**Effect of Body Mass Index Category on Body Surface Area Calculation in Children Undergoing Cardiac Procedures**

Olubukola O. Nafiu, MD, FRCA, MS, Kwaku Owusu-Bediako, MBChB, MPH, and S. Devi Chiravuri, MD

**BACKGROUND:** Many of the common equations used for body surface area determination were either introduced before the widespread prevalence of childhood obesity, contained very few children in their sample, or have not been assessed in overweight/obese children. Therefore, we compared 6 body surface area formulae to determine their performance across body mass index categories using cross-sectional anthropometric data of children who underwent elective cardiac procedures.

**METHODS:** We selected 6 formulae from the literature that included data from pediatric subjects in their derivation. We then substituted measured height and weight into each equation to compute body surface area data for the study subjects. The average values of the 6 formulae were calculated for each patient and used as reference for comparison. Comparisons between each formula and the reference standard were made with the 1-way ANOVA, Pearson correlation coefficient (measure of precision), the Lin concordance correlation coefficient (measure of bias and precision), and the Bland-Altman limit-of-agreement. All comparisons were made across age, sex, and body mass index categories.

**RESULTS:** Among the 1000 (mostly Caucasian: 76.1%) subjects, 16.7% were overweight, while 14.1% were obese and 51.2% were girls. All calculated body surface area data showed a strong positive correlation with each other and the derived reference body surface area values (0.99–1.00; \( P < .001 \)). Calculated body surface area values for all the formulae were significantly higher in overweight and obese children across every age group.

**CONCLUSIONS:** Obesity status is a critical factor in the determination of body surface area values in children undergoing elective cardiac procedures. We caution that indexed hemodynamic and other therapeutic interventions may be inappropriate if limitations of body surface area formulae and the effect of obesity are not taken into consideration when caring for overweight and obese children. Body surface area studies utilizing accurate contemporary techniques that include sufficient number of overweight and obese children of various races are urgently needed. (Anesth Analg 2020;130:452–61)

**KEY POINTS**

- **Question:** Body surface area estimation formulae that were derived several decades ago may significantly underestimate this parameter in contemporary American children. Therefore, we asked, how well do common body surface area estimation formulae agree and to what extent does a child’s obesity status affect the body surface area values obtained from these formulae?

- **Findings:** Despite strong correlation between the various body surface area formulae, there is a wide, body mass index–dependent variability in the values obtained from them.

- **Meaning:** Body mass index category affects the values obtained from common body surface area formulae suggesting that therapeutic errors are likely in interventions requiring body surface area calculations in overweight and obese children. Practitioners must be aware of these limitations in children of high body mass index categories.

Body surface area is a critical index of physiologic functions in both adults and children and it is used in several medical disciplines including cardiology, transplant medicine, oncology, burns management, and nephrology.\(^1\)\(^-\)\(^4\) In children with cardiovascular diseases, body surface area calculation is used for making many critical decisions such as estimation of cardiac index, glomerular filtration rate, oxygen consumption, and basal metabolic rate.\(^5\)\(^-\)\(^7\) In the operative setting, blood flow during cardiopulmonary bypass\(^8\) and cardioplegia flow\(^9\) are indexed to body surface area. Furthermore, dosing of several medications (especially those with narrow therapeutic indices) are often based on calculated body surface area.\(^10\)\(^-\)\(^12\)

Undoubtedly, accurate measurement of body surface area is essential for personalized care; however, its direct measurement is difficult, expensive, and...
impractical in clinical settings. Consequently, several geometric formulae are available for calculating body surface area. Nearly all available body surface area formulae rely on 2 anthropometric parameters: height and weight. Unfortunately, many of these equations were either introduced before the widespread prevalence of childhood obesity or have not been assessed in overweight/obese children. For example, the oldest and most commonly used body surface area formula was introduced in 1916 by Du Bois and Du Bois using data from 9 subjects that included only 1 cachectic child.

Since the introduction of the Du Bois and Du Bois formula, several body surface area studies that strove to include children in their study cohorts have been published. However, 1 major drawback of all the body surface area formulae currently in use is that they were derived from data collected from a small, relatively homogeneous group of subjects with few pediatric subjects. In addition, only 1 of these studies made a concerted effort to include obese patients in the sample used to derive their body surface area formula.

Childhood obesity is increasingly prevalent in the general US population with approximately 18% of children classifiable as obese. A predictable consequence of the secular trend in childhood obesity prevalence is that an increasing proportion of patients presenting for care in health institutions are either overweight, obese, or severely obese. Obesity and severe obesity can have significant influence on estimated body surface area results. For example, clinically significant variability was shown in derived body surface area values with increasing obesity status in adults.

To date, the prevalence of obesity in children undergoing cardiac procedures is not well described. Furthermore, the performance of common body surface area formulae in a large sample of normal, overweight, and obese children undergoing cardiac procedures is unknown. Therefore, this study describes the prevalence of high body mass index status among children undergoing cardiac procedures and compared the body surface area data obtained from common formulae across body mass index categories (normal, overweight, and obese) in these children.

**METHODS**

Following institutional review board approval and waiver of written informed consent (HUM00068850), we used deidentified, cross-sectional demographic and anthropometric data from 1000 children ages 2–17 years who underwent various cardiac (nonpump) procedures. Basic demographic data including age (in years), sex, ethnicity (recorded as African American, Hispanic, Caucasian, and others), as well as American Society of Anesthesiologists (ASA) physical status were noted in all patients. Only children classified as ASA physical status I–III were included in the present analysis. Those classified as ASA physical status IV–VI were excluded because they largely represent severely ill patients (some of whom may be bed ridden) and thus may be difficult to accurately obtain their anthropometric data (weight and height).

**Anthropometric Data**

Measurement and documentation of height and weight is part of routine preoperative evaluation at our institution. Typically, a preoperative care nurse or appropriately trained medical assistant measured the patient’s height and weight. Height was measured to the nearest 0.1 cm using a wall-mounted stadiometer with a wooden headboard. Body weight was measured with patients wearing light clothing, to the nearest 0.1 kg, using a calibrated electronic weighing scale.

**Body Surface Area Formulae**

We chose 6 common body surface area estimation formulae (Figure 1) to calculate body surface area values

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**Formulas for calculating body surface area**

1. **Du Bois and Du Bois (1916):**
   \[ \text{BSA (m^2)} = 0.007184 \times \text{Weight (kg)}^{0.425} \times \text{height (cm)}^{0.725} \]

2. **Boyd (1935):**
   \[ \text{BSA (m^2)} = 0.17827 \times \text{Weight (kg)}^{0.438} \times \text{height (cm)}^{0.73} \]

3. **Gehan and George (1970):**
   \[ \text{BSA (m^2)} = 0.02350 \times \text{Weight (kg)}^{0.4146} \times \text{height (cm)}^{0.4246} \]

4. **Haycock and Schwarz (1978):**
   \[ \text{BSA (m^2)} = 0.024265 \times \text{Weight (kg)}^{0.5718} \times \text{height (cm)}^{0.3964} \]

5. **Mosteller (1987):**
   \[ \text{BSA (m^2)} = (\text{Height (cm)} \times \text{Weight (kg)})^{0.3600} \]

6. **Yu (2003):**
   \[ \text{BSA (m^2)} = 0.015925 \times \text{Height (cm)} \times \text{Weight (kg)}^{0.10} \]

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**Figure 1.** Commonly used pediatric body surface area formulae including the more recent 3-dimensional–based Yu formula. BSA indicates body surface area.
for each patient. These equations were selected either because data from children were included in their computation, they were derived from independent studies using direct methods of body surface area measurement, or the investigators utilized contemporary methods to derive body surface area data. We substituted measured height and weight into each body surface area formula to determine the calculated body surface area.

**Statistical Analysis Outline**

Data analyses were performed using PASW Statistics v.24.0 program for Windows (SPSS Inc, Chicago, IL) and with MedCalc for Windows, version 9.6.0.0. Continuous variables (age, height, weight, and body mass index) were examined for normal distribution with the Kolmogorov-Smirnov test. Body mass index was calculated as weight in kilograms divided by the square of the height in meters (body mass index = kg/m²). Children were then classified as normal weight (body mass index <85th percentile), overweight (body mass index ≥85th percentile and <95th percentile), or obese (body mass index ≥95th percentile) using age and sex-specific reference growth charts²¹ from the National Center for Health Statistics/Centers for Disease Control and Prevention. Weight categories were described as frequencies or percentages and compared across sex. We also stratified the patients according to age group thus: preschool (age 2–6 years), school age (age 7–11 years), and young adolescents (age 12–17 years).

We computed each child’s estimated body surface area using the equations displayed in Figure 1. Means and SDs of each body surface area value were calculated by body mass index and sex categories. Group comparisons were made with 1-way ANOVA with the Tukey pairwise comparison procedure to control for multiple testing was used to examine differences in the mean body surface area values obtained with each formula against the reference body surface area across age and body mass index categories.

**Correlation.** We used Pearson correlation coefficient (r) to explore the strength of the linear relation between body surface area derived from the 6 formulae and the reference body surface area. The Pearson correlation coefficient measures the strength and direction of a linear relation between 2 continuous variables but fails to detect any departure from the 45° line.²⁷ It only reveals associations among variables and does not provide any inferences about causation, no matter the size of the correlation coefficient. Despite being a measure of precision, it is not a measure of agreement between 2 quantitative measurements.²⁷

**Agreement.** This quantifies how often a pair of quantitative tests yield similar results when applied to the same patient.²² The agreement between the different body surface area estimation methods and the reference body surface area across body mass index categories was tested using the Bland-Altman method²⁴ and the Lin concordance correlation method.²⁸ The Bland-Altman plot provides an insight into the pattern (and extent) of the agreement between pairs of measurements. Thus, it is a scatterplot of the difference (in m²) between the calculated body surface area and the reference body surface area plotted on the y-axis (y values) against the mean of the calculated and the reference body surface area on the x-axis (x values).²⁴

Horizontal lines were drawn at the mean difference (bias) between formula-derived body surface area and reference body surface area (solid line where y = x) and 95% limit-of-agreement (mean bias ± 1.96 × SD). The dotted lines on either side of the solid line (upper and lower limit-of-agreement) represent the limits within which 95% of differences are expected to fall. A narrower 95% limit-of-agreement indicates better agreement between calculated and reference body surface area values. A positive value (y > x) indicates overestimation by the formulae, while a negative value (y < x) implies underestimation.²⁴

We also applied the Lin concordance correlation coefficient method²⁸ to our data. Commonly described as an index of reliability or agreement between 2 measurements, it is infrequently used outside statistical journals²⁹ and has not being previously applied to body surface area estimation studies. Unlike the Pearson correlation coefficient, the Lin concordance correlation coefficient provides a measure that describes the extent to which the points in a scatterplot align to the best fitting line. Conceptually like the Pearson correlation coefficient, the Lin concordance correlation coefficient...
modifies the Pearson correlation coefficient by assessing not only how close data points are about the line of best fit, but also how far that line is from the 45° line.29 For all analyses, statistical significance was set at $P < .05$.

**RESULTS**

Among the 1000 (mostly Caucasian: 76.1%) subjects, 16.7% were overweight while 14.1% were obese. There were slightly more girls, 512 (51.2%). Notable differences between the subjects are detailed in Table 1. Although there was no significant difference between the groups by age, all the anthropometric indices were significantly higher among overweight and obese children. Furthermore, boys were taller and had higher body surface area by all the formulae than girls (Table 1).

Calculated body surface area data obtained with the different formulas across body mass index categories are detailed in Table 1. Overall, calculated body surface area values increased as a function of body mass index group with obese children having significantly higher values than overweight or normal-weight children.

**Table 1. Anthropometric and Body Surface Area Data According to Body Mass Index and Sex Groups**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Overall (N = 1000)</th>
<th>Normal Body Mass Index (N = 692)</th>
<th>Overweight (N = 167)</th>
<th>Obese (N = 141)</th>
<th>Male (N = 488)</th>
<th>Female (N = 512)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>11.0 ± 4.4</td>
<td>10.8 ± 4.6</td>
<td>11.3 ± 3.9</td>
<td>11.7 ± 3.6</td>
<td>11.2 ± 4.2</td>
<td>10.9 ± 4.6</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>45.7 ± 22.0</td>
<td>39.8 ± 17.9</td>
<td>51.9 ± 19.8</td>
<td>67.4 ± 26.5$^b$</td>
<td>46.8 ± 22.4</td>
<td>44.6 ± 21.5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>145.1 ± 26.2</td>
<td>143.7 ± 27.3</td>
<td>148.0 ± 22.8</td>
<td>148.5 ± 23.4</td>
<td>147.7 ± 25.9</td>
<td>142.6 ± 26.2$^c$</td>
</tr>
<tr>
<td>Body mass index (kg/m$^2$)</td>
<td>20.2 ± 5.3</td>
<td>17.9 ± 2.8</td>
<td>22.4 ± 3.1</td>
<td>29.1 ± 6.2$^b$</td>
<td>20.1 ± 5.1</td>
<td>20.4 ± 5.4</td>
</tr>
<tr>
<td>Mosteller</td>
<td>1.33 ± 0.43</td>
<td>1.24 ± 0.40</td>
<td>1.44 ± 0.39</td>
<td>1.65 ± 0.45$^b$</td>
<td>1.36 ± 0.44</td>
<td>1.31 ± 0.43$^c$</td>
</tr>
<tr>
<td>DuBois–DuBois</td>
<td>1.33 ± 0.43</td>
<td>1.25 ± 0.41</td>
<td>1.43 ± 0.39</td>
<td>1.60 ± 0.44$^b$</td>
<td>1.36 ± 0.43</td>
<td>1.30 ± 0.42$^c$</td>
</tr>
<tr>
<td>Haycock</td>
<td>1.34 ± 0.44</td>
<td>1.24 ± 0.40</td>
<td>1.45 ± 0.40</td>
<td>1.67 ± 0.46$^b$</td>
<td>1.36 ± 0.44</td>
<td>1.31 ± 0.43$^c$</td>
</tr>
<tr>
<td>Boyd</td>
<td>1.34 ± 0.42</td>
<td>1.25 ± 0.39</td>
<td>1.45 ± 0.39</td>
<td>1.64 ± 0.44$^b$</td>
<td>1.37 ± 0.43</td>
<td>1.31 ± 0.42$^c$</td>
</tr>
<tr>
<td>Gehan</td>
<td>1.35 ± 0.43</td>
<td>1.25 ± 0.40</td>
<td>1.46 ± 0.39</td>
<td>1.67 ± 0.45$^b$</td>
<td>1.38 ± 0.44</td>
<td>1.32 ± 0.43$^c$</td>
</tr>
<tr>
<td>Yu</td>
<td>1.27 ± 0.41</td>
<td>1.19 ± 0.38</td>
<td>1.38 ± 0.38</td>
<td>1.57 ± 0.43$^b$</td>
<td>1.31 ± 0.42</td>
<td>1.25 ± 0.41$^c$</td>
</tr>
<tr>
<td>Mean body surface area</td>
<td>1.33 ± 0.43</td>
<td>1.24 ± 0.40</td>
<td>1.44 ± 0.39</td>
<td>1.63 ± 0.45$^b$</td>
<td>1.36 ± 0.43</td>
<td>1.30 ± 0.42$^c$</td>
</tr>
</tbody>
</table>

$^P$ values for all group comparisons generated with ANOVA with Tukey pairwise comparisons.

$^aP < .001$ obese compared with normal weight.

$^bP < .001$ obese compared with overweight.

$^cP < .05$ male compared with females.

**Table 2. Calculated Body Surface Area Data According to Body Mass Index and Age Groups**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Age 2–6 y</th>
<th>Age 7–11 y</th>
<th>Age 12–17 y</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>126</td>
<td>207</td>
<td>359</td>
</tr>
<tr>
<td>Mosteller</td>
<td>0.64 ± 0.09</td>
<td>1.04 ± 0.18</td>
<td>1.57 ± 0.18</td>
</tr>
<tr>
<td>DuBois–DuBois</td>
<td>0.63 ± 0.09</td>
<td>1.04 ± 0.18</td>
<td>1.58 ± 0.18</td>
</tr>
<tr>
<td>Haycock</td>
<td>0.64 ± 0.09</td>
<td>1.03 ± 0.18</td>
<td>1.57 ± 0.18</td>
</tr>
<tr>
<td>Boyd</td>
<td>0.66 ± 0.09</td>
<td>1.05 ± 0.17</td>
<td>1.58 ± 0.17</td>
</tr>
<tr>
<td>Gehan</td>
<td>0.66 ± 0.09</td>
<td>1.05 ± 0.17</td>
<td>1.58 ± 0.18</td>
</tr>
<tr>
<td>Yu</td>
<td>0.61 ± 0.09</td>
<td>0.99 ± 0.17</td>
<td>1.50 ± 0.17</td>
</tr>
<tr>
<td>Mean body surface area</td>
<td>0.64 ± 0.09</td>
<td>1.04 ± 0.17</td>
<td>1.56 ± 0.17</td>
</tr>
</tbody>
</table>

$^P$ values for all group comparisons generated with ANOVA with Tukey pairwise comparisons.

$^a$Not significant $P < .005$ pairwise comparisons normal versus overweight; obese versus normal; overweight versus obese not significant.

$^bP < .001$ across all pairwise comparisons (normal versus overweight; normal versus obese; overweight versus obese) in the 7- to 11-y-old cluster.

$^cP < .001$ male compared with females.
Body Surface Area in Overweight or Obese Children

with the Tukey pairwise comparison procedure to control for multiple testing revealed that the mean body surface area values for overweight and obese children obtained for each formula were significantly higher than for normal body mass index children in the 2- to 6-year age category. However, there was no significant difference between the overweight versus obese cluster (Table 2). Among the older children (7–11 and 12–17 years), pairwise comparisons were significantly higher with increasing body mass index categories.

For clinical perspective and to illustrate the effect of obesity status on body surface area values, we calculated the average height and weight of a 7-year-old child in our sample. The mean height was not significantly different between the normal body mass index versus overweight or obese cohorts (123.2 vs 126.2 vs 125.9 cm; \( P = .568 \)), respectively. On the other hand, the mean weight varied significantly between the groups (normal body mass index = 23.5 kg versus overweight = 28.3 kg versus obese = 36.9 kg; \( P < .001 \)). Consequently, the mean body surface area values (using the Haycock formula, for example) for this group ranged from 0.89 m\(^2\) for normal body mass index, 0.99 m\(^2\) for overweight, and 1.15 m\(^2\) for the obese group. The body surface area difference between the normal body mass index and obese child (change in body surface area from 0.89 to 1.15 m\(^2\)) represents a weight difference of 13.4 kg.

Figure 2 displays the differences in body surface area values obtained from the different formulae across body mass index categories. Notably, all the formulae demonstrated minimal differences in normal body mass index children and significant dispersion with increasing body mass index category. The popular DuBois–DuBois formula tended to underestimate BSA in overweight and obese children. The Yu formula produced the lowest BSA values across all BMI groups.

Agreement of Common Body Surface Area Formulae With Reference Body Surface Area Values

Table 3 displays the mean difference between each formula and the derived reference body surface area as well as the respective Pearson correlation coefficients.

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**Table 3. Pearson Correlation Coefficients and Mean Difference Between Formula-Derived and Reference Body Surface Area**

<table>
<thead>
<tr>
<th>Pairings</th>
<th>Normal Body Mass Index (N = 692)</th>
<th>Overweight (N = 167)</th>
<th>Obese (N = 141)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD (95% CI)</td>
<td>Correlation</td>
<td>Mean ± SD (95% CI)</td>
</tr>
<tr>
<td>Mosteller</td>
<td>−0.005 ± 0.003 (^a)</td>
<td>1.000(^b)</td>
<td>−0.008 ± 0.004 (^c)</td>
</tr>
<tr>
<td></td>
<td>(-0.005 to −0.005)</td>
<td></td>
<td>(-0.009 to −0.008)</td>
</tr>
<tr>
<td>DuBois</td>
<td>−0.013 ± 0.014 (^a)</td>
<td>1.000(^b)</td>
<td>0.005 ± 0.008 (^c)</td>
</tr>
<tr>
<td></td>
<td>(-0.014 to −0.012)</td>
<td></td>
<td>(0.003−0.006)</td>
</tr>
<tr>
<td>Haycock</td>
<td>−0.002 ± 0.007 (^a)</td>
<td>1.000(^b)</td>
<td>−0.016 ± 0.008 (^c)</td>
</tr>
<tr>
<td></td>
<td>(-0.002 to −0.001)</td>
<td></td>
<td>(-0.017 to −0.014)</td>
</tr>
<tr>
<td>Boyd</td>
<td>−0.013 ± 0.002 (^a)</td>
<td>1.000(^b)</td>
<td>−0.014 ± 0.003 (^c)</td>
</tr>
<tr>
<td></td>
<td>(-0.013 to −0.012)</td>
<td></td>
<td>(-0.012 to −0.011)</td>
</tr>
<tr>
<td>Gehan</td>
<td>−0.017 ± 0.004 (^a)</td>
<td>1.000(^b)</td>
<td>−0.025 ± 0.004 (^c)</td>
</tr>
<tr>
<td></td>
<td>(-0.017 to −0.016)</td>
<td></td>
<td>(-0.026 to −0.025)</td>
</tr>
<tr>
<td>Yu</td>
<td>0.050 ± 0.014 (^a)</td>
<td>1.000(^b)</td>
<td>0.056 ± 0.013 (^c)</td>
</tr>
<tr>
<td></td>
<td>(0.049−0.051)</td>
<td></td>
<td>(0.054−0.058)</td>
</tr>
</tbody>
</table>

Values generated by \( t \) test. Mean ± SD represents mean difference and SD of the mean difference.

\(^a\) \( P < .001 \) across normal body mass index category.

\(^b\) \( P < .001 \) for all correlation coefficients across body mass index groups.

\(^c\) \( P < .001 \) across overweight category.

\(^d\) \( P < .001 \) across obese category.
across body mass index categories. All the formulae demonstrated near-perfect correlation with the reference body surface area across the 3 body mass index categories (0.999–1.000). Despite this, t test comparison demonstrated statistically significant systematic differences between each formula and the reference body surface area (Table 3).

Figure 3 displays the Bland-Altman plots of the agreement between body surface area values derived by the 6 formulae across body mass index categories with the reference body surface area data. Each graph provides a plot on the vertical axis, the differences between the reference body surface area, and the formula being examined. The horizontal axis represents the mean of the reference body surface area and formula-derived body surface area. The plot for the DuBois–DuBois formula indicates that in normal and overweight children, there was consistent variability around the line of identity (95% limit-of-agreement). However, in obese patients, all body surface area values were above the line of identity, which indicates that the mean body surface area values from the DuBois–DuBois formula are consistently lower than the derived reference body surface area values (Figure 2A).

Conversely, the Haycock and Gehan formulae demonstrated good agreement with the reference formula in normal body mass index and overweight children but displayed a tendency to overestimate body surface area values in obese children as the body surface area increases (Figure 2C, E). On the other hand, the Yu formula at low body surface area values consistently produced overestimated body surface area values and at high values produced underestimated values suggesting that this formula may be wholly inappropriate to use in contemporary American children.

Finally, Pearson correlation and Lin concordance correlation between formula-derived and reference body surface area were very similar and near-perfect, suggesting no systematic bias (Table 4).

**DISCUSSION**

The present study provides body surface area calculations derived from measured height and weight in normal-weight, overweight, and obese children, who underwent cardiac, nonpump procedures. It is the first study with clearly stated proportions of overweight and obese subjects in the study cohort from whom body surface area data were derived. About one-third of our subjects were classifiable as overweight or obese, which is in line with the prevailing overweight and obesity rates among contemporary American children.21

Consistent with previous reports,23,26 we found that nearly all the body surface area formulae assessed had modest agreement in normal body mass index children. However, these formulae do not yield identical estimates of body surface area from the same height and weight data, the discrepancy in calculated body surface area values increasing with increasing body mass index categories. The body surface area formula by Yu et al30, although derived using contemporary (3-dimensional scan) methods, provided the lowest estimated body surface area data in our subjects. Given that it was derived using data obtained from Chinese adults, it may not be extrapolatable to contemporary American children. Furthermore, the 3-dimensional method may not fully account for axillary, abdominal girth, groin, submammary, and skin fold surface area which may lead to significant underestimation of body surface area especially among obese adolescents. Similarly, many of the original and century-old formulae do not represent today’s Western population.

We further observed that, despite near-perfect correlation coefficient values of all the formulae with the more accurate reference body surface area, there were systematic differences when agreement between each formula and the derived reference body surface area was assessed with the Bland-Altman plot. This is consistent with previous reports, which indicates that, when comparing a predictor with a reference value, measuring only the correlation coefficient can be quite misleading.24

Few studies on body surface area have included a cohort of obese patients.19,23 To date, we are unaware of any pediatric studies specifically detailing the effect of obesity status on calculated body surface area using commonly cited formulae. Given that with obesity, weight increases disproportionately to height, it is possible that the body surface area–predicting equations that include height as a coefficient would systematically miscalculate body surface area for obese patients.20 Because many clinically important measurements in pediatric cardiology are indexed to body surface area, systematic errors in body surface area estimation may negatively influence therapeutic decisions concerning obese patients, including children. Recent data indicated that, in obese patients with repaired tetralogy of Fallot,31 right ventricular volume measurements indexed to body surface area were significantly over- or underestimated at extremes of body weight. The authors argued that, because referrals for pulmonary valve replacement are determined by these indexed right ventricular measurements, errors due to high body mass index category could lead to unnecessarily early surgical referral, thereby needlessly exposing patients to operative risks. Conversely, delaying surgical referral due to errors in body surface area calculations can theoretically lead to increased incidence of arrhythmia and ventricular dysfunction.31

Variability in calculated body surface area values can also lead to large differences in the dose of...
Figure 3. Bland-Altman charts evaluating the agreement between 6 body surface area (BSA) formulae and the reference BSA formula. Solid horizontal line indicates the mean difference (line of identity) between each formula and the reference BSA. The 2 dashed horizontal lines correspond to the respective 95% limit-of-agreement. The wider the separation between the dashed lines, the poorer the agreement between formula-derived BSA and the reference BSA values. The vertical axis represents the differences between the reference and the formula being examined. The horizontal axis represents the mean of reference BSA and formula-derived BSA. Values below the line of identity indicate that formula-derived values are higher than the reference, while values above the line indicate that formula-derived values are lower (underestimation) than the reference. BMI indicates body mass index; BSA ref., reference BSA values.
medications. Thus, drug underexposure due to body surface area–based dosing can occur because the fundamental assumption of this approach is that drugs are dosed as a nonlinear function of weight.20 Children with obesity have disproportionate weight gain compared to height, and thus have different overall geometric structure which limits the utility of existing body surface area equations that were derived from adults with more proportional expected height to weight ratios.

Given the rising obesity rates among American children and the wide variability in the body surface area values obtained from the various formulae when applied to children in the high body mass index categories, it is important to recognize the pitfalls inherent in using these body surface area formulae for therapeutic decisions. Specifically, that many of the body surface area formulae in current use may not be applicable in obese children. A recent study highlighted the importance of morbid obesity status on calculated body surface area values in adults, and the authors cautioned that, not only should practitioners be aware of the widespread variability in the body surface area values obtained from different formulae but they also need to be aware that many of the commonly used devices for cardiac output determination have built-in algorithms that utilize the DuBois–DuBois formula for body surface area determination.32 Practitioners need to be aware of the limitations of such devices when used in obese children.

Several investigators have cautioned against the continued use of the DuBois–DuBois formula.23,31,32 Our results agree with these investigators. We found that, although the DuBois–DuBois and other formulae give comparable body surface area values in non-obese children, it tends to underestimate body surface area values in overweight and obese children.

**Study Strengths, Limitations, and Future Directions**

This study has several strengths including use of directly measured height and weight data to calculate the body surface area values for each formula as well as a large sample of children who underwent various cardiac (nonpump) procedures. Furthermore, that our study confirmed the simulated adult data reported by Adler et al32 suggests that it is critical to consider the effect of high body mass index on body surface area data in any diagnostic or therapeutic interventions in children. Finally, our study is one of few body surface area studies that specifically described the proportion of children in the high body mass index category.

Despite these strengths, there are some limitations to the study. Given that body surface area formulae are simply mathematical equations and such equations will compute results for almost any number imputed into them, the limits within which such equations are valid must be understood.32 The anthropometric parameters of contemporary American population are different from those of the subjects studied by Du Bois-Du Bois14 or by Haycock et al17. Therefore, we acknowledge the inherent limitations of all the formulae assessed in our study. We also acknowledge the fact that we only used height and weight in the body surface area equations for our study. It has been suggested that these 2 anthropometric variables may not be sufficient for the estimation of human body surface area.33 We therefore encourage future studies to consider incorporating body measures such as abdominal and neck circumference, hip girth, and other anthropometric variables into the equations used to derive body surface area.

The present report could also be criticized for having minimal relevance to daily anesthesia practice given that many “anesthesia drugs” are not dosed by body surface area. However, published data appear to indicate that several parameters that we rely on in routine anesthesia practice (cardiac index, glomerular filtration rate estimation, cardioplegia dose, and flow on cardiopulmonary bypass) are indexed to body surface area.5,10 On a broader scale, the majority of chemotherapeutic agents are indexed to body surface area.10,11 The effect of high body mass index in these clinical situations deserves clarification, and our data suggest that practitioners need to be aware of the limitations of individual body surface area equations.

<table>
<thead>
<tr>
<th>Body Surface Area Formulae</th>
<th>Pearson Correlation Coefficient (ρ)</th>
<th>Lin Concordance Coefficient (ρ̃) (95% CI)</th>
<th>Bias Correction Factor (C_b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mosteller</td>
<td>0.99 (0.99–0.99)</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>DuBois</td>
<td>0.99 (0.99–0.99)</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Haycock</td>
<td>0.99 (0.99–0.99)</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Boyd</td>
<td>0.99 (0.99–0.99)</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>Gehan</td>
<td>0.99 (0.99–0.99)</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Yu</td>
<td>0.99 (0.99–0.99)</td>
<td>1.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>

$C_b$: bias correction factor ($\hat{\rho} / \rho$).
especially in overweight and obese children. Many of the formulae we assessed are used in hemodynamic monitoring devices with the presumption that they are accurate or, at the very least, constant in error. We have shown that these assumptions are not necessarily correct in overweight and obese children.

Another limitation of the present report is that we did not directly measure the body surface area of our subjects and the values used for comparisons were derived from existing equations. To this end, ours is not a validation study. We however applied sound statistical principles to derive the reference body surface area values used for comparison in our study. We utilized the mean body surface area approach given that the mean of the distinct formulae derived in different populations by different researchers is the best estimate we have of the true body surface area. Despite this, the inherent weakness of this statistical approach is acknowledged given that some of the methods may be more reliable than others and averaging the means across these formulae would not account for this.

Finally, we do not know the dry weight of these patients given that they were all “cardiac patients” undergoing nonpump procedures. It is possible that expanded total body fluid or generalized edema could affect the weight of our subjects which could also affect the body mass index category for the patients. However, we limited our analysis to children classified as ASA physical status I–III and we believe that, in general, children with generalized edema will be assigned higher ASA physical status. We must also note that our study does not imply causality, because this cannot be determined from a retrospective study. Our findings are simply mathematical associations and observations.

In summary, the performance of 6 body surface area estimation formulae was assessed and all showed considerable variability in the derived body surface area values. This observed variability was significantly higher with increasing obesity status. These inconsistencies could potentially affect diagnostic and therapeutic interventions that are indexed to body surface area in children undergoing cardiac procedures. Perioperative caregivers need to be aware of the limitations of these formulae in overweight and obese children. Estimation formulae that consider a child’s obesity status are urgently needed. Future studies should endeavor to include anthropometric measurements such as abdominal and neck circumferences in the body surface area prediction equations because height and weight may not be sufficient in body surface area estimation of contemporary American children.

DISCLOSURES
Name: Olubukola O. Nafiu, MD, FRCA, MS.
Contribution: This author helped with study idea, design, data analyses, and manuscript preparation.

Name: Kwaku Owusu-Bediako, MBChB, MPH.
Contribution: This author helped analyze the data and edit the manuscript.

Name: S. Devi Chiravuri, MD.
Contribution: This author helped design the study and edit the manuscript.

REFERENCES