling labor progress, as demonstrated by its higher accuracy in predicting the time to reach full CD. In addition, we predicted the time (11.4 hours) to reach full CD using the logistic labor curve using the mean parameters (the power of CD = 0.97 cm/hours, a midpoint of the active phase = 7.60 hours, and the initial CD = 2.11 cm). Our new parameters and model can predict the time to reach full CD, which can aid in the forecasting of prolonged labor and the timing of interventions, with the end goal being normal vaginal birth.

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Introduction

Labor is the presence of uterine contractions of sufficient frequency, duration, and intensity to cause demonstrable effacement and dilatation of the cervix [1]. It is a continuum that culminates in birth. Multiple fixed factors such as parity, maternal weight, and fetal weight, as well as commonly employed interventions (e.g., oxytocin augmentation and epidural use) may significantly affect the duration of labor [2]. Childbirth is a complex and dynamic process that incorporates cervical dilation (CD), uterine contractions, and the descent of the fetal head. CD and the duration of CD are good diagnostic indicators of prolonged labor [3–6]. Friedman [7] produced a chart to illustrate the relationship between CD and the duration of the labor process and to aid in differentiation between normal and abnormal labors. He also established a series of definitions of labor protraction and arrest. These definitions have been widely adopted and applied in practice in the past half-century [8]. However, as there is no universal definition of "normal" labor, and diagnosing prolonged labor is inherently difficult [9].

Some studies have argued that the Friedman curve is no longer appropriate for induced or actively managed labor [10,11]. As a reassessment of the labor curve, Zhang et al. [12] used repeated-measures regression with a 10th-order polynomial function to define an average labor curve, suggesting that the pattern of labor progression in contemporary practice differs significantly from the Friedman curve [12]. Vahratian et al. [13] provided an overview of Friedman’s work, addressed methodological challenges in studying labor progression, and described the utility of more advanced statistical methods for studying labor progression, such as survival analysis, compared with other approaches. Some of these studies have focused mainly on assisting in the diagnosis of prolonged labor and the timing of interventions, with the aim of achieving natural vaginal birth, but they have not identified useful tools for predicting prolonged labor.

We therefore reconsider full CD in this study, redefine the parameters of Friedman’s labor curve (e.g., latent and active phase, deceleration phase), and develop clinically useful statistical models. We applied a three-parameter logistic model to the labor curve and redefined the three parameters of Friedman’s labor curve with a logistic model using the genetic algorithm (GA) and Newton–Raphson (NR) method to predict the time necessary to reach full CD [14,15]. We also evaluated and compared the performances of the mathematical inference method (NR) and evolutionary computation method (GA).

To our knowledge, this is the first report of estimating the time to full uterine CD using the GA.

Materials and methods

Research participants

We extracted the clinical record data of 594 singleton nulliparous women in the last months of their pregnancies who underwent vaginal delivery at Hanyang University Hospital, Seoul, South Korea, between October 2004 and February 2009. Inclusion criteria were gestational age between 38 and 42 weeks, spontaneous onset of labor, vertex presentation at admission, CD < 7 cm at admission, and duration of labor from admission to delivery > 3 hours [16]. We performed CD measurements at least once per hour, thereby establishing a consistent data collection. We excluded cases involving cesarean delivery, labor induction, and/or epidural anesthesia.

This study was conducted with the approval of the Institutional Review Board Committee of the Hanyang University Hospital, Seoul, South Korea.

Redefining the parameters of Friedman’s labor curve

The three-parameter logistic model is defined as follows:

\[ y_j = \frac{a}{1 + \exp(-\beta \times (x_j - \gamma))} \]

where \( a > 0 \) is the final size achieved, \( \beta > 0 \) is the scale parameter, and \( \gamma \) is the inflection point on the curve at the vertical coordinate \( x_j \). When \( x_j \rightarrow -\infty \), for all and any \( y_j \), each \( y_j \) converges to 0 or \( a \). At \((x_j, y_j) = (\gamma, a/2)\), this curve has a maximum slope of \( a\beta/4 \).

We applied an adjusted three-parameter logistic model with an upper bound set to 10 cm and defined the lower asymptote as the "initial CD" due to the different dilation starting times. Dilation at each time \( t_j \), the \( j^{th} \) hour after admission) was defined as \( y_j \) (cm). The logistic model has an upper asymptote, \( y_j = 10 \) (cm), defined as follows:

\[ y_j = c + (10 - c)/[1 + \exp(-a \times (t_j - b))] \]

Additionally, the three parameters \((a, b, c)\) are described as follows:

\( a \) = a scale parameter, is related to the maximum slope (cm/h) at the point of inflection on the labor curve. This parameter indicates the "power" of the CD, and it can be used to determine the time it takes to reach full CD, which is the final objective of our study.

\( b \) = the location parameter at \( t_j = b \) (hours). Eq. (1) has a maximum slope of \( a \times (10 - c)/4 \) (cm/h) at the point of inflection where \((t_j, y_j) = (b, 10 - c)/2\). This parameter is "a midpoint of the active phase" in Friedman’s labor curve.

\( c \) = is a lower asymptote, and is the initial CD, giving a lower asymptote \( y_j = c \) (cm) as \( t_j \rightarrow -\infty \). The upper asymptote is \( y_j = 10 \) (cm) as \( t_j \rightarrow +\infty \). It is also used in estimating CD at admission or before admission.

Fig. 1 shows a logistic labor curve in which \( a = 0.92, b = 6.83 \) hours, \( c = 0.75 \) cm, and the maximum slope is 2.13 cm/h.

The following is an example of what the equation, using the above parameters, would look like:

\[ y_j = 0.75 + (10 - 0.75)/(1 + \exp(-0.9 \times (t_j - 6.83))] \]

Estimation of a three-parameter logistic model in the labor curve

GA is the most fundamental and widely known evolutionary computation currently used in application research. The most important feature in GA design is chromosome encoding, as the chromosomes must be mapped to the sets
of parameters that need to be estimated. We have adopted a real value representation, rather than a classic binary representation, for the application of the logistic model Eq. (1).

When applying the GA (Appendix 1), the number of chromosomes \( m \) was set to 100, and the number of maximum iterations (i.e., \( \text{gen} \)) was set to 20,000. In the selection process, after randomly choosing a number \( r \) from \((0, 1)\), the numerical value \([100 \times r]\) (\([\ ]\) indicates a Gauss function) was obtained by roulette wheel selection (number of precision = 6 and precision integer = 2). The arithmetical crossover operator’s weight was set to 0.8, the crossover rate \( p_c \) to 0.2, and the mutation rate \( p_m \) to 0.01 (Appendix 2, Fig. I).

When applying the NR method (Appendix 3), we applied PROC NLIN of the SAS package (Ver. 9.1; SAS Institute Inc., Cary, NC, USA) to the three-parameter logistic models, with the initial values for each model based on the published SAS methods described by Rogers et al. [17].

Results

Table 1 presents the baseline characteristics of the overall study sample. Physicians performed an average of 10.05 pelvic examinations from admission to the first stage of labor (standard deviation, 2.37). The mean age at the time of delivery was 30.32 (2.46) years. The CD at the time of admission was 2.11 (1.68) cm. The mean number of gestational weeks at delivery was 40.26 (0.11), and the first stage of labor was 12.01 hours (5.19). The average weight of the newborns was 3396 g (310). The average Apgar scores were 6.95 (0.25) and 8.88 (0.33) at 1 and 5 minutes, respectively.

We found that the prediction accuracy (sum of square error; root mean square error; statistic measuring the accuracy of forecast, \( U \); Theil’s inequality coefficient, \( U \) ) [18] of GA was higher than that of the NR method, and that GA was more appropriate than NR in the optimization of the three-parameter logistic model in the labor curve (Table 2).

As shown in Table 3, the time predicted by GA was closer to the observed time than that predicted by NR. Hence, the models estimated by GA can be regarded as more effective for modeling labor progress than those estimated by NR.

The estimated labor curves at various dilations are given in Figs. 2A and 2B. In Fig. 2A (top), the first labor curve (a.1) used only four observed data-points (3 hours after admission), while (a.2) used five observed data-points (4 hours after admission). In (a.4), the estimated arrival time to CD (about 10 cm) was about 10.8 hours (root mean square error = 0.1), which was approximately the actual arrival time of the patient (11.0 hours). As shown in Fig. 2B (bottom), the initial CD of the labor curve (b) was smaller than that of labor curve (a), and the “active phase” of labor curve (b) began 7 hours after admission.

Fig. 3 shows various patterns of estimated labor curves to full dilation by GA. The time to reach full CD in curve (b) was longer than in curve (a) (5.4 vs. 13.6 hours), although the CD on admission in curve (b) was bigger than curve (a) (1 vs. 5 cm).

Discussion

In general, measuring CD can be subjective, and such measurements are only estimates because observations are rounded to the nearest centimeter [19]. This measure, although generally accepted, may not be precise and there are no reported trials of either interobserver or intraobserver reproducibility. Women are admitted into labor and delivery at various levels of CD, and it is difficult to predict the chances of a normal vaginal delivery and the duration of labor in the first stage [2,20]. A nonparametric method might also provide a direct fit to the data, but the disadvantage of such methods is the inefficient use of individual data on labor progression, in the sense that estimates assume a cluster of points at neighboring dilations [21].

Friedman’s labor curve was derived from observations of CD and fetal station plotted against time elapsed from the onset of labor (in hours). The typical S-shaped curve for most laboring women defines the normal limits for labors with healthy outcomes or for identifying abnormal labor. However, the management of labor and delivery has changed since Friedman’s series of publications on evaluating labor in clinical practice. Specifically, there has been an increased use of obstetric interventions during labor and

### Table 1
General characteristics of the study sample (\( N = 594 \)).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pelvic examinations</td>
<td>10.05 ± 2.37</td>
</tr>
<tr>
<td>Maternal age (y)</td>
<td>30.32 ± 2.46</td>
</tr>
<tr>
<td>Gestational age at delivery (wk)</td>
<td>40.26 ± 0.11</td>
</tr>
<tr>
<td>Cervical dilation at admission (cm)</td>
<td>2.11 ± 1.68</td>
</tr>
<tr>
<td>Duration of first stage of labor (h)</td>
<td>12.01 ± 5.19</td>
</tr>
<tr>
<td>Birth height (cm)</td>
<td>49.87 ± 2.16</td>
</tr>
<tr>
<td>Birth weight (gm)</td>
<td>3396 ± 310</td>
</tr>
<tr>
<td>1-min Apgar score</td>
<td>6.95 ± 0.25</td>
</tr>
<tr>
<td>5-min Apgar score</td>
<td>8.88 ± 0.33</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation (SD).
Full cervical dilation (CD) is approximately 10 cm if the estimate of CD duration, maximum slope, deceleration phase duration, and overall first stage duration.

The calibration (inverse estimation) of the latent (onset of labor to 4 cm dilation) and active (4–10 cm) phases \([27]\) can be easily performed by using Eq. (3), which is induced by Eq. (1) in the section "Redefining the parameters of Friedman's labor curve":

\[
t_j = \left( -1/a \right) \times \log_e \left[ \left( 10 - y_j \right) / (y_j - c) \right] + b
\]

For example, in Fig. 1 we can calculate the latent (6.16 hours; \(t_j = (-1/0.97) \times \log_e(10-4)/(4-0.75)\) + 6.83) and active phases (4.81 hours; \(dt_j = 10.97 - 6.16\) of the first stage of labor. We also predict the time (11.4 hours) to reach full CD using the logistic labor curve with mean parameters (i.e., \(a = 0.97, b = 7.60, \) and \(c = 2.11; \) Table 2).

Comparing the estimates of duration of labor across studies, especially for the first stage, is difficult for several reasons (e.g., different starting points to calculate the duration of labor, variation in sample restriction, exclusion of induced labor and cesarean deliveries) \([28]\).

We are convinced that such biases could be reduced by introducing mathematical modeling and a method known for accuracy (the logistic and GA models, respectively). In this research, we applied the three-parameter logistic model to labor curves. Obviously, three measurements obtained within a couple of hours of admission will not yield a satisfactory "prediction accuracy." Thus, a fourth and a fifth addition of observed data-points to the above

### Table 2 Comparisons of estimated parameters and prediction accuracies for the genetic algorithm and the Newton–Raphson method.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Genetic algorithm</th>
<th>Newton–Raphson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale parameter (a)</td>
<td>Mean ± SE</td>
<td>Median (range)</td>
</tr>
<tr>
<td>Location parameter (b) (h)</td>
<td>0.97 ± 0.08</td>
<td>1.00 (0.33–9.97)</td>
</tr>
<tr>
<td>Lower asymptote (c) (cm)</td>
<td>2.11 ± 0.03</td>
<td>2.50 (0.00–6.57)</td>
</tr>
<tr>
<td>Maximal slope (cm/h)</td>
<td>1.83 ± 0.16</td>
<td>1.54 (0.70–21.12)</td>
</tr>
<tr>
<td>SSE</td>
<td>2.01 ± 0.04</td>
<td>1.84 (0.00–4.91)</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.39 ± 0.10</td>
<td>0.37 (0.00–5.52)</td>
</tr>
<tr>
<td>(U_1)</td>
<td>0.05 ± 0.01</td>
<td>0.05 (0.00–1.10)</td>
</tr>
<tr>
<td>(U)</td>
<td>0.03 ± 0.00</td>
<td>0.02 (0.00–0.41)</td>
</tr>
</tbody>
</table>

**RMSE** = root mean square error; **SE** = standard error; **SSE** = sum of square error; **\(U_1\)** = statistic measuring the accuracy of the forecast; **\(U\)** = Theil's inequality coefficient.

### Table 3 Comparison of predicted time to full cervical dilation (10 cm)\(^a\) estimated by the genetic algorithm and the Newton–Raphson methods.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Genetic algorithm</th>
<th>Newton–Raphson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time prediction (h)(^b)</td>
<td>Mean ± SE</td>
<td>Median (range)</td>
</tr>
<tr>
<td>MAE</td>
<td>11.44 ± 0.11</td>
<td>11.75 (5.0–19.0)</td>
</tr>
<tr>
<td>MSE</td>
<td>0.50 ± 0.02</td>
<td>0.31 (0.00–2.00)</td>
</tr>
</tbody>
</table>

**MAE** = mean absolute error; **MSE** = mean squared error; **SE** = standard error.

\(^a\) Full cervical dilation (CD) is approximately 10 cm if the estimate of CD ≥ 9.8 cm.

\(^b\) 95% confidence interval; genetic algorithm = (11.22–11.68) versus Newton–Raphson = (12.43–12.91).
steps will produce a more accurate result. The number of parameters used in our study, 3 \((a, b, c)\), is chosen as a minimum number of nonlinear model to explain the labor curve. Using our three parameters not only enables users to calculate the parameters currently used but also to calculate the time to full uterine CD, and even the overall duration of first stage using the time calculated. As for predictive accuracy, we found that the parameters from GA were closer to the optimal solution, and that GA was better than the NR method at solving optimization problems. GA is more effective than NR for modeling labor progress, as demonstrated by its higher accuracy in predicting the time to reach full CD. Our study focused on estimating the time to full uterine CD using the GA, which

Figure 2. Estimated labor curves calculated using the genetic algorithm for (A) (a.1) 3 hours, (a.2) 4 hours, (a.3) 5 hours, and (a.4) 6 hours of observation; (B) (b.1) 3 hours, (b.2) 4 hours, (b.3) 5 hours, and (b.4) 8 hours of observation after admission. Note. (a.1) the first estimated labor curve used only four observed data-points \((n = 4, \bigcirc);\) RMSE = 2.4, and the 10 cm* arrival time was approximately 7.8 hours (true, 11.0 hours), (a.4) \(n = 7, 10.8\) hours \((\text{RMSE} = 0.1);\) (b.1) \(n = 4, 19.5\) hours \((\text{RMSE} = 0.1;\) true, 19.0 hours), (b.4) \(n = 9, 18.7\) hours \((\text{RMSE} = 0.1).\)* Full CD is approximately 10 cm if the estimate of CD \(\geq 9.8\) cm. CD = cervical dilation; RMS = root mean square error.

Figure 3. Estimated labor curves to full CD (approximately 10 cm of cervical dilation)* according to the genetic algorithm. (a) 5.4 hours, (b) 13.6 hours, (c) mean = 11.4 hours (i.e., labor curve with \(a = 0.97, b = 7.60, c = 2.11\) in Table 3), (d) 20.0 hours, and (e) 17.8 hours. *Full cervical dilation (CD) is approximately 10 cm if the estimate of CD \(\geq 9.8\) cm.
is prioritized to any other, in order to figure out the “labor mechanism.” In the future, we will be able to provide direct “criteria for normal labor” subjected to greater data further proving the model to be a useful one in prediction of prolonged labor.

Our research had the following limitations. First, we were unable to confirm that delays in the progression of labor were actually associated with increases in incidence of cesarean delivery, augmentation of labor, or number of vaginal examinations [29]. Second, we were unable to demonstrate whether there were any similarities between the duration of labor and the pattern of labor progress among nulliparous and multiparous mothers [30]. Finally, our sample was drawn from a single tertiary care hospital in South Korea, which may limit the generalizability of our results. Regarding the problem of having study participants from a hospital, we plan to conduct a more extensive research through a multicenter study in the future.

In conclusion, we have developed a three-parameter logistic model to predict the time to reach full dilation. This model may be useful for diagnosis of prolonged labor and the timing of interventions, and may facilitate the achievement of normal vaginal birth.

Acknowledgments

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Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.kjms.2012.02.012.

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