DEMOGRAPHIC MODELS OF BIRTH OUTCOMES AND INFANT MORTALITY: AN ALTERNATIVE MEASUREMENT APPROACH*

PATRICIO SOLÍS, STARLING G. PULLUM, AND W. PARKER FRISBIE

Most demographic studies use 2,500 grams of birth weight and 37 weeks of gestation as cutpoints for evaluating the effects of adverse birth outcomes on infant mortality. We propose an alternative strategy, which relies on continuous measures of birth outcomes, identifies an optimal combination of birth weight and gestational age for infant survival, and estimates the effects of adverse birth outcomes in terms of their departure from this "optimal point." We illustrate the advantages of this approach by estimating a logistic model using data from the 1989–1991 NCHS linked birth/infant death files. Finally, we discuss future applications and methodological issues to be resolved in subsequent research.

Clinical, epidemiological, and demographic studies have found consistently that the risk of infant mortality increases among premature and low-birth-weight infants (Cramer 1987; Frisbie, Forbes, and Hummer 1998; Hack et al. 1994; Hack, Klein, and Taylor 1995; Kiely and Susser 1992; Kline, Stein, and Susser 1989; McCormick 1985). Despite the strength and consistency of the relationship between birth outcomes and infant health, there are relatively few developments in the design of measurement strategies to analyze this association in detail. This problem has been noted in recent demographic studies, which have proposed refinements to usual classifications of birth outcomes based on birth weight and gestational age (Frisbie, Forbes, and Pullum 1996; Frisbie et al. 1997; Hummer et al. 1995; Kallan 1993). Despite these substantial improvements, even the most refined of these classifications yield an oversimplified picture of the association between birth outcomes and infant mortality.

In this paper we propose an alternative measurement strategy that allows us to analyze in greater detail the effect of birth outcomes on infant mortality. We suggest that a fuller representation of the effect of gestational age and birth weight may be achieved by conceptualizing these two outcomes as continuous variables. In addition, we propose that the effects of gestational age and birth weight on infant mortality should be evaluated in terms of their deviation from an "optimal" combination: that is, the combination of gestational age and birth weight that produces the lowest levels of infant mortality.

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We begin with a brief review of the classifications of birth outcomes used in recent demographic research. Next we describe the principal characteristics of our data set and explain in detail the attributes of our proposed methodology. Then we present the results of a logistic regression model predicting infant mortality that implements these methodological changes. Finally we discuss these results, suggest some applications for future research, and consider some of the problems that need to be addressed in further studies.

DEMOGRAPHIC CLASSIFICATIONS OF BIRTH OUTCOMES

Most demographic studies have implemented a "dichotomous approach" in classifying birth outcomes and evaluating their effects on infant health and mortality. In this approach, traditional fixed cutoff points are employed to segment birth weight and gestational age distributions into two separate groups: "normal" and "compromised" birth outcomes. The traditional standards are 2,500 grams for low birth weight and 37 weeks of gestation for prematurity (Kline et al. 1989).

Studies that employ only one of these two dichotomies (especially low birth weight versus normal birth weight) remain common in demographic and public health literature on birth outcomes and perinatal health. It is increasingly recognized, however, that more refined measures must be created, as well as classifications that combine birth weight and gestational age into new, relevant categories of birth outcomes. The standard for implementing new measurement strategies was set early on by Yerushalmy (1967), who stated that "*an adequate classification system must facilitate the subdivision of low-birth-weight infants according to gestational age in meaningful subgroups*"—meaningful in the sense that the measure identifies infants at greater risk of "mortality, morbidity, and congenital anomalies" (p. 165; author's emphasis).

The task of developing more adequate methods of classification has occupied an important place in recent demographic research on birth outcomes. For instance, in their analysis of the effect of sociodemographic, health-related, and behavioral variables on birth outcomes, Kallan (1993) and then Hummer and colleagues (1995) adopted a classification that divides births into three outcomes: low birth weight associated with intrauterine growth retardation (IUGR), low birth weight associated with prematurity, and normal birth outcomes. The first category contains births with weight less than 2,500 grams and more than 36 weeks of gestation, the second corresponds to births of less than

2,500 grams and 36 or fewer weeks, and the normal group consists of infants weighing 2,500 grams or more at birth. This classification is a simplified version of the five-category measure proposed by Yerushalmy (1967). The difference is that Yerushalmy's approach distinguished infants of very low birth weight (< 1,500 grams) from heavier newborns.

More recently, Frisbie and colleagues (1996, 1997) proposed additional modifications to this classification. First, they incorporated the distinction between newborns of normal gestational age and birth weight (> 36 weeks, ≥ 2,500 grams) and heavy premature infants (< 37 weeks, ≥ 2,500 grams). The second modification involves the use of the fetal growth ratio (FGR), originally proposed by Kramer and colleagues (1989), as a method for identifying immature births that would not be detected by using the original classification (Frisbie et al. 1996).[1] The FGR is a useful proxy for immaturity when evaluated against clinical evidence, including ultrasound estimates (Balcazar 1993; Balcazar, Keefer, and Chard 1994; Kramer et al. 1989). Using a cutoff point of 0.85 in the FGR, Frisbie and colleagues proposed a third dichotomy to distinguish immature or "growth-retarded" births from normal births. Then they cross-tabulated this dichotomy with the conventional dichotomies of low versus normal birth weight (cutoff point at 2,500g) and short versus term gestation (cutoff point at 37 weeks) to produce a new classification of birth outcomes.

Although these classifications are useful for many purposes, even the most detailed give rise to limitations in analyzing the complex pattern of association between gestational age, birth weight, and infant mortality. Perhaps the principal problem of current classifications is that they create an image of discontinuity in the association between birth outcomes and infant mortality. In other words, representations of infant mortality with categorical typologies suggest that the level of infant mortality is very similar within risk groups or categories of birth outcomes, and that it changes abruptly when infants cross a fixed cutoff point in the continuous distribution of birth weight, gestational age, or FGR.

Such representations may lead to inappropriate characterizations of the effect of birth outcomes on infant mortality. For example, the categorical approach would suggest, within similar categories of birth weight, that an infant with 36 weeks of gestation is just as likely to die as an infant with 30 weeks of gestation, but has a much larger risk of mortality than a newborn with 37 weeks of gestation. The empirical evidence suggests a quite different picture.

The second problem in current demographic classifications is that they overlook significant patterns of variation in infant mortality within birth outcome categories. They actually may obscure the presence of thresholds that are closer to reality. For example, there is some reason to believe that if normal birth weight is conceptualized as referring to optimal weight for survival, the cutpoint would be several hundred grams higher than the conventional 2,500 grams. Further gains in birth weight beyond this optimal point produce an increase in the risk of infant mortality (Myers and Ferguson 1989; Wilcox and Russell 1983).

These considerations suggest that the current categorical approaches at least should be supplemented by examination of continuous data for a proper portrayal of the association between birth outcomes and infant mortality. The introduction of additional dichotomies would not result in substantial improvements because dichotomous strategies are unable to characterize precisely a continuous association. We propose that a more appropriate alternative, which avoids further "conflation of indices that has so troubled the analyses and the understanding of the developmental phenomena observed at birth" (Kline et al. 1989:173), is to transcend the dichotomous perspective and to conceptualize both gestational age and birth weight as continuous variables. In addition, the nonlinear association between birth outcomes and infant mortality suggests the presence of a point beyond which there is a change in the effect of birth outcomes on infant mortality. To depict this nonlinear pattern, we suggest that the effect of birth outcomes should be evaluated in relation to this point, which is the area with the lowest infant mortality.

DATA AND METHODS

The data used in this study come from the combined 1989, 1990, and 1991 NCHS linked birth/infant death files. This data set offers cohort information on infant mortality at the individual level for all births registered in the United States during those three years. Along with sociodemographic characteristics, this data set includes the infant's gestational age in completed weeks, as well as birth weight in grams. For the purposes of this paper, to avoid the possibility of errors introduced by the classification of stillbirths as live births, we restricted our cases to births of more than 28 weeks of gestation and 500 grams of birth weight (more than 99.5% of the total number of cases).

Another important restriction of this paper is that we limit our analysis to non-Hispanic white females (hereafter "whites"). Several studies suggest that the distributions of birth weight and gestational age, as well as their effect on infant mortality, differ significantly between sexes and across racial/ethnic groups (Frisbie et al. 1996; Kline et al. 1989; Wilcox 1981; Wilcox and Russell 1986) The exclusion of males and other ethnic groups is intended to eliminate the variance associated with this heterogeneity; it allows us to concentrate on modeling the patterns of association between gestational age, birth weight, and infant mortality, with the ultimate aim of expanding our research to both sex- and race/ethnicity-specific populations. The total number of white female births, slightly less than 3.65 million, constitutes our universe of study. Table 1 presents some descriptive statistics on the distribution of birth weight and gestational age for this group.

Our methodological strategy begins with a graphic analysis of the patterns of correlation between birth outcomes and infant mortality. The main difficulty in perform-

1. The FGR is "the ratio of the observed birth weight at a given gestational age to the mean birth weight for gestational age of a sex specific fetal growth distribution" (Balcazar 1994:149).

TABLE 1. DESCRIPTIVE STATISTICS OF THE DISTRIBUTION OF BIRTH WEIGHT BY GESTATIONAL AGE: NON-HISPANIC WHITE FEMALES, 1989–1991

Gestational Age	Number of Births	Cumulative Frequency (%)	Mean Birth Weight (Grams)	*SD* Birth Weight
28	3,957	0.11	1,702.1	949.5
29	5,003	0.25	1,856.8	920.5
30	7,215	0.44	2,061.3	887.2
31	8,919	0.69	2,214.5	834.1
32	12,176	1.02	2,379.5	792.8
33	18,083	1.52	2,500.1	707.8
34	32,229	2.41	2,677.7	652.6
35	56,091	3.95	2,827.9	589.5
36	101,537	6.74	2,943.1	524.5
37	199,627	12.23	3,087.9	480.6
38	443,649	24.42	3,250.9	454.6
39	806,927	46.60	3,383.3	443.2
40	903,043	71.42	3,482.5	445.3
41	589,856	87.63	3,551.8	455.8
42	238,541	94.19	3,548.4	474.0
43	98,555	96.90	3,470.0	478.8
44	55,558	98.42	3,461.7	474.3
45	31,300	99.28	3,475.4	481.5
46	16,683	99.74	3,473.6	489.0
47+	9,384	100.00	3,452.3	490.6

Source: 1989, 1990, and 1991 NCHS Linked Birth/Infant Death Files.

ing such an analysis is representing infant mortality as a third dimension in conventional two-dimensional graphs. The use of three-dimensional figures might represent a solution to this problem. The interpretation of such graphs, however, depends strongly on the viewer's "position": that is, on the angle from which the graph is visualized. To circumvent these difficulties, we employed an alternative technique. Adapting the software designed by Vaupel and colleagues (1997) to represent Lexis diagrams graphically, we prepared a contour plot depicting the variations in infant mortality across different birth weight groups and individual gestational ages.

The results of the application of this method are presented in Figure 1. In this graph, infant mortality rates (IMRs) are grouped at different levels, each depicted in a different tone of gray. The darker areas represent combinations of birth weight groups[2] and gestational age that produce *lower* risks of infant mortality.

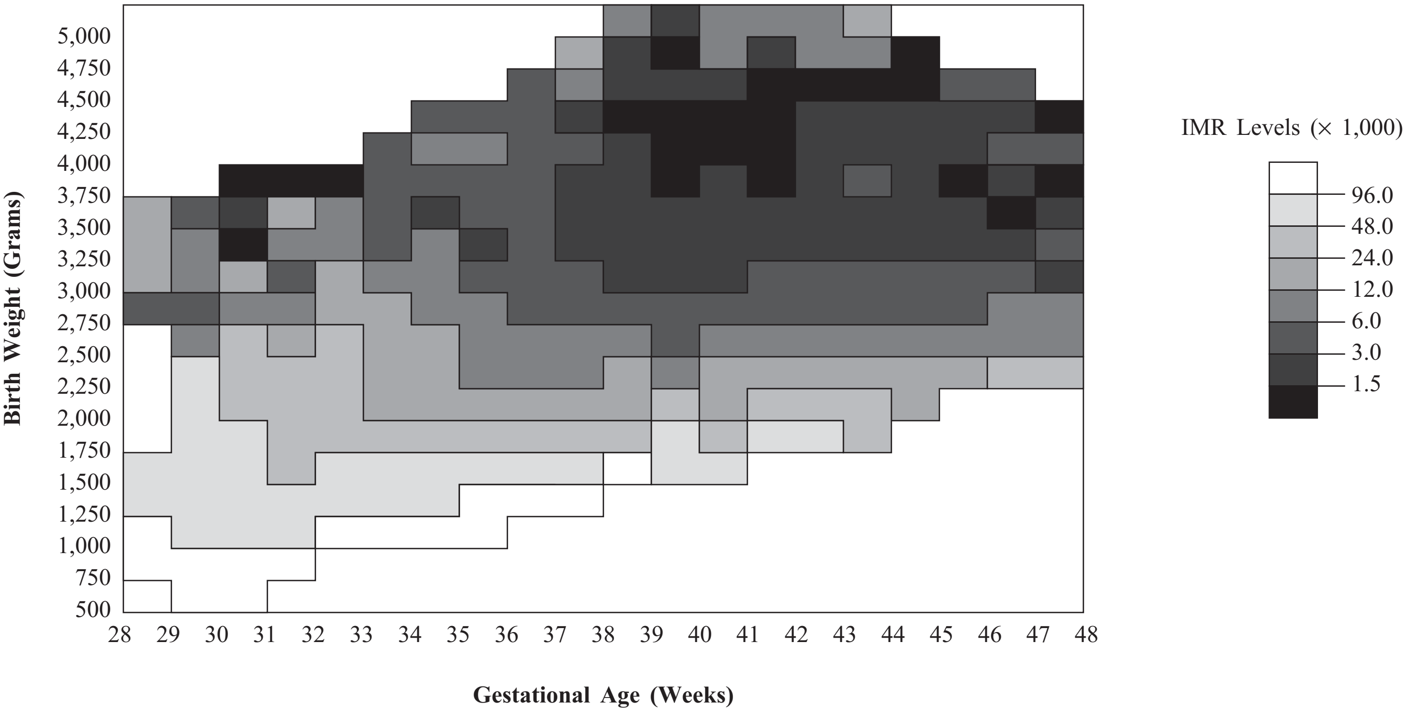
Perhaps the most important pattern to emerge from the graph is that the lowest mortality tends to concentrate in a very limited combination of birth weights and gestational ages. This combination is demarcated by 39 to 41 completed weeks of gestation and birth weights between 3,750 and 4,500 grams. Infants born within these boundaries register an IMR below 1.5 per thousand. The low mortality observed in this "region" is reflected in the disproportionality between the numbers of births and infant deaths: 14.7% of the total number of births occur within its limits, but only 5.17% of the total number of infant deaths. In addition, with the apparent exception of a combined increase in gestational age and birth weight, the graph shows that any departure from this "optimal region" seems to be associated with an increase in infant mortality.

This pattern of variation suggests that the effect of birth outcomes on infant mortality might be evaluated by assessing how far birth weight and gestational age depart from the combination that produces the lowest risk of such mortality. There remains, however, the issue of determining how these distances from the optimal combination should be measured. The simplest solution is to calculate absolute deviation measures in grams and weeks. For example, if 39–41 weeks and 4,000 grams were taken as the optimum, a newborn of 35 weeks and 2,500 grams would be classified respectively with negative deviations of 4 weeks and 1,500 grams.

The drawback to this approach is that it obscures the partial dependency of birth weight on gestational age (Kline et al. 1989; Wilcox and Skjærven 1992). Specifically, it neglects the likelihood that similarity in absolute weight for infants at different gestational ages may reflect great dissimilarity in intrauterine development. This problem can be il-

2. Births are classified in 250-gram groups. To avoid variations associated with a small number of births, we display only groups containing 150 or more cases.

FIGURE 1. INFANT MORTALITY RATES BY GESTATIONAL AGE AND BIRTH WEIGHT: NON-HISPANIC WHITE FEMALES, 1989–1991



Source: 1989–1991 NCHS Linked Birth/Infant Death Files.

lustrated by comparing two 2,500-gram infants, one at 30 weeks of gestation and the other at 40 weeks. On an absolute scale, these two infants obviously weigh the same, but on a scale relative to the gestational-age-specific distribution of birth weight, the former is heavier than the latter. In other words, the premature infant is *large* for its gestational age, while the full-term infant is *small* for its gestational age. Indeed, the premature infant's weight is 0.49 standard deviation (*SD*) *above* the 30-week average, whereas the mature infant's weight is 2.21 *SD below* the 40-week average. (The means and standard deviations are taken from Table 1.)

The distinction between absolute and relative-to-gestation birth weight is not trivial. Indeed, a detailed analysis performed by Wilcox and Skjærven (1992) indicates that standardizing birth weight to a scale relative to gestational age is fundamental for correctly assessing the effect of gestational age on mortality. This may be the case because most of the effect of gestational age on mortality is expressed through birth weight. In any case, as Wilcox and Skjærven argue, any analysis that simultaneously compares the effects of gestational age and birth weight without standardizing the latter will find that gestational age has only a small direct effect on infant mortality.

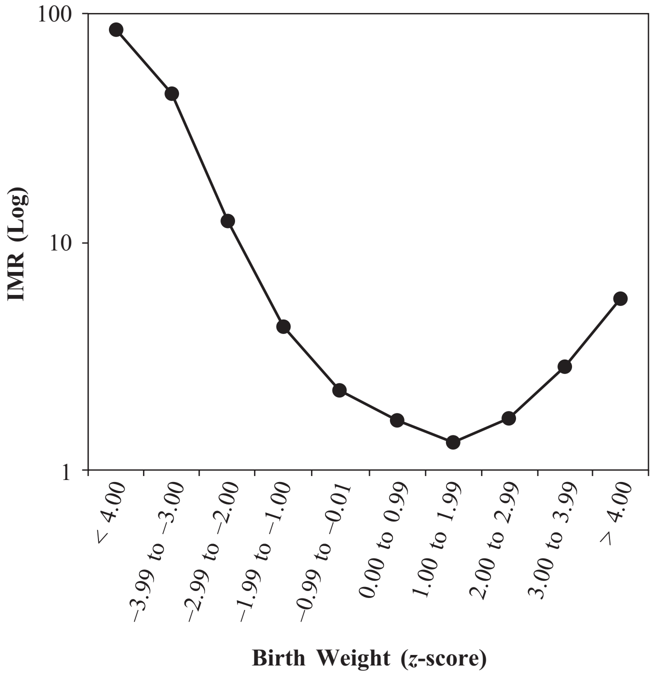
The solution proposed by Wilcox and Skjærven is to standardize weight to a *z*-score scale that expresses in standard-deviation units the infant's position in the gestational-age-specific birth weight distribution. The effect of gestational age on perinatal mortality then is estimated at fixed gestational-age-relative weights.

In this study we adapt this approach to quantify the distance between individual birth weight and the optimal birth weight based on a gestational-age-specific scale. This method begins with the transformation of birth weight to a gestational-age-specific *z*-score scale, employing the Gaussian parameters shown in Table 1.

Next, the optimal value of birth weight must be determined in a *z*-score scale. Figure 2 presents IMRs per thousand live births by *z*-score birth weight groups for 39 to 41 completed weeks of gestation. This figure suggests that the lowest levels of infant mortality are located between one and two *SD* above the average birth weight. Defining the location of the exact optimal relative birth weight is outside the scope of this paper, but we assume for modeling purposes that this optimal point is located one *SD* over the mean (*z*-score = 1).

Finally, we calculate the distance in relative weight, using the value of +1 *SD* as reference point. This distance is interpreted as the number of standard deviations that separate the weight of a given birth from the weight equivalent to the mean *plus one standard deviation* of the gestational-age-specific distribution of birth weight.

FIGURE 2. *z*-SCORE-SPECIFIC INFANT MORTALITY RATES (× 1,000) FOR BIRTHS WITH 39–41 WEEKS OF GESTATION: NON-HISPANIC WHITE FEMALES, 1989–1991



Source: 1989–1991 NCHS Linked Birth/Infant Death Files.

These steps provide a reference framework for quantifying the distances in birth weight and gestational age from the optimal combination and evaluating their effect on infant mortality. Four separate deviations may be distinguished. First, infant mortality variations may be analyzed as a function of the number of weeks by which the delivery precedes the "optimal" minimum of 39 weeks ("Early" or *E*). Second, the effect of gestational age also may be evaluated for postterm newborns by quantifying the number of weeks by which the delivery occurs after the forty-first week of gestation ("Late" or *L*). The third deviation ("Small" or *S*) reflects the difference in a *z*-score scale between the optimal birth weight, defined as the mean plus one *SD* in the gestational-age-specific distribution of birth weight, and the weight of infants *lighter* than this optimal figure. Finally, the fourth deviation ("Heavy" or *H*) measures the difference in a *z*-score scale between the optimal and the observed birth weight for infants *heavier* than the optimal.

To illustrate how these distances are obtained, we calculate their value for two hypothetical cases: the first with 30 weeks of gestation and 2,000 grams birth weight, and the second with 43 weeks of gestation and 4,300 grams. The calculation of the deviations in terms of weeks of gestation implies a simple subtraction indicating the number of weeks that separate a particular birth from the optimal duration of gestation. In the first case, this distance is equal to nine weeks (9 weeks = 39 weeks – 30 weeks) and corresponds to a premature birth; thus we assign a value of 9 to *E* and set the *L* value to 0. In the second case, this distance is equal to two weeks (2 weeks = 43 weeks – 41 weeks) and corresponds to a postterm birth; thus we assign a value of 2 to *L* and set the *E* value to 0.

To calculate the distance of the birth weight from the optimal, we must use the age-specific means and standard deviations shown in Table 1. In the first example, at 30 weeks of gestation the average birth weight is 2,061.3 grams and the *SD* is 887.2 grams. At this particular gestational age, a birth weighing 2,000 grams is 1.069 *SD* below the reference of one *SD* over the mean. That is,

$$S = 1.069 = \frac{\left(2{,}061.3\text{g} + 887.2\text{g}\right) - 2{,}000\text{g}}{887.2\text{g}}.$$

This distance corresponds to a negative deviation from the optimal birth weight; therefore the value of *H* is set to 0.

In the second example, the mean and the *SD* of birth weight at 43 weeks of gestation are 3,470.0 grams and 478.8 grams respectively, and the distance from the optimal is given by

$$H = 0.734 = \frac{4{,}300\text{g}\left(3{,}470.0\text{g} - 478.8\text{g}\right)}{478.8\text{g}}.$$

In this case, the distance corresponds to a positive deviation from the optimal birth weight. We assign this distance to *H*, setting the *S* value to 0.

The effect of these distances on infant mortality can be evaluated within the framework of the general linear model by adjusting a logistic regression equation. The equation for estimating these effects takes the form

$$\log\,(p/1 - p) = \alpha + \beta_1 E + \beta_2 L + \beta_3 S + \beta_4 H + \beta_5 ES + \beta_6 EH + \beta_7 LS + \beta_8 LH,$$

where p represents the infant mortality risk, α symbolizes the logit of the estimated infant mortality risk for infants in the "optimal" combination of gestational age and birth weight, and the group of β_i represents regression coefficients that summarize the effect of each individual distance and their interactions on infant mortality.

RESULTS

Table 2 presents the estimated coefficients that result from applying the logistic regression model to data for white females. According to our expectations, the four deviations from the optimal combination of gestational age and birth weight are related significantly and positively to infant mortality.

The effect of the coefficients can be summarized as follows. First, there is a strong association between preterm pregnancies and infant mortality. The estimated odds of infant mortality increase almost 30% (odds ratio = 1.296) for every week of prematurity. Second, the likelihood of survival decreases when the delivery occurs after the normal

TABLE 2. LOGISTIC REGRESSION COEFFICIENTS AND ODDS RATIOS FOR A MODEL OF INFANT MORTALITY: NON-HISPANIC WHITE FEMALES, 1989–1991

	Coefficient	Standard Error	Odds Ratio
Intercept	–7.0590**	0.0222	—
Early Birth (*E*)	0.2595**	0.0082	1.296
Late Birth (*L*)	0.1175**	0.0220	1.125
Low Weight (*S*)	0.7596**	0.0108	2.137
Heavy Weight (*H*)	0.5520**	0.0366	1.737
ES	0.0625**	0.0044	1.065
EH	–0.0400*	0.0179	0.961
LS	–0.0013	0.0104	0.999
LH	–0.0179	0.0434	0.982
N = 3,638,333			
Log-Likelihood = –83,268.615			
Model Chi-Square = 19,148.50**			

$^*p < .05$; $^{**}p < .01$

gestational age. Indeed, the model estimates that the odds of infant mortality increase 12.5% for every week the birth is deferred after the forty-first week of gestation. Third, the model indicates that low relative birth weight has a strong impact on infant mortality. The estimated infant mortality at weights equal to the gestational-age-specific average ($S = 1$) is 114% higher than at weights equivalent to one standard deviation over the mean (odds ratio = 2.137). Finally, the effect associated with heavy weight (*H*) reflects the increase in the odds of infant mortality among very heavy full-term newborns: The shift from one standard deviation over the mean ($H = 0$) to two standard deviations over the mean ($H = 1$) in the gestational-age-specific birth weight distribution is associated with a 74% increase in the predicted odds of infant mortality.

The effects of the interactions of prematurity with birth weight are also statistically significant. The *ES* interaction shows a positive effect (odds ratio = 1.065), indicating that the combination of prematurity and low relative birth weight produces an additional increase in the estimated risk of infant mortality. Conversely, the *EH* interaction exerts a negative effect (odds ratio = 0.961). Even though this coefficient may have been affected by possible reporting errors,[3] we believe that it represents the survival advantage of "heavy preemies" over their lower-weight counterparts, also identified by previous studies that take a categorical approach (Frisbie et al. 1996).

Does the model reflect with precision the patterns of variation of infant mortality across the different combinations of gestational age and birth weight? The statistical significance of the chi-square of the model presented in Table 2 reveals only that the proposed model fits better than the null model; it does not provide an absolute measure of the goodness of fit. In addition, we are interested in evaluating the fit of the model only in relation to the variations associated with birth outcomes, because the model is not intended to reflect the differences in infant mortality associated with other sociodemographic and behavioral variables. A plausible alternative is to compare the closeness of predicted and observed IMRs with each other at different combinations of gestational age and birth weight.

The predicted IMRs are plotted in Figure 3, with a method similar to that used in Figure 1. To facilitate comparison with Figure 1, we display only the combinations with 150 or more cases. The pattern of variation in the expected mortality risks follows the restrictions proposed by the model. First, the lowest expected risks are concentrated in an optimal region. The location of this region coincides with the area of lowest observed mortality identified in Figure 1. Second, the predicted risks tend to increase as a function of the distance from this optimal region; this pattern also resembles the pattern in observed rates seen in Figure 1. In addition, the model does not reflect the fluctuations in infant mortality that characterize the upper end of the birth weight distribution, especially after the thirty-fourth week of gestation. Instead it predicts a smooth increase in infant mortality rates as birth weight gradually exceeds the optimal point of one *SD*. This discrepancy does not necessarily reflect a failure of the model, because the observed variations in infant mortality may result from random variations associated with the combination of a relatively small number of births and deaths.

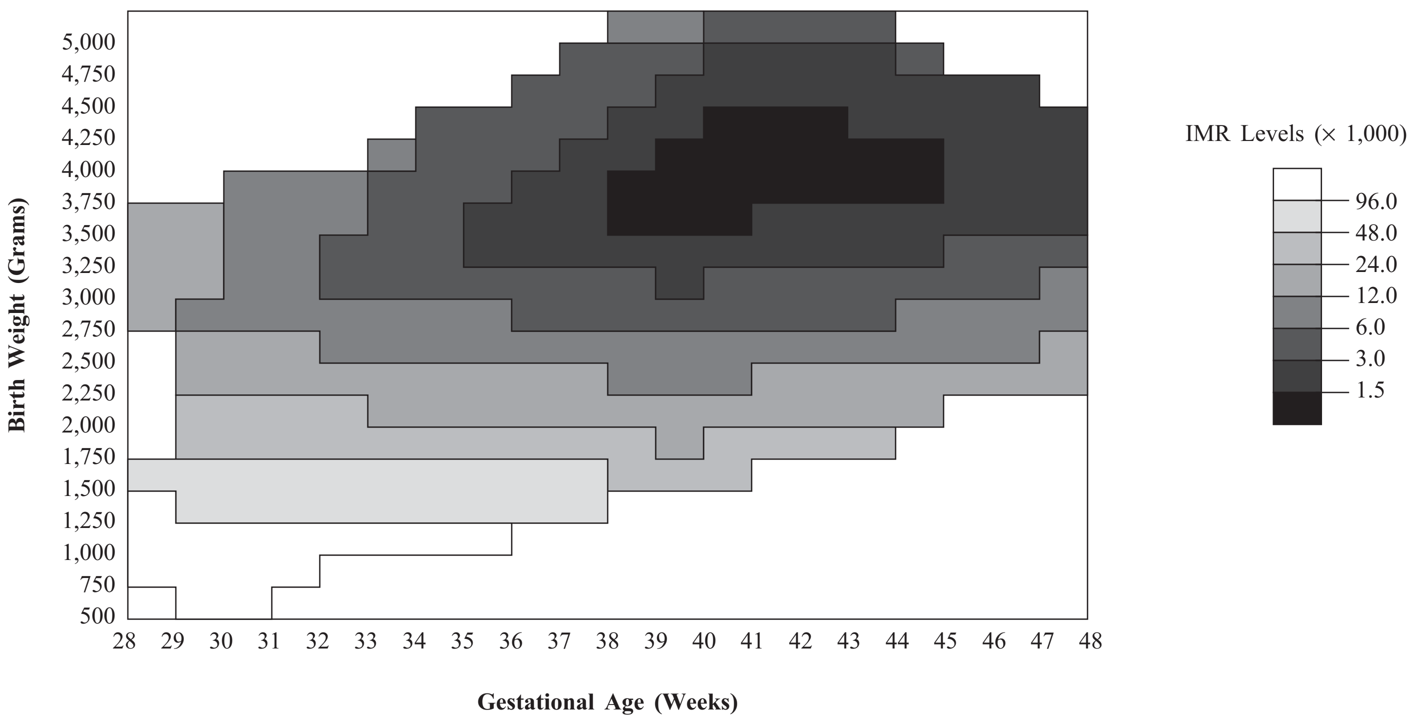
Figure 4 presents a more detailed perspective of the model's goodness of fit: Observed and predicted infant mortality risks are compared at cross-sections of 28, 31, 34, 37, 40, and 44 weeks of gestation. Figure 4 shows that the effect of birth weight is predicted as positive and curvilinear at early gestational ages (28 and 31 weeks). At 37 weeks, the slightly negative effect of weight above the optimal is apparent. At 40 and 44 weeks, however, the relationship between birth weight and gestational age is U-shaped, a pattern also followed closely by the model. These findings are consistent with the view of Wilcox and Russell (1983) that birth weight represents a "lethal dose" at both extremes of the distribution for full-term and postterm infants. Of course, these results do not imply that the risk of death is the same among very heavy and low-weight births. Certainly, infant mortality increases among very heavy infants, but survival is still significantly higher for them than for their low-birth-weight counterparts.

DISCUSSION AND CONCLUSION

In this paper we propose an alternative method for evaluating the effect of gestational age and birth weight on infant mortality. Current demographic classifications of birth outcomes are based on a categorical approach, relying on dichotomies to distinguish high-risk from low-risk newborns. The latter approach entails a representation of a discontinu-

3. This may be true particularly in regard to infants reported as having gestational ages lower than their true length of gestation.

FIGURE 3. PREDICTED INFANT MORTALITY RATES BY GESTATIONAL AGE AND BIRTH WEIGHT: NON-HISPANIC WHITE FEMALES, 1989–1991



Source: Predicted IMRs based on the logistic model presented in Table 2.

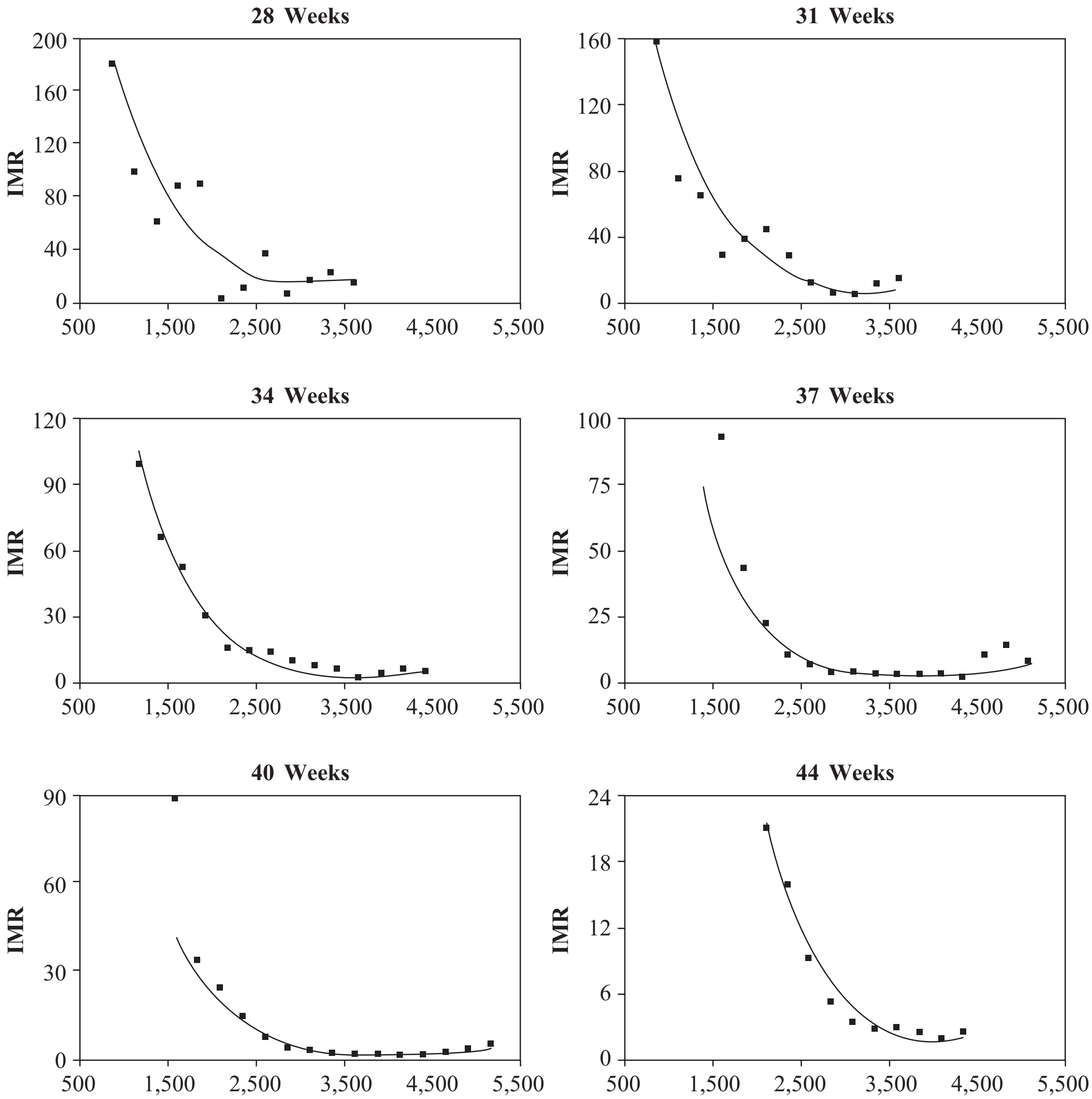
ous association between birth outcomes and infant mortality. We recognize that such conventional typologies (including the simple distinction of low versus normal birth weight) have been quite useful in studies on the determinants and consequences of adverse birth outcomes and that, for many purposes, these venerable measures continue to serve us well.

Yet for analyses requiring a more precise and more fully detailed representation of the association between gestational age, birth weight, and infant mortality, we suggest that at least three modifications are needed. First, gestational age and birth weight should be measured in their original metric: that is, as continuous variables. Second, the effect of gestational age and birth weight should be evaluated in terms of the deviation from an optimal combination, defined by the lowest infant mortality. Finally, differences in birth weight should be measured in relation to the gestational-age-specific distribution of birth weight rather than in absolute terms.

The results of a logistic regression model that implements these modifications and predicts infant mortality illustrate some of the advantages of the proposed measurement strategy over the typologies currently in use. The first of these advantages is that changes are portrayed in a continuous—but not linear—form, reflecting more precisely the association between birth outcomes and infant mortality. A second advantage is that this method isolates the effect of birth outcomes in terms of individual parameters and their interactions, simultaneously providing a detailed and integrated perspective of the association between birth outcomes and infant mortality.

The findings regarding the effect of heavy weight on infant mortality are a telling example of the benefits offered by this analytical approach. The adverse effect of low birth weight on survival is captured well by the model. Moreover, the *ES* interaction suggests that the deleterious effect of low birth weight for gestational age is more severe for preterm infants than for their full-term counterparts. On the other hand, previous studies reported that very heavy newborns are exposed to higher health and mortality risks than normal-weight infants (Myers and Ferguson 1989; Wilcox and Russell 1983). The results of our model confirm these findings. They also indicate, however, that this relationship fades among infants at early gestational ages; this finding suggests that although very heavy weight may harm full-term infants, relatively heavy weight may well be advantageous for preterm infants' survival. The *EH* interaction term in Table 2 summarizes this effect and provides an insight

FIGURE 4. OBSERVED VERSUS PREDICTED INFANT MORTALITY RATES BY BIRTH WEIGHT (GRAMS) AT SELECTED GESTATIONAL AGES: NON-HISPANIC WHITE FEMALES, 1989–1991



Sources: 1989–1991 NCHS Linked Birth/Infant Death Files and predicted rates from the logistic model presented in Table 2.

Notes: Infant mortality rates are shown per thousand. The lines represent the IMRs as predicted by the model.

into the risk associated with the category of infants denoted as "heavy preemies" (Frisbie et al. 1996).

Another advantage of this model is that it identifies effects that were overlooked by studies employing the usual demographic classifications of birth outcomes. This is the case with the negative effect of late delivery: Although it was identified early in public health and clinical research, it cannot be assessed when gestational age is segmented into a dichotomous classification. In this sense, the introduction of a variable that captures the effect of late delivery (L) is an important step toward a more fully detailed specification of the effect of birth outcomes on infant mortality.

In addition to its analytical advantages, the proposed method may prove useful in future demographic research on infant health and mortality. Among these applications, three stand out as potentially most important.

First, the proposed measurement strategy can replace the usual demographic classifications in multivariate models that are intended to estimate the direct effect of other sociodemographic and behavioral determinants on infant mortality.[4] In other words, future multivariate models can include the four proposed deviations and their significant interactions to control for the effect of birth outcomes, instead of relying on categorical measures. Because our strategy reflects more precisely the association between birth outcomes and infant mortality, this substitution should result in more realistic estimates of the effects of other variables *not* due to variations in birth outcomes.

Second, the model proposed here may be used to elaborate classifications of birth outcomes that depend on the infant mortality levels set by the researcher, rather than on the conventional cutoff points in gestational age and birth weight distributions. These classifications may be obtained by setting the predicted infant mortality in the logistic regression equation to a certain level and obtaining all the solutions on the right-hand side of the equation that produce higher infant mortality risks. For example, if a threshold of three deaths per thousand is used to distinguish low-risk from high-risk birth outcomes, all combinations of gestational age and birth weight that produce an expected infant mortality risk above three per thousand would be classified as high-risk birth outcomes. The extension and location of these combinations can be visualized in Figure 3, where the two darkest areas represent the regions with infant mortality lower than three per thousand.

A third possible application of the model pertains to studies intended to evaluate the impact of birth outcomes on child health and development. Evidence suggests that adverse birth outcomes are related not only to mortality, but also to neurodevelopmental and behavioral disorders and to poorer educational achievement and family functioning (Hack et al. 1994; Hack et al. 1995; Kline et al. 1989; McCormick 1985). By applying a continuous measure of the severity of adverse birth outcomes, one may obtain superior predictions of surviving children's health and developmental status. Moreover, in some circumstances, such as in multivariate analyses with a relatively small number of cases, it might be useful to utilize the infant mortality risks predicted by the model instead of the four measures of birth outcomes and their interactions, in order to control for the effect of adverse birth outcomes on health and development among surviving children.

Despite the advantages that we believe attend the approach we suggest here, at least two methodological difficulties still must be resolved. The first is the need to identify precisely the optimal combination of gestational age and birth weight: that is, the combination of these two birth outcomes that produces the lowest infant mortality. Because the effect of birth outcomes is estimated as a function of the distance from this optimum, incorrect assumptions about the location of this combination are likely to alter the results of the model significantly.

The location of this optimum for gestational age seems hardly to be in doubt. The infant mortality trends presented in Figure 1 indicate that the lowest risks tend to cluster on the durations corresponding to the normal length of pregnancy (39–41 weeks). Yet it is questionable whether one standard deviation over the gestational-age-specific mean defines the optimum in the case of birth weight, and whether this point should remain fixed or should change across different gestational ages. The answers to these questions are beyond the objectives of this paper, but the design of more adequate methods for identifying the optimal birth weight and exploring its location at different gestational ages is an important topic for further research.

The second methodological problem is related to the Gaussian parameters employed to estimate deviations in birth weight at early gestational ages. We are particularly concerned about the long tails made evident by the large standard deviations at early gestational ages (see also Wilcox and Skjeovern 1992). Even if this problem does not significantly affect our conclusions, it may introduce biases in the estimation of birth weight effects, especially among preterm infants.

A possible solution in future applications is to replace the estimated Gaussian parameters at early gestational durations with others that reflect more accurately the gestational-age-specific distribution of birth weight. Another option is to use alternative measures of relative birth weight not based on a Gaussian distribution, such as the ratio between observed and gestational-age-specific optimal birth weight. Preliminary analyses using the latter strategy (not shown) produce results similar to those presented here.

Finally, an important characteristic of the model presented in this paper is that it is restricted to white females. On the basis of our preliminary analysis (not shown), we are confident that the approach recommended here is equally relevant to other sex- and race/ethnicity-specific infant populations. There is no apparent reason why future studies of this sort cannot identify the optimum value for infant survival and child health for white males, African American males, African American females, Latino females, Latino males, and so on. Future applications should concentrate on defining these race/ethnicity- and sex-specific optimums and evaluating the effect of deviations from these points on infant health and mortality. Previous research reported that, within similar birth outcome categories, most Hispanic groups are at lower risk of infant mortality than whites (Frisbie et al. 1998). Similarly, mortality is lower among low-weight African American infants than among their white counterparts (Wilcox and Russell 1990). The extension of the model presented here to other racial/ethnic groups may result in new evidence about these findings. It also may add insights to the debate about the relationship of race/ethnicity to infant health and mortality.

4. The results presented here allow us to use this application only among white females. Our current research, however, indicates that the model can be extended to males and to other racial/ethnic groups, provided of course that there are enough cases to permit an estimate of the optimal combination of birth outcomes within each group.

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