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BMI Is a Better Body Proportionality Measure than the Ponderal Index and Weight-for-Length for Preterm Infants

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Keywords

BMI · Ponderal index · Body proportionality · Preterm infants · Growth curves

Abstract

Background: Clinicians have observed preterm infants in the neonatal intensive care unit growing disproportionally; however, the only growth charts that have been available were from preterm infants born in the 1950s which utilized the ponderal index. Prior to creating the recently published BMI curves, we found only 1 reference justifying the use of the ponderal index. ***Objectives:*** To determine the best measure of body proportionality for assessing growth in US preterm infants. ***Methods:*** Using a dataset of 391,681 infants, we determined the body proportionality measure that was most correlated with weight and least correlated with length. We examined the sex-specific overall correlations and then stratified further by gestational age (GA). We then plotted the body proportionality measures versus length to visualize apparent discrepancies in the appropriate measure. ***Results:*** The overall correlations showed weight/length^3 (ponderal index) was the best measure but stratification by GA indicated that BMI (weight/length^2) was the best measure. This seeming inconsistency was due to negative correlations between ponderal index and length at each GA. BMI, on the other hand, had a correlation with length across GAs, but was uncorrelated with length within GAs. Both ponderal index and BMI were positively correlated with weight. ***Conclusions:*** BMI is the appropriate measure of body proportionality for preterm infants, contrary to current practice.

Introduction

Growth curves based on birth data are available for the assessment of size in preterm infants; these include the Lubchenco curves [1, 2] and the Fenton curves [3, 4]. In 2010, we published a set of growth curves based on a large set of US birth data assessing the length, weight, and head circumference-for-age in preterm infants [5]. Our goal was to allow clinicians to better define large and small for gestational age (GA). However, in addition, a tool was needed to assess whether abnormalities in growth in preterm infants are symmetric (i.e., affecting weight and

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length) or asymmetric (i.e., affecting weight but not length, or vice versa). Body proportionality is usually measured as an index of weight/length^{power}). The most commonly used powers are 1, 2, and 3, corresponding to birth weight/length^1, weight/length^2 (BMI), and weight/length^3 (ponderal index). Our paper on BMI curves [6] provided a reference to assess body proportionality in preterm infants, but we had insufficient space to describe how we selected BMI as the best measure of body proportionality.

Although the "ideal" measure of body proportionality might be determined using body composition data and health outcomes data, similar to in older age groups, these data are limited and difficult to acquire in preterm infants. Benn [7] defined the "best" measure of body proportionality as the measure most correlated with weight and least correlated with length. According to a study by Cole et al. [8] using Benn's methods, the best measure for body proportionality in preterm infants varied greatly over the continuum of GA, but power for length generally rounded to 3, the ponderal index. We thus modeled our methods after Cole's, in order to determine the most appropriate measure of body proportionality in a large, contemporary sample, stratifying by gender and GA.

The purpose of this report is to describe and explain our findings about the best measure of body proportionality for preterm infants.

Methods

Study Population

The data, sample collection, and study population have been previously described [5]. Briefly, all 4 curves (weight, length, head circumference, and BMI) were created, purposefully utilizing the same data for use with preterm infants in the neonatal intensive care unit (NICU). The deidentified sample of 391,681 infants in the NICU (aged 22–42 weeks at birth) was collected between 1998 and 2006 from 248 US hospitals in 33 states by the Pediatrix Medical Group, Inc., whose neonatologists estimated GA using obstetric history and examinations, prenatal ultrasound, and postnatal physical examination. Data about how each specific neonatologist made this decision are not available, but any error in classification would be expected to follow the same general distribution of misclassification by neonatologists in the population. Infants were excluded for missing growth measurement data (weight = 0.53%, length = 6.5%, or head circumference = 0.96%) and the exclusion criteria described previously. The exclusion criteria identified infants with factors associated with reduced intrauterine growth (e.g., multiple births, congenital anomalies, mortality before discharge, 25% excluded). Extreme outliers, defined as infants with growth measurement values >2 times the interquartile range >75th or <25th percentile of the whole sample, were also excluded (1.6%). The final sample had 257,855 singleton infants who survived to discharge, 51% of whom were classified as being of white race.

The sample was split by gender due to size differences, and the SAS SURVEYSELECT procedure was used to split each gender-specific sample into 2 random samples stratified by GA, race, and birth hospital state [9]. One sample was used for analysis and the second was used to recreate the analysis for validation purposes. The analysis dataset for girls had 55,721 infants and the one for boys had 74,390 infants. The validation sample had 54,569 girls and 73,175 boys. This predominance of boys is known to occur in infants admitted to NICU, particularly at older GAs, and is likely due to the fact that male infants more often develop respiratory distress than female infants of the same GA [10–12].

It was not necessary to obtain ethics approval; this study was exempted from review by the official institutional review board of the Kennesaw State University because the data provided to our research team had been deidentified.

Identification of Body Proportionality Index

To identify the best body proportionality index for this population, we based our methods on those described by both Benn [7] and Cole et al. [8]. The first step identified the GA and gender-specific Benn indices by running regression models using the natural log of birth length to predict the natural log of birth weight, using the resultant regression coefficient as the power coefficient in the Benn index for each group. Next, we identified which of 6 body proportionality indices were most correlated with weight and least correlated with length for each gender and GA. As suggested by Cole et al. [8], we considered a negative correlation to represent an overcorrection for length, while a positive correlation indicated undercorrection.

We ran correlation analyses on: Weight/Length, Weight/Length$^{1/2}$, Weight/ln(Length), Weight/Length^2, Weight/Length^3, Weight/Length^p, where "p" is the Benn's index power. For each GA, we determined which measure had the highest Pearson correlation with weight (strong being defined as $r > 0.7$) while being uncorrelated (defined as $r < 0.3$ away from zero), and scored the measures based on these criteria.

To compare our results to those of Cole et al. [8], we reran analyses stratifying by year, antenatal steroid use, individual sites (if $n > 600$), and race. We also reran analyses including only excluded infants and only multiple births. We created sampling distributions of the Benn power designed to reflect Cole's sample size, smaller infants, and predominantly white infants (1,000 samples per GA). Analyses were conducted in SAS v9.4 and R v3.0.

Results

Table 1 shows birth weight, length, BMI, and ponderal index means by GA overall, and for boys and girls separately. Girls' means were consistently smaller than boys. Our sample size for the infants of 22 and 23 weeks' GA was insufficient ($n = 28$ and $n = 286$, respectively) for an accurate assessment of infant size at these GAs (Table 1).

We present the results of the analysis to determine the measure(s) most correlated with weight and uncorrelated with length in Tables 2 and 3. All measures except BMI and Benn's index were correlated with length when strat-

Table 1. Measures of growth at birth by gender and gestational age (GA) expressed as means (SD)

GA, weeks		*n*	Weight, g	Length, cm	BMI	Ponderal index
22	Overall	28	547 (79)	28.9 (1.6)	6.53 (0.66)	2.27 (0.28)
	Girls	13	520 (68)	29 (1.2)	6.18 (0.56)	2.13 (0.21)
	Boys	15	570 (82)	28.9 (1.9)	6.84 (0.61)	2.38 (0.30)
23	Overall	286	606 (78)	30.2 (1.7)	6.66 (0.82)	2.22 (0.35)
	Girls	133	587 (80)	29.9 (1.8)	6.59 (0.86)	2.22 (0.38)
	Boys	153	622 (74)	30.5 (1.6)	6.73 (0.79)	2.22 (0.32)
24	Overall	889	669 (95)	31.3 (1.8)	6.85 (0.82)	2.20 (0.32)
	Girls	438	649 (89)	31.0 (1.7)	6.74 (0.83)	2.18 (0.33)
	Boys	451	689 (96)	31.5 (1.8)	6.96 (0.79)	2.22 (0.31)
25	Overall	1,325	759 (120)	32.5 (2.1)	7.16 (0.89)	2.21 (0.33)
	Girls	603	738 (121)	32.3 (2.0)	7.06 (0.86)	2.20 (0.31)
	Boys	722	777 (116)	32.8 (2.1)	7.24 (0.9)	2.23 (0.35)
26	Overall	1,654	857 (148)	33.9 (2.3)	7.45 (0.91)	2.21 (0.32)
	Girls	773	822 (143)	33.4 (2.2)	7.33 (0.9)	2.21 (0.31)
	Boys	881	888 (145)	34.2 (2.2)	7.56 (0.9)	2.20 (0.32)
27	Overall	1,996	969 (172)	35.3 (2.4)	7.74 (0.95)	2.20 (0.32)
	Girls	966	934 (168)	35.0 (2.3)	7.58 (0.88)	2.17 (0.28)
	Boys	1,030	1,001 (170)	35.6 (2.4)	7.89 (0.98)	2.23 (0.34)
28	Overall	2,468	1,100 (206)	36.8 (2.6)	8.07 (1.03)	2.20 (0.32)
	Girls	1,187	1,058 (203)	36.4 (2.5)	7.96 (1.05)	2.20 (0.33)
	Boys	1,281	1,138 (203)	37.2 (2.5)	8.17 (1)	2.21 (0.31)
29	Overall	2,759	1,242 (225)	38.2 (2.6)	8.45 (1.04)	2.22 (0.31)
	Girls	1,254	1,199 (226)	37.9 (2.7)	8.32 (1.06)	2.21 (0.33)
	Boys	1,505	1,277 (218)	38.6 (2.5)	8.55 (1.01)	2.23 (0.30)
30	Overall	3,598	1,409 (256)	39.8 (2.7)	8.87 (1.17)	2.24 (0.35)
	Girls	1,606	1,376 (246)	39.6 (2.6)	8.74 (1.07)	2.22 (0.31)
	Boys	1,992	1,435 (261)	39.9 (2.8)	8.97 (1.24)	2.26 (0.38)
31	Overall	4,504	1,595 (276)	41.2 (2.6)	9.35 (1.17)	2.28 (0.33)
	Girls	2,044	1,548 (271)	40.9 (2.6)	9.24 (1.15)	2.27 (0.33)
	Boys	2,460	1,633 (275)	41.5 (2.5)	9.44 (1.18)	2.28 (0.33)
32	Overall	6,684	1,781 (307)	42.5 (2.7)	9.82 (1.22)	2.32 (0.33)
	Girls	3,007	1,730 (300)	42.1 (2.6)	9.7 (1.23)	2.31 (0.33)
	Boys	3,677	1,823 (306)	42.8 (2.7)	9.92 (1.21)	2.33 (0.33)
33	Overall	9,200	2,013 (338)	44.0 (2.6)	10.35 (1.27)	2.33 (0.32)
	Girls	4,186	1,960 (328)	43.7 (2.6)	10.24 (1.26)	2.35 (0.32)
	Boys	5,014	2,058 (341)	44.3 (2.6)	10.45 (1.27)	2.37 (0.32)
34	Overall	13,227	2,246 (364)	45.3 (2.6)	10.9 (1.33)	2.41 (0.34)
	Girls	5,936	2,194 (357)	45.0 (2.6)	10.82 (1.34)	2.42 (0.34)
	Boys	7,291	2,288 (364)	45.6 (2.6)	10.97 (1.32)	2.41 (0.33)
35	Overall	12,034	2,483 (439)	46.5 (2.7)	11.45 (1.49)	2.47 (0.35)
	Girls	5,082	2,420 (440)	46.0 (2.7)	11.36 (1.51)	2.48 (0.36)
	Boys	6,952	2,529 (433)	46.8 (2.7)	11.52 (1.47)	2.47 (0.34)
36	Overall	11,701	2,749 (508)	47.7 (2.8)	12.02 (1.62)	2.53 (0.36)
	Girls	4,690	2,675 (514)	47.3 (2.8)	11.91 (1.66)	2.53 (0.37)
	Boys	7,011	2,798 (498)	48.0 (2.8)	12.09 (1.59)	2.53 (0.36)

Table 1 (continued)

GA, weeks		*n*	Weight, g	Length, cm	BMI	Ponderal index
37	Overall	11,064	3,014 (534)	48.9 (2.8)	12.55 (1.67)	2.57 (0.37)
	Girls	4,372	2,946 (551)	48.4 (2.8)	12.51 (1.74)	2.59 (0.38)
	Boys	6,692	3,058 (518)	49.2 (2.7)	12.58 (1.61)	2.56 (0.36)
38	Overall	14,541	3,265 (525)	49.9 (2.6)	13.06 (1.64)	2.62 (0.36)
	Girls	5,755	3,184 (512)	49.5 (2.6)	12.96 (1.64)	2.62 (0.36)
	Boys	8,786	3,319 (527)	50.2 (2.7)	13.13 (1.64)	2.62 (0.36)
39	Overall	14,302	3,420 (499)	50.6 (2.5)	13.33 (1.58)	2.64 (0.35)
	Girls	5,978	3,342 (489)	50.1 (2.5)	13.27 (1.59)	2.66 (0.36)
	Boys	8,324	3,476 (498)	51.0 (2.4)	13.36 (1.57)	2.63 (0.35)
40	Overall	12,764	3,530 (485)	51.2 (2.4)	13.45 (1.52)	2.63 (0.34)
	Girls	5,529	3,461 (465)	50.7 (2.4)	13.44 (1.52)	2.66 (0.34)
	Boys	7,235	3,583 (493)	51.6 (2.4)	13.45 (1.52)	2.62 (0.33)
41	Overall	4,444	3,629 (506)	51.8 (2.5)	13.52 (1.52)	2.62 (0.33)
	Girls	1,906	3,546 (477)	51.3 (2.4)	13.45 (1.5)	2.63 (0.34)
	Boys	2,538	3,691 (518)	52.1 (2.5)	13.57 (1.53)	2.61 (0.33)
42	Overall	643	3,609 (520)	51.7 (2.6)	13.48 (1.56)	2.61 (0.34)
	Girls	263	3,503 (531)	50.9 (2.6)	13.51 (1.66)	2.66 (0.36)
	Boys	380	3,682 (500)	52.3 (2.5)	13.46 (1.5)	2.58 (0.32)

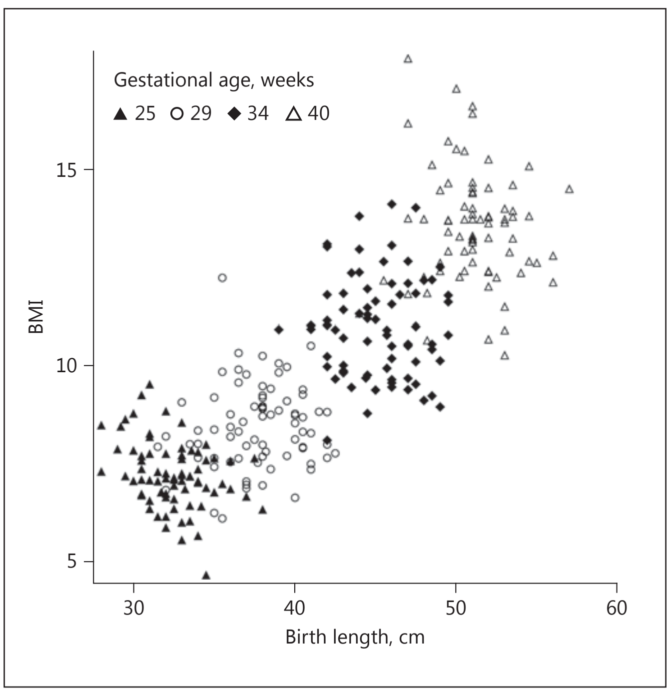

Fig. 1. Scatterplot of BMI versus birth length (*n* = 75 per GA).

ified by GA, and were therefore inappropriate for use as a body proportionality measure. The Benn's index correlations with length were not exactly zero because we calculated the correlations on the untransformed scale. For girls, BMI was the superior measure, with 11 of the highest correlation coefficients with weight, including 1 tie. For boys, Benn's index was superior, also having 11 of the highest correlated values and 1 tie. As illustrated in the final column in Tables 2 and 3, the Benn's index power rounded to 2 in all but 3 of the 42 comparisons. Furthermore, the difference in correlation coefficients between Benn's index and BMI was small. The average differences in the correlation coefficient for weight and length were, respectively, 0.01 and 0.06 for girls and 0.03 and 0.07 for boys. Although the numbers were slightly different between girls and boys, the ultimate conclusion that the Benn power rounded to 2 was similar for both sexes. Thus, we selected BMI as the appropriate measure since it is a single measure that is universally recognized.

The last row of Tables 2 and 3 show the correlation between the candidate measures, weight and length, without taking GA into account. If the data are analyzed this way, the ponderal index (weight/length^3) appears to be the best measure, but this is not the case when the analysis is stratified by GA. BMI appears to be strongly correlated with both weight and length in the aggregate analysis. The rea-

Table 2. Girls' correlation coefficients between weight/length proportionality index, weight, and length by gestational age at birth in 55,721 infants

GA, weeks	Weight/Length		Weight/Length^2		Weight/Length^3		Weight/Length$^{1/2}$		Weight/ ln(Length)		Benn's index (Weight/Length^p)		
	weight	length	weight	length	weight	length	weight	length	weight	length	weight	length	p
22	0.96	0.44	**0.75**	**0.03**	0.39	−0.41	0.99	0.58	1.00	0.62	**0.75**	**0.03**	2.00
23	0.89	0.11	0.55	−0.39	0.24	−0.67	0.98	0.35	0.99	0.44	**0.83**	**−0.01**	1.22
24	0.92	0.19	0.63	−0.27	0.31	−0.59	0.98	0.40	0.99	0.48	**0.81**	**−0.02**	1.45
25	0.94	0.39	0.65	−0.09	0.25	−0.52	0.99	0.57	1.00	0.62	**0.71**	**−0.02**	1.86
26	0.94	0.45	0.67	−0.03	0.24	−0.49	0.99	0.61	1.00	0.66	**0.68**	**−0.01**	1.97
27	0.95	0.55	**0.69**	**0.09**	0.21	−0.44	0.99	0.69	1.00	0.73	0.61	−0.02	2.18
28	0.95	0.52	**0.70**	**0.06**	0.27	−0.42	0.99	0.66	1.00	0.71	0.63	−0.03	2.17
29	0.95	0.53	**0.67**	**0.06**	0.22	−0.43	0.99	0.68	1.00	0.72	0.60	−0.03	2.17
30	0.95	0.50	**0.68**	**0.04**	0.25	−0.44	0.99	0.65	1.00	0.70	0.64	−0.02	2.11
31	0.95	0.47	**0.69**	**0.01**	0.28	−0.45	0.99	0.62	1.00	0.67	0.67	−0.02	2.06
32	0.95	0.46	**0.72**	**0.02**	0.34	−0.41	0.99	0.60	1.00	0.66	0.68	−0.02	2.10
33	0.95	0.43	**0.72**	**0.00**	0.36	−0.42	0.99	0.58	1.00	0.64	0.71	−0.02	2.04
34	0.94	0.39	0.71	−0.04	0.35	−0.45	0.99	0.55	1.00	0.61	**0.72**	**−0.02**	1.95
35	0.96	0.47	**0.77**	**0.08**	0.43	−0.34	0.99	0.60	1.00	0.65	0.70	−0.02	2.22
36	0.96	0.50	**0.80**	**0.15**	0.48	−0.26	0.99	0.62	1.00	0.67	0.69	−0.02	2.39
37	0.96	0.47	**0.79**	**0.11**	0.48	−0.30	0.99	0.59	1.00	0.64	0.70	−0.02	2.30
38	0.96	0.38	**0.77**	**0.01**	0.47	−0.37	0.99	0.52	1.00	0.58	0.76	−0.02	2.05
39	0.95	0.30	0.74	−0.10	0.43	−0.46	0.99	0.47	1.00	0.53	**0.79**	**−0.01**	1.79
40	0.94	0.27	0.73	−0.14	0.43	−0.48	0.99	0.44	1.00	0.51	**0.81**	**−0.01**	1.70
41	0.94	0.29	0.73	−0.12	0.43	−0.47	0.99	0.46	1.00	0.52	**0.80**	**−0.01**	1.74
42	0.95	0.34	0.75	−0.04	0.46	−0.41	0.99	0.50	1.00	0.56	**0.77**	**−0.02**	1.95
All GA	0.99	0.85	0.91	0.69	**0.54**	**0.18**	1.00	0.88	1.00	0.90	0.49	0.35	3.24

Bold type indicates the highest weight correlation that is uncorrelated with length. The final column is not a correlation but the power (^{p}) used in the Benn's index. GA, gestational age.

son for this is evident in Figure 1, which was created from a random sample of 75 infants at each GA. Length and BMI both increase with GA, resulting in a linear pattern overall. The scatterplot shows the difference in overall size for younger versus older infants, and clearly illustrates that the 25 weeks' GA infants are a different population from the infants with GAs of 29, 34, and 40 weeks. Within each GA, there is no correlation between length and BMI. In addition, BMI is not correlated with length in infants ≥37 weeks at birth ($r = 0.03$), although it remains correlated with weight ($r = 0.76$). In infants <37 weeks at birth, the correlation between BMI and length is 0.62 if not stratified by GA. In contrast, the ponderal index appears to be the best measure when examined overall, as it has the highest correlation with weight and the lowest correlation with length. However, as Figure 2 illustrates, within GAs, the ponderal index is negatively correlated with length (Fig. 1, 2 were created using the validation data during repeat of analysis; similar figures were initially created using the analysis data showing the same patterns).

Table 3. Boys' correlation coefficients between weight/length proportionality index, weight, and length by gestational age at birth in 74,390 infants

GA, weeks	Weight/Length		Weight/Length^2		Weight/Length^3		Weight/Length$^{1/2}$		Weight/ ln(Length)		Benn's index (Weight/Length^p)		
	weight	length	weight	length	weight	length	weight	length	weight	length	weight	length	p
22	0.92	0.50	0.42	–0.20	–0.14	–0.69	0.99	0.69	1.00	0.74	**0.59**	**0.00**	1.74
23	0.90	0.01	0.61	–0.43	0.33	–0.69	0.98	0.25	0.99	0.34	**0.89**	**–0.01**	1.03
24	0.92	0.26	0.61	–0.24	0.24	–0.61	0.98	0.47	0.99	0.54	**0.78**	**–0.01**	1.53
25	0.91	0.26	0.59	–0.25	0.22	–0.60	0.98	0.48	0.99	0.55	**0.76**	**–0.02**	1.55
26	0.93	0.43	0.63	–0.07	0.20	–0.51	0.99	0.61	1.00	0.66	**0.66**	**–0.02**	1.91
27	0.93	0.44	0.62	–0.08	0.19	–0.52	0.99	0.61	1.00	0.67	**0.65**	**–0.03**	1.92
28	0.95	0.51	**0.67**	**0.03**	0.22	–0.46	0.99	0.65	1.00	0.70	0.63	–0.02	2.10
29	0.95	0.50	**0.68**	**0.03**	0.25	–0.45	0.99	0.65	1.00	0.70	0.64	–0.02	2.10
30	0.94	0.43	0.65	–0.05	0.25	–0.47	0.99	0.59	1.00	0.65	**0.66**	**–0.04**	1.98
31	0.95	0.44	**0.70**	**–0.01**	0.32	–0.44	0.99	0.59	1.00	0.65	0.69	–0.02	2.03
32	0.94	0.45	**0.68**	**–0.01**	0.28	–0.46	0.99	0.60	1.00	0.66	0.67	–0.03	2.02
33	0.95	0.44	**0.72**	**0.01**	0.34	–0.42	0.99	0.59	1.00	0.64	0.70	–0.02	2.06
34	0.95	0.41	**0.72**	**–0.02**	0.36	–0.43	0.99	0.56	1.00	0.62	**0.72**	**–0.02**	2.00
35	0.95	0.44	**0.75**	**0.04**	0.41	–0.37	0.99	0.58	1.00	0.63	0.71	–0.02	2.13
36	0.96	0.46	**0.76**	**0.07**	0.42	–0.35	0.99	0.59	1.00	0.64	0.70	–0.02	2.20
37	0.96	0.42	**0.77**	**0.04**	0.45	–0.36	0.99	0.56	1.00	0.62	0.73	–0.01	2.13
38	0.95	0.38	**0.75**	**–0.01**	0.44	–0.40	0.99	0.53	1.00	0.59	0.75	–0.02	2.02
39	0.95	0.31	0.75	–0.08	0.45	–0.44	0.99	0.47	1.00	0.53	**0.79**	**–0.01**	1.82
40	0.94	0.30	0.73	–0.10	0.43	–0.46	0.99	0.47	1.00	0.54	**0.79**	**–0.01**	1.78
41	0.95	0.33	0.75	–0.07	0.44	–0.43	0.99	0.49	1.00	0.55	**0.78**	**–0.01**	1.87
42	0.95	0.32	0.74	–0.09	0.43	–0.45	0.99	0.48	1.00	0.55	**0.78**	**–0.02**	1.84
All GA	0.99	0.84	0.90	0.66	**0.50**	**0.12**	1.00	0.88	1.00	0.89	0.31	0.16	3.18

Bold type indicates the highest weight correlation that is uncorrelated with length. The final column is not a correlation but the power (^{p}) used in the Benn's index. GA, gestational age.

Finally, we used GA as an interaction term with length in a linear regression model, in an attempt to duplicate the results from Cole et al. [8]. The results show that the interaction term is essentially zero, at –0.02 ($p < 0.0001$). Figure 3 shows the change of Benn powers across GA for our study and Cole et al. [8], illustrating a progressive drop in Benn power in their results as opposed to the monotonic relationship evident in ours. Figure 4 shows that the Benn powers found by Cole et al. [8] are within the sampling distributions that we created to mirror his sample, and are thus plausible but also consistently higher than the sampling distribution mean based on our data.

Discussion

Our study results show that BMI is the best measure of body proportionality in preterm infants admitted to the NICU. Stokes et al. [13] found no significant difference in waist circumference/length and ponderal index

Fig. 2. Scatterplot of ponderal index versus birth length (n = 75 per GA).

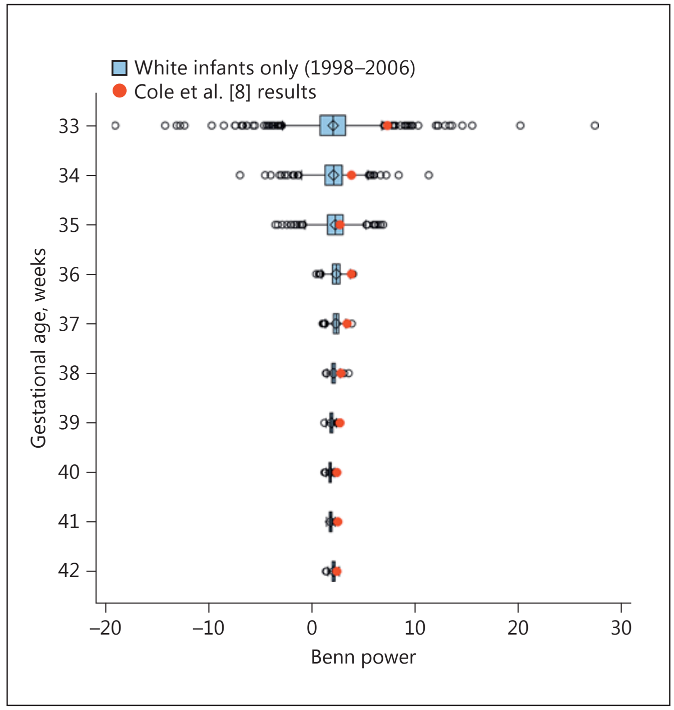

Fig. 4. Benn power sampling distributions by gestational age.

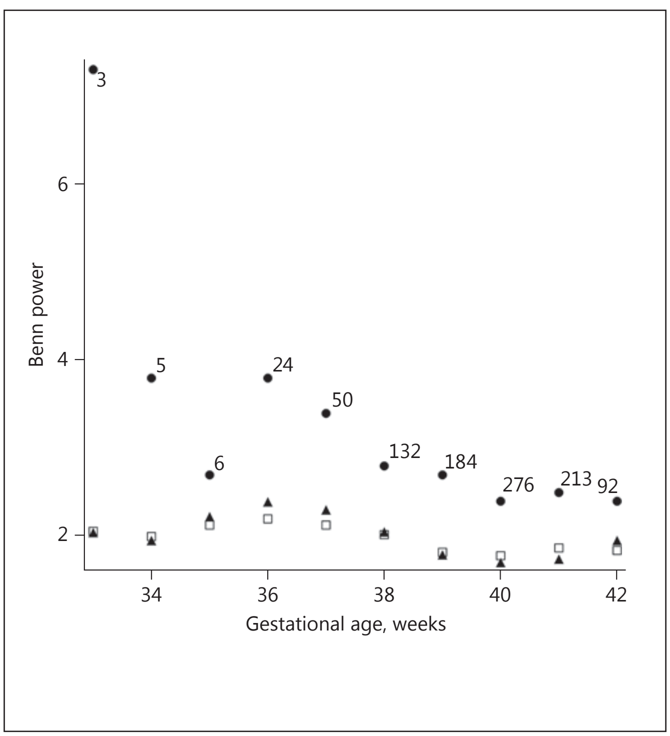

Fig. 3. Comparison of Benn powers for girls (1998–2006; ▲), boys (1998–2006; □), and Cole et al. [8] data (1987–1988; ●).

between the largest preterm infants and full-term infants at birth, providing evidence that body proportionality measures are similar in these groups. Nonetheless, our results apply only to preterm infants who were in the NICU immediately following birth.

Previously, the ponderal index (weight/length^3) was proposed as the most appropriate single measure of proportional growth in preterm infants [2, 8, 14]. It has been used in multiple research studies on preterm infants and was recently used to determine several clinical outcomes [15]. Our research indicates that neither ponderal index nor weight for length are appropriate measures, as the first overcorrects and the second undercorrects for length. The ponderal index, in particular, seems to be the best fit when GA is not considered. However, when looking at the scatterplots and the GA-specific correlation coefficients, the large negative values, particularly in the younger GAs, indicate a substantial overcorrection for length exacerbated by the larger sample sizes for older infants.

Furthermore, a recent report on BMI compared to percent and actual fat mass, fat-free mass and bone-mineral content measured by dual-energy X-ray absorptiometry (DEXA) in preterm infants showed relatively strong correlations between BMI and these measures (ranging from 0.74 to 0.81) [16]. Stokes et al. [17] recently found that MRI fat measurements align closely with BMI in preterm infants, providing further evidence that BMI is the best easily calculated measure of preterm infant body composition.

In the 1997 paper on which we modeled this decision process, Cole et al. [8] suggested using GA as an interaction term in a regression model to account for differences within GAs. The coefficient for log length was 10.1 and the coefficient for the interaction was –0.19. This is in stark contrast to our findings in which the log length coefficient was 2.79 and the interaction term had a coefficient of –0.02. Although statistically significant because of the large sample, the interaction term is essentially zero. An increase from 26 to 36 weeks' GA would result in the Benn power decreasing by only 0.2, similar to the change in 1 week in Cole et al. [8]. This large difference between the 2 studies suggests a fundamental difference in our samples.

In addition, Cole et al. [8] found the Benn's index power to generally round to 3, while we found it rounded to 3 in our unstratified sample and to 2 in our GA-stratified sample. This may be due to the fact that our samples of preterm infants came from different populations. Separate analyses showed that our findings are the same for: white and nonwhite infants; across years; combined genders; multiples; infants excluded from the analysis; infants from a single medical center; and those who received/did not receive antenatal steroids. We thought that sample size, race, and infant size might account for the discrepancy, and so we created multiple samples from our data that reflected the Cole et al. [8] study sample for each GA, with lighter-weight, white infants. If sampling error were responsible for the difference, then we would expect the Benn powers from their study to be distributed randomly around the mean of the sampling distribution; this was not the case, however.

It is possible that changes in rates of preterm delivery since the late 1980s have resulted in a change in the population. The CDC reports that preterm infant birth rates increased in the period from 1990 to 2006, apparently due to an increase in the rates of preterm birth from cesarean section and induction of labor [12]. While we would not expect this to change which measure of proportionality would be best, it is conceivable that it is partly the reason for the differences between our results and those obtained by Cole et al. [8].

Conclusions

In our multiethnic US sample, BMI appeared to be the best single measure of body proportionality in preterm infants. Creating growth curves using a single measure is important for ease of use and understanding, for clinicians and parents alike. The statistical methods described in this paper are intended to provide a comprehensive description of how we determined BMI to be the "best" weight-to-length ratio, or that which was most correlated to weight and least to length, in preterm infants, as recommended by Benn [7] and, later, Cole et al. [8].

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Disclosure Statement

The authors have no conflicts of interest relevant to this article to disclose.

Author Contributions

A.N.F. conducted the validation study, confirmed analysis, and drafted the manuscript. M.L.L. designed most of the study, supervised and conducted analyses and drafted portions of the manuscript. S.C.G. and R.C. conducted the initial correlation analyses and provided critical feedback on the manuscript. I.E.O. designed the initial methods to identify the body proportionality index and edited the manuscript. W.N.B. and J.C. conducted the analysis into differences between these results and Cole's and drafted portions of the manuscript. R.H.C. provided the data and edited the manuscript.

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