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Brief Communication: Comparison of Methods for Estimating Chronological Age at Linear Enamel Formation on Anterior Dentition

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ABSTRACT Linear enamel hypoplasia (LEH) is an enamel defect that records the effects of physiological stress on tooth formation. Estimating the age at which LEH defects form is integral to the reconstruction of population health in bioarcheological studies. Two principal methods for aging LEH defects have been introduced in the literature. The conventional approach employs regression equations based on a linear model of tooth growth. The newer, Reid and Dean [Am J Phys Anthropol 113 (2000) 135–139] approach, is based upon a histologically derived curvilinear model of enamel development and therefore likely provides more accurate age estimates. However, the extent to which the Reid and Dean method produces estimated ages at defect formation differing from those of the regression equations has not, until now, been determined. This study quantifies the differences between these two methods. Evaluating the degree to which these methods differ is essential for interpreting the accuracy of LEH age estimates given in previous bioarcheological studies. Age estimates of LEH defects on 338 anterior teeth from the Hamann–Todd osteological sample were calculated using both methods. The resulting estimated ages were compared through a randomized block ANOVA. However, the mean differences between the estimated ages yielded by both methods range from 4 months or less depending on the tooth type with an overall average of 2.63 months. The discussion focuses on the degree to which this difference affects answers to bioarcheological questions. Am J Phys Anthropol 135:362–365, 2008. ©2007 Wiley-Liss, Inc.

Identification and interpretation of developmental defects of enamel (DDE) receive significant attention in the physical anthropology literature. Evaluation of one class of DDE, linear enamel hypoplasia (LEH), is routine in bioarcheological analysis of skeletal material (Rose et al., 1985; Goodman and Rose, 1990; Larsen, 2002). LEH appears as lines or grooves on the tooth's enamel surface and is most often caused by systemic physiological stresses, such as illness and poor nutrition, which disrupt normal enamel growth (Goodman and Rose, 1990; Hillson and Bond, 1997). Because enamel does not remodel, LEH defects provide a permanent record of enamel growth disruption in unworn portion of the crown. For these reasons, and because teeth are the most often preserved skeletal elements, analysis of LEH can yield insight into the health of past peoples.

Unlike hypoplastic pits that sometimes form in dental enamel, LEH defects are clearly associated with enamel growth layers (Hillson and Bond, 1997), which form with regularity over time (Fitzgerald, 1998). These layers form first in the cusp of the tooth, and continue along the sides of the tooth until the crown is complete (Hillson, 1996). Thus, an individual's approximate age when an LEH defect formed can be inferred from a defect's location on the tooth crown (Skinner and Goodman, 1992). The utility of LEH for recording changes in health status during development has been recognized by a variety of researchers going back several decades (Kreshover, 1940; Massler et al., 1941; Sarnat and Schour, 1941; Swärdstedt, 1966; Cohen and Armelagos, 1984).

The present investigation evaluates two different methods for aging LEH defects, which differ primarily in their assumptions about the rate of enamel growth. This investigation focuses on anterior teeth because they are much more often affected by LEH than posterior teeth (Goodman and Rose, 1990). The first method was introduced by Swärdstedt (1966) using the tooth developmental standard of Massler et al. (1941) to determine the age at which a defect formed. Swärdstedt employed the ages at which crown formation starts and terminates as reference points and interpolated the age at which a defect formed by measuring its distance from the cemento-enamel junction (CEJ). This method assumes that the rate of enamel formation is constant from the beginning to the completion of crown, such that the distance from any point on the crown to the CEJ is a linear function of time. Over the next several decades, charts for determining age at LEH formation published by Swärdstedt (1966) were used as the basis for estimating age at LEH formation. Specifically, these charts were used to construct regression equations based on the mean crown height (CH) per tooth type (Goodman et al., 1980; Goodman and Song, 1998). Each equation, how-

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TABLE 1. Division of anterior teeth in sample

	UI1	UI2	UC	LI1	LI2	LC	Total
Number of teeth used in comparison	36	44	57	63	61	78	339

ever, consists of a slight modification of the original chart to address population variation in CH.

The second method for aging LEH defects was introduced by Reid and Dean (2000). These authors developed a decile chart of anterior tooth enamel growth using established histological techniques for use in estimating ages at which LEH defects form. Histological data revealed that the rate of enamel growth is not constant as tooth formation proceeds from cusp to cervix. Specifically, enamel growth progressively slows from the beginning to end of crown formation, such that enamel growth curves are curvilinear rather than linear, as previously assumed. The decile chart reflects this fact. Theoretically, the decile chart should yield more accurate age estimates than the linear regression models used in previous research. Testing the accuracy of the Reid and Dean method would require known ages of LEH formation, and because this information is not routinely included in health records, an accuracy test is difficult to perform. However, it is possible to compare the Reid and Dean method and the regression methods that preceded it to determine how much they differ in the age estimates each yield. Reid and Dean (2000) did not compare the estimates given by the two methods, so that the degree to which their estimates differ from those given by the regression methods is not currently known. Assuming that the Reid and Dean method is the more accurate one, a large difference between the two methods would mean that all preceding studies employing the regression method include inaccurate estimated ages at defect formation. A small difference between the two methods would imply that the age estimates given in preceding studies are not so different from the most accurate values that can currently be obtained by using the Reid and Dean method.

The question this study addresses is two-fold: 1) Do these two methods (decile chart and regression equations) produce statistically significantly different estimates of the age at which an LEH defect forms? 2) If these methods do produce statistically significant differences, by how much do they differ? To answer these questions, the dental remains of the Hamann–Todd osteological collection were examined for the prevalence of LEH, and defects were aged by the two different methods.

MATERIALS AND METHODS

The Hamann–Todd osteological collection consists of the remains of an ethnically diverse sample of individuals who died in the vicinity of Cleveland, Ohio between the end of the 19th century and the first quarter of the 20th century. The Hamann–Todd osteological collection does not constitute a population. Therefore, the interpretation of health of the sample is not an objective of this study. Determining whether LEH defects were a result of systemic stressors is also not a concern of this study. The aim of this research is to compare different methods for aging LEH defects.

Hypoplastic defects were macroscopically observed and recorded on the anterior teeth of 102 individuals. For analysis, however, only individuals (n = 60) estimated to have 80% or more of their CH intact (i.e., minimally worn teeth) were selected for comparison. The number of teeth for each tooth type is given in Table 1.

TABLE 2. Regression equations constructed by Walker from Swärdstedt (1966)

Tooth	Equation
C^1	Age[a] = ($-0.609 \times$ Ht[b]) + 6.00
I^2	Age = ($-0.396 \times$ Ht) + 4.60
I^1	Age = ($-0.439 \times$ Ht) + 4.55
C_1	Age = ($-0.588 \times$ Ht) + 6.50
I_2	Age = ($-0.422 \times$ Ht) + 3.90
I_1	Age = ($-0.465 \times$ Ht) + 3.90

[a] Age in years.
[b] Ht = height (mm) of LEH defect from the CEJ to the middle of the defect.

The majority of LEH defects were visible for examination to the naked eye under natural lighting, but a hand-held magnifying glass with a magnification of 4× was used in some instances to visually enhance the defect. An LEH defect was defined as a marked horizontal groove or line in the enamel (Goodman et al., 1980).

Fine-tipped Mitutoyo digimatic calipers calibrated to the nearest 0.01 mm were used to measure CH. Where CH could not be completely measured due to wear, the remaining portion of the crown was measured and the unworn CH was calculated based on the percentage of crown estimated to be present. Original CH projections for the worn anterior dentition were reconstructed based on crown morphology. In canine teeth, CH was reconstructed by following the contour of each side of the tooth cusp and projecting it until the sides meet. Reconstruction of CH in incisor teeth was based on the morphology of more complete incisor crowns of the Hamann–Todd collection.

The location of an LEH defect on the tooth crown was determined by measuring from the CEJ to the middle of the LEH defect. The middle of the defect was used as the reference point within the stress episode to translate the location of the defect to an estimated age at which the defect formed. Comparison of the decile and regression methods required only the position of the stress episode on the anterior tooth crown and the CH of the anterior tooth. For the purpose of this comparison, it did not matter whether the occlusal border of the defect, the middle of the defect, or the cervical border of the defect was used as a reference point, as long as the same reference point was used for all defects.

The distance between the LEH defect and the CEJ was measured three times. The average of the three measurements represented the location of the LEH defect on the tooth crown and was inserted into the regression equation for the appropriate anterior tooth type. These regression equations are derived from Swärdstedt's (1966:38) table, in which the chronology of tooth formation is correlated with CH measurements (Table 2). These equations are similar to those of Goodman and Song (1998), which are also based on Swärdstedt (1966). The small difference between Walker's regression equations and Goodman's simply reflect differences in the CHs of the populations studied.

The decile chart is based on the anterior dentition of people from Newcastle upon Tyne, England (Reid and Dean, 2000). To compute an estimated age at defect formation from the decile chart, the distance measurements of LEH defects from the CEJ were converted into percentages of CH. Conversions were performed by dividing the LEH measurement by the CH for unworn teeth and reconstructed CH for worn teeth, and then multiplying by 100.

Ages associated with each decile are clearly defined; however, the ages at which enamel forms within each decile are not defined. Estimated ages at defect formation for defects that fell within deciles were performed using a nonlinear interpolation to account for the nonlinear pattern of tooth growth. Additionally, a linear interpolation was performed for comparison. These interpolations produced the same estimated ages at defect formation. The linear interpolation, therefore, was sufficient.

Intraobserver measurement error for the distance of the defect from the CEJ was evaluated by distances by individuals ANOVA. Each distance was calculated three times and measurement error is the square root of the error mean square in the unit of measurement (mm). A randomized block ANOVA was performed on each anterior tooth type to test if the two methods produce different age estimates for defect location. To evaluate the differences in magnitude between the two methods, the mean differences between the estimated ages at defect formation produced by each method was calculated (as in a paired comparisons test) along with the standard error of the mean difference and the 95% confidence interval.

TABLE 3. Randomized block ANOVA analysis results: relationship between the regression and decile methods for estimating ages at LEH formation

	DF	SSQ	MSQ	*F*	*P* > *F*
UI1					
Methods	1	0.91576	0.9158	38.89	<0.001
Individual	35	22.749	0.65	27.6	<0.001
Error	35	0.82414	0.0235		
UI2					
Methods	1	2.0557	2.0557	267.91	<0.001
Individual	43	24.602	0.57214	74.57	<0.001
Error	43	0.32994	0.0077		
UC					
Methods	1	2.2823	2.2823	28.51	<0.001
Individual	56	57.0663	1.019	12.73	<0.001
Error	56	4.4833	0.0801		
LI1					
Methods	1	0.07578	0.07578	4.4	0.04
Individual	62	37.473	0.6044	35.09	<0.001
Error	62	1.0679	0.0172		
LI2					
Methods	1	0.16086	0.16086	10.51	0.0019
Individual	60	37.3632	0.62272	40.7	<0.001
Error	60	0.9181	0.0153		
LC					
Methods	1	4.9955	4.9955	119.58	<0.001
Individual	77	79.2094	1.0287	24.63	<0.001
Error	77	3.2166	0.04177		

RESULTS

The intraobserver error analysis revealed a very low error in the measurement of the LEH defect position for all tooth types examined. The one-way ANOVA results ranged from 0.01 to 0.2 mm, depending on tooth type. Measurement error is a very minor source of variation in this analysis.

Summary statistics of the randomized block ANOVA procedures of the Hamann–Todd anterior dentition are reported in Table 3.

All tests are statistically significant for each anterior tooth type indicating that estimated ages at LEH formation produced by the two methods are statistically significantly different. The two highest *F*-values are observed for the I^2 (267.9) and the C_1 (119.6). The I_1 exhibits the lowest *F*-value (4.4) and is close to the alpha level (0.05), but still represents a statistically significant difference.

Table 4 contains the differences in age estimates from the two methods for each tooth, their standard error, and the 95% confidence intervals. The average estimated ages at LEH formation from the decile chart are higher for I^1, I^2, and I_2, but are lower than the estimated ages of the regression equations for I_1, C^1, and C_1. The mean difference between the age estimates of each method ranges from just below 1 month to 4 months with an absolute average of 2.63 months for the anterior dentition.

DISCUSSION AND CONCLUSIONS

The present analysis clearly indicates a statistically significant difference between the regression and decile chart methods for estimating ages at LEH formation. A time difference from 1 to 4 months, however, is seldom biologically meaningful in terms of the kinds of questions that bioarcheologists generally use LEH age estimates to answer.

For example, some common purposes for which anthropologists age LEH defects include the reconstruction of weaning ages and the comparison of nutritional statuses in different archeological populations. A small difference in weaning age between two archeological populations would not be biologically significant, because weaning is a process that occurs over a period of time, not an event occurring at a precise time in a child's life. Additionally, a small difference in the age at which a stressor (assumed to be nutritional) affected two different archeological populations is not likely to be critical in describing overall popu-

TABLE 4. Univariate results of the mean difference of age estimates produced by the regression and decile methods

Tooth type	Number	Mean month difference between the paired observations (Walker–Reid and Dean)[a]	Standard error between the paired observations	95% Confidence interval (months)
UI1	36	−2.70	0.4332	(−3.59), (1.84)
UI2	44	−3.70	0.2244	(−4.15), (−3.25)
UC	57	3.40	0.6360	(2.13), (4.67)
LI1	63	0.60	0.2808	(0.04), (1.16)
LI2	61	−1.00	0.2688	(−1.54), (−0.46)
LC	78	4.40	0.3477	(3.65), (5.15)
Absolute mean month difference for anterior tooth types		2.63		

[a] Mean defect age based on age estimation from Walker's method minus age estimation from Reid and Dean's method.

lation health. In addition, this small difference would not be meaningful in evaluating the consequences of contact in a population, since it is the prevalence and broad time of occurrence of LEH defects in the population rather than precise times are most important to such studies. Thus, previous bioarcheological studies employing linear regression to age defects have not produced estimates that differ greatly from what the Reid and Dean method would have yielded.

Nevertheless, considerations of nonlinear growth, hidden enamel, and variation in crown formation per tooth type in the decile charts makes the Reid and Dean method the more accurate one for estimating ages at LEH formation. Despite these improvements, the Reid and Dean method could be further refined. The decile chart introduces a subjective element into estimation of ages at LEH formation, because one is forced to interpolate between the represented intervals. In addition, Reid and Dean (2006) have shown that enamel formation times vary considerably among human populations. These results suggest that there should be population specific standards, but an as yet unanswered question is the extent to which population variation in enamel formation results in large differences in LEH age estimates.

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