

Estimating Head Circumference from Pediatric Imaging Studies: An Improved Method¹

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Rationale and Objectives. Head circumference (HC) is an important developmental measure used both clinically and in research. This paper advances a method to estimate HC from imaging studies when a direct HC-tape measurement cannot be secured. Unlike former approaches, the model takes into account the fact that growth is nonlinear, and that HC growth rates are sexually dimorphic.

Materials and Methods. A model was first established based on published data to represent the normative HC growth curves for males and females. Then, using magnetic resonance (MR) studies of 90 subjects (birth to 18 years), a linear method to estimate HC was adapted to take into account the nonlinear and sex-specific HC normative growth curves. The accuracy of this model was tested prospectively by comparing the estimated HC with HC measurements from twelve computed tomography (CT) studies using the perimeter tracing of oblique slices that correspond to the plane at which a clinical HC-tape measurement is secured.

Results. Prospective comparison of estimated HC to HC tracings using a paired t-test validates that the model provides an accurate estimation of the measured HC ($t=-.845$, $p=0.416$ overall; $t=.54$, $p=.615$ for females and $t=-2.34$, $p=.066$ for males).

Discussion. HC can be calculated indirectly from imaging studies. The model is highly predictive of HC-tape measurements and provides the physician or scientist with a very reliable method to secure HC when it is not feasible to secure the HC-tape measurement.

Key Words. Head circumference; magnetic resonance (MR); computed tomography (CT); head imaging; normative growth

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Table 1
Summary of Studies with Normative Head Circumference Measurements

Study	Year	Total (N)		Age Range	Geography	How HC was Measured
		Male	Female			
Pryor	1966	12000 6000 (M) 6000 (F)		One to 15 years	US Caucasians	Millimeter tapes with spring handles to regulate tension.
Nellhaus	1968	NA		Birth to 18 years	North America, Scotland, Belgium, Sweden, Switzerland, England, Japan, Finland, Czechoslovakia	Tape applied over the greatest frontal protuberances; means and standard deviations for age and sex were calculated from the pooled variances of reports of HC published since 1948.
Roche	1987	888		Birth to 18 years	US (Ohio)	The tape was placed with its inferior margin just touching the superior borders of the eyebrows. The posterior part of the tape was aligned so that the maximum head circumference was recorded.
Farkas	1992	1596 792 (M) 804 (F)		One to 18 years	North American Caucasians	Measurements taken directly from head of subject; on glabella-opisthocranion plane.
CDC Centers for Disease Control & Prevention	2000	362		Birth to 36 months	US (National Survey)	Data for HC at birth from 362 infants in the Fels Longitudinal Study who were born between the years 1960 and 1994, corresponding to the national surveys.

INTRODUCTION

Measurements of head size, both prenatally and postnatally, are medically important to assess the growth of the cranium. The typical prenatal ultrasound measurement is based on biparietal (BP) diameter or head circumference (HC) tracing (1-4). The conventional postnatal clinical method, which is reportedly a highly reliable measurement (5), is to secure a direct HC measurement by applying a measuring tape around the frontal forehead and occiput (HC-tape). HC-tape measurement is typically not secured clinically after age 2 and is therefore not always a readily available measurement to secure retrospectively for medical or research purposes. Thus, the purpose of this paper is to estimate HC from imaging studies when a direct HC-tape measurement or HC tracing cannot be secured.

There are only a few studies that report on HC measurement throughout the developmental age range, *i.e.*, approximately the first two decades of life (Table 1) (6-10). The HC measurements reported by Nellhaus (7) span the entire developmental age range and are used as the

normative standard in most specialty clinics (11). HC follows the neural growth curve, as defined by Scammon; by age 6 years HC has reached 80 % of its adult size, but continues to increase at a more gradual rate until about age 18 (12) (Figure 1).

Oba, Terada and colleagues developed and tested a linear mathematical model to determine HC indirectly from magnetic resonance (MR) images when directly measured values are unavailable (13,14). Their method entails calculating the circumference of an ellipse using the antero-posterior (AP) and BP diameters of the head from an axial slice in the region of the basal ganglia as an estimate of HC. They do not report comparison of mean statistics but report a correlation of $r = .98$ between the HC they calculated and the conventional HC-tape method, and a slightly better correlation when a linear correction factor was applied to the calculated HC ($r = .99$ $p < .001$). Their semi-quantitative method to classify patients with atypical cranial growth, where HC was estimated with the linear correction method, was 62% to 88% accurate.

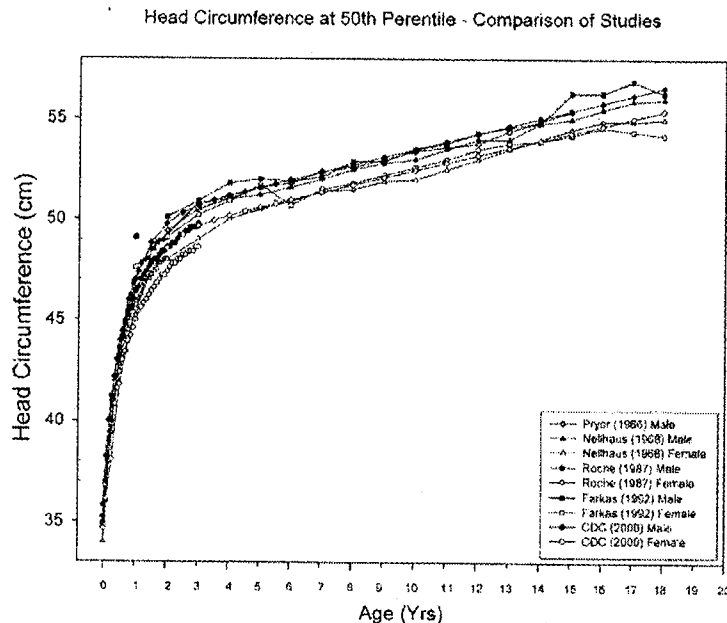


Figure 1. A graphical presentation of the 50th percentile direct HC measurements, for males and females where available, as reported by the studies listed in Table 1.

We have adapted Oba and Terada's method for securing indirect HC measurements from imaging studies (13,14). This model can be applied when AP-BP diameters are not available. More importantly, we propose a correction factor that takes into account two critical facts: a) growth is nonlinear with age; and b) growth rates are sexually dimorphic.

MATERIALS AND METHODS

First, we developed a mathematical model to represent Nellhaus' nonlinear normative growth curve for males and females (formulae 2.1 & 2.2). Next, using two measurements from an imaging database (described below), we estimated HC by calculating the circumference of an ellipse—an adaptation of Oba's and Terada's HC estimation method (formula 3.1). We then subjected that estimate to a correction factor using the normative HC model that is based on Nellhaus' growth curves (formulae 4.1 and 4.2 for females and males respectively). Finally, using a different set of subjects, we confirmed the validity of this model to estimate HC by prospectively comparing the HC estimated values with HC-tape equivalent measurements using a paired t-test statistic.

Subjects

The measurements used in model development are from different sets of subjects. The first model on normative HC development (formulae 2.1 and 2.2) was based on Nellhaus' data using the 50th percentile fits. Their exact n was not reported, but it is from a large set of subjects across the developmental age range (birth to 18) (7).

The remaining measurements are from two imaging databases of individuals who received head and neck imaging for various medical reasons that are presumed not to affect growth and development. These imaging databases were developed to assess the typical growth of structures in the vicinity of the oral and pharyngeal cavities. Additional details on how images were secured and measured are provided elsewhere (15).

The first imaging database was used to develop the model for estimating HC. This database consists of the MR images of 90 subjects (45 males and 45 females) who had received repeat imaging studies totaling 232 studies or cases (136 males and 96 females), spanning the developmental age range of birth to 18 years.

The second imaging database was used for the prospective validation test of the model. This database consists of 12 computed tomography (CT) studies which had full head imaging where an oblique slice could be recon-

structed to trace the HC in the same plane used for clinical tape measurement of HC.

Measurements

The head length (HL) measurement is defined as the distance from the glabella to the opisthocranium secured from a midsagittal slice. The mandibular width (ManW) measurement is defined as the distance between the most lateral points of the mandibular condyles on an axial slice of the head. These measurements were used as an equivalent to the AP-BP diameters proposed by Oba and colleagues to calculate HC because, for most of the cases, an axial slice in the region of basal ganglia was not readily available to secure the AP-BP diameters. Bony structures measured from MRI are comparable to those measured from CT (paired t-test=-0.227; p=0.822).

For the prospective validation study of the model, HC-tape equivalent measurements were used. Measurements were made by tracing the outer perimeter of a reconstructed oblique axial slice from the forehead (glabella) to the occiput (opisthocranium), a plane similar to that used in clinical tape measurement of HC (HC-oblique tracing).

RESULTS

Normative HC Development Model

The development of the initial model that is representative of Nellhaus' nonlinear and sex specific growth curve entailed the use of the Box-Cox transformation (16) to remove nonlinearity of data, and it was iteratively applied twice to ensure sufficient fitting of the data. The Box-Cox transformation g of a predictor x associated with a parameter λ is defined as:

$$g(x, \lambda) = \begin{cases} (x^\lambda - 1)/\lambda, & \lambda \neq 0 \\ \log x, & \lambda = 0 \end{cases} \quad (1.1)$$

A second Box-Cox transformation was then applied and a regression model (17) was set up:

$$Y = \beta_0 + \beta_1 g(x, \lambda) + \beta_2 g(x, \gamma) + e, \quad (1.2)$$

This model (1.2) will be referred to as a generalized Box-Cox transformation model where Y is the response variable, x is the predictor and e is the error term. $\beta_0, \beta_1, \beta_2$ are unknown parameters of the model that need to be estimated. The unknown parameters (λ, γ) are estimated

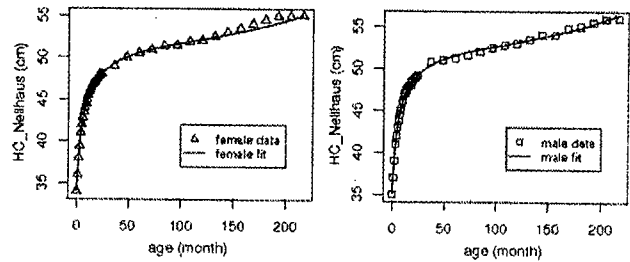


Figure 2. A display of Nellhaus' 50th percentile normative data for females (left, open triangle) and males (right, open square) with the line fit for each data set using the generalized Box-Cox transformation as specified in formula 2.1 (female) & 2.2 (male).

by maximizing the R-squared values of (1.2). The accuracy of the model fit was further improved by applying the residuals of the first regression to this generalized Box-Cox transformation again. The sex-specific growth model for Nellhaus HC measurements is thus given by:

$$\begin{aligned} \text{Female: } HC_{\text{Nellhaus}} = & 34.0530 + 8.1589 \times g(\text{age} + 1, \\ & -0.25) - 7.6527 \times g(\text{age} + 1, \\ & -2) - 0.0187 \times g(\text{age} + 1, 1.75) \\ & + 0.0155 \times g(\text{age} + 1, 1.79) \quad (2.1) \end{aligned}$$

$$\begin{aligned} \text{Male: } HC_{\text{Nellhaus}} = & 35.0923 + 9.2739 \times g(\text{age} + 1, \\ & -0.30) - 9.6138 \times g(\text{age} + 1, -2) \\ & + 0.0659 \times g(\text{age} + 1, 1.80) \\ & - 0.0690 \times g(\text{age} + 1, 1.79) \quad (2.2) \end{aligned}$$

The line fits for this growth model for males and females with Nellhaus' normative data are depicted in Figure 2.

Estimating HC Using the Normative HC Development Model

We calculated HC using an adaptation of the method of Oba and colleagues (13) (HC_{Lab}), substituting measurements of HL and ManW for the AP and BP measurements used by Oba and colleagues. Thus, HC_{Lab} was calculated as follows:

$$HC_{\text{Lab}} = \pi \times \sqrt{0.5 \times (HL^2 + ManW^2)} \quad (3.1)$$

This HC_{Lab} value was then inserted into sex-specific statistical models (4.1 for females and 4.2 for males), which

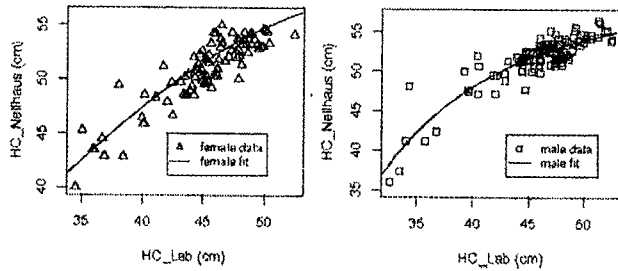


Figure 3. Scatter plots of $HC_{Nellhaus}$ versus HC_{Lab} (left, triangles, female & right, squares, male). The x-axis is the HC_{Lab} calculated by (3.1) and the y-axis is the $HC_{Nellhaus}$ calculated by (2.1) and (2.2). Superimposed on this scatterplot are the fits for corrected HC values - $HC_{Lab-corrected/Nellhaus}$ obtained from (4.1) and (4.2).

apply a nonlinear correction factor based on Nellhaus' model for normative data, producing $HC_{Lab-corrected/Nellhaus}$. The application of such a correction factor ensures that nonlinear growth and sex differences in HC are accounted for when estimating age-specific HC.

$$\text{Female: } HC_{Lab-corrected/Nellhaus} = 7.7550 - 5.3610 \\ \times g(HC_{Lab}, 2) + 5.5860 \times g(HC_{Lab}, 1.99) \quad (4.1)$$

$$\text{Male: } HC_{Lab-corrected/Nellhaus} = -91017 \\ - 706402 \times g(HC_{Lab}, -1.95) \\ + 906667 \times g(HC_{Lab}, -2) \quad (4.2)$$

Comparison of $HC_{Nellhaus}$ (formulae 2.1 and 2.2) with HC_{Lab} (formula 3.1) produces the scatter plots depicted in Figure 3. These correlations have R-squared values of .81 for females and .75 for males. The $HC_{Lab-corrected/Nellhaus}$ fits derived from (4.1) and (4.2) are superimposed over the scatterplots in Figure 3. Correlations between $HC_{Lab-corrected/Nellhaus}$ measurements (formulae 4.1 and 4.2) and $HC_{Nellhaus}$ have an R-squared value of .82 for females and .80 for males. This is an improvement over uncorrected HC_{Lab} values, especially for males, and clearly demonstrates the need for a nonlinear correction procedure.

Prospective Verification of the Model

To further validate the accuracy of the second model ($HC_{Lab-corrected/Nellhaus}$), additional HL and ManW measurements were secured from twelve (6 male and 6 female) imaging studies that were not included in the model fitting analysis. The HL and ManW measurements from these addi-

tional studies were inserted into formula 3.1 to calculate HC_{Lab} . The nonlinear correction factors (formulae 4.1 and 4.2) were then applied to calculate $HC_{Lab-corrected/Nellhaus}$. Next, HC-tape equivalent measurements were secured by tracing the outer perimeter of an oblique axial slice glabella to opisthocranium ($HC_{oblique\ tracing}$), a plane similar to that used in clinical HC-tape measurement.

A paired t-test comparing measurements secured by $HC_{oblique\ tracing}$ to HC_{Lab} was $t = -8.39$, $p < .001$ (for females $t = -5.45$, $p = .003$; and for males $t = -5.96$, $p = .002$), and $HC_{oblique\ tracing}$ to $HC_{Lab-corrected/Nellhaus}$ was $t = -.85$, $p = .416$ (for females $t = .54$, $p = .615$; and for males $t = -2.34$, $p = .066$). The overall correlation of $HC_{oblique\ tracing}$ to $HC_{Lab-corrected/Nellhaus}$ was .93 ($p = .00001$). These findings indicate that our models with the correction factor (formulae 4.1 & 4.2) provide a very accurate estimation of measured HC (HC-tape).

DISCUSSION

In this study, we used Nellhaus' HC data to model normative HC development ($HC_{Nellhaus}$) for females and males (formulae 2.1 and 2.2). We then used those models to develop nonlinear correction factors to estimate HC from two skeletal measurements in two different planes, producing a second set of sex-specific models, as specified in formulae 4.1 and 4.2. Finally, we confirmed the accuracy of such an application prospectively by reliably estimating HC using measurements from head imaging studies.

For both clinical and research purposes, a method for accurately estimating HC retrospectively from an imaging study is needed when a direct HC tape measurement is not available. Clinically, the HC estimate could, for example, be used to evaluate for large or small head size, head/brain development, or to assess the rapidity of head enlargement, when prior medical records are not available but the patient provides the clinic with an old MRI or CT scan. In research, the negative effects of treatment (chemotherapy or radiation treatment) on brain growth/development can be assessed when HC measurements are not available but old CT or MRI scans are available.

Both the method advanced by Oba, Terada and colleagues and the method presented in this paper indicate the need to apply a correction factor to calculated HC. These correction factors improve estimation of HC and are best assessed using paired t-test statistic, instead of a correlation value. The correction factor provided by Oba,

Terada and colleagues is linear, whereas the correction factor in this paper is nonlinear.

The objective of the estimated HC measurement will determine the nature of the correction factor used. The table published by Terada and colleagues (14), which incorporates a linear correction factor, is adequate for most purposes of medical diagnoses when AP-BP measurements are available. However, physician in a specialty clinic (11,18–21), physicians needing to comparatively assess head/brain development or rapidity of head enlargement, or scientists studying the growth of head and neck structures may need a more accurate HC estimation to use as a local index of growth. In these cases, a nonlinear correction factor that reflects nonlinear growth and takes into account sex differences in rates of growth should be used.

Another advantage of the method presented here is that it demonstrates the application of alternate measurements that correspond to AP-BP measurements when AP-BP measurements are not available. Thus, other measurements from imaging studies that correspond to AP-BP measurements can be used along with the normative HC model (HC_{Nellhaus}) presented here to develop nonlinear correction factors to predict HC across the entire developmental age range.

We have shown that HC can be estimated indirectly and with high accuracy from an imaging study when a direct HC tape measurement cannot be secured. A nonlinear correction factor must be applied to improve the accuracy of the estimate by accounting for nonlinear growth rates and sex differences in head growth. This method of HC estimation can be very useful in both clinical and research settings.

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