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This supplementary material has been provided by the authors to give readers additional information about their work.
eAppendix 1. Historical Origin of TMI.

During the 1800’s, a number of researchers tested body fat indices of the form $M/H^n$ or $M^{1/n}/H$, where $n=2, 3$, etc. To our knowledge, Buffon first suggested the index $M/H^3$ in the early 1800’s.\(^1\) But Livi (1897) was the first to give a name to an $n=3$ index, developing what he called the Ponderal Index.\(^2\) The Ponderal Index is $100*M^{1/3}/H$, where mass is measured in grams and height in cm.

In the early 1900’s, Rohrer recognized the value of Livi’s index, citing it by name, in his seminal 1908 work.\(^3\) Rohrer realized that the Ponderal Index lacked some attractive scaling and dimensional properties. He instead proposed an index—which he called the “corpulence index” but has since been called the Rohrer Index—which has the form $100 \ M/H^3$, where weight is measured in g and height in cm. Typical values for the Rohrer Index are in the 1.0-1.9 range.\(^4\)

Over the years, many scientists have used these indices in children and adolescents with success, such as in the Bogalusa Heart Study.\(^5,6\) But the history behind these indices is muddled. The two indices have been confused with each other, and multiple formulas have used under the name of either index. For instance, both $100 \ M/H^3$ and $M/H^3$ (with different units even) have been referred to as the Rohrer Index. As a result, many believe that the Ponderal Index is the same as the Rohrer index, but this is not true. Moreover, both indices are different from the $M/H^3$ index, where mass is in kg and height in m. The Rohrer index is a factor of 10 smaller and is calculated in different units than the $M/H^3$ index, and both indices are different in mathematical properties from the Ponderal Index by a homomorphic transformation.

In reviewing the history of $n=3$ indices, we discovered that the $M/H^3$ index has never been appropriately named. To give credit to the original developer of the ponderal index (which was developed before the Rohrer index), we therefore dubbed $M/H^3$ the tri-ponderal mass index (TMI). This also has the benefit of standardizing terminology relative to BMI. The prefix “tri” is a reminder that height is raised to the third power, whereas in the original Ponderal Index, height is raised only to the first power.
eAppendix 2. Comparison of All Six Body Fat Indices.

Determining the best body fat index to use during adolescent development is more difficult than it seems because it requires careful consideration of both growth allometry (scaling relations across different age groups) and static allometry (scaling relations within the same age group). During the adolescent growth spurt, %fat changes both with age (growth allometric effect) and with height (static allometric effect). These two effects limit the application of standard regression equations. Below, we first discuss how these effects determine which regression equation is best for estimating body fat or percent body fat levels (%fat). Second, we discuss the limitations in using this regression equation to formulate a clinically relevant body fat index for classifying individuals as overweight versus normal weight. As we illustrate below, estimating %fat is not the same thing as classifying individuals as overweight versus normal weight, and understanding this subtle distinction turns out to be very important for formulating a body fat index to diagnose overweight status.

Estimating Body Fat
(Consideration of Static Allometric Effects)

For the past century, body fat indices have most often been formulated by regressing $M \propto H^n$ on cross-sectional data, where $\propto$ denotes the expression “is proportional to”. For example, if $M \propto H^2$, then $M/H^2$ is taken as the optimal index to estimate %fat. This is the basis of the body mass index (BMI = $M/H^2$).

However, this approach is accurate only when the assumption %fat is independent of height is true. In children and adolescents, this assumption is not true: %fat is associated with height. In particular, more overweight individuals are taller than their leaner counterparts at the beginning of adolescent development, and there is a second late-bloomer effect in females at ages 16-17, where the opposite is true and leaner individuals are taller.

These static allometric effects in children and adolescents—that height depends on %fat—skew the scaling relation $M \propto H^n$. What this means is that when %fat depends on height, the regressions $M \propto H^n$ and %fat $\propto M/H^n$ do not produce the same exponent $n$, as we show in eFigure 2. This leads to the very important conclusion: the regression $M \propto H^n$ should no longer be used in children and adolescents to estimate body fat levels. Moreover, previous approaches to formulating a body fat index in children and adolescents based on the regression $M \propto H^n$ are inaccurate. Instead, because %fat depends on height during adolescent development, the correct regression model to estimate body fat levels in children and adolescents is %fat $\propto M/H^n$.

Classifying Overweight Versus Normal Weight Status
(Consideration of Growth Allometric Effects)

Although %fat $\propto M/H^n$ is the correct regression model to use to estimate %fat levels, it does not necessarily follow that the regression %fat $\propto M/H^n$ produces the optimal index to classify overweight versus normal weight status in a binary manner. The reason why is because the classification of overweight status does not depend on a single %fat threshold that applies universally for all ages. Instead, because average body fat levels change with age (growth allometric effect), the classification of overweight status implicitly depends on %fat percentiles (i.e., %fat levels adjusted for age). In particular, the ≥85th percentile of %fat is designated as overweight and the ≥95th percentile as obese.

Adiposity estimation via the %fat $\propto M/H^n$ regression applied to the entire adolescent cohort does not take these age-dependent changes in mean %fat levels into account. Incidentally, these growth allometric effects may explain (at least in part) why the scaling exponent in the relation %fat $\propto M/H^n$ is not exactly $n=3$, but is a bit lower than 3 in females (2.8) and higher than 3 in males (3.5). Therefore, the regression equation that best estimates %fat across all ages cannot directly be used to devise a body fat index to classify overweight status. Instead, other criteria—such as temporal stability and misclassification rates—are needed to determine the optimal body fat index. We therefore decided to use a combination of criteria, which are described below.

Our Approach To Formulating a Body Fat Index

We used a combination of three main criteria—plus one ancillary criterion—to determine the optimal body fat index of the form $M/H^n$ to use in individuals aged 8-17 years:

1. Stability With Age: Stability of the population mean value of $M/H^n$ for each sex as a function of age group. A stable index means that the population average for 10-to-11-year-olds, for example, would not be statistically different from the population average for 15-to-16-year-olds.
2. **Body Fat Estimation**: Ability to estimate %fat across the whole spectrum of adiposity. This was assessed via polynomial regressions of %fat versus the index M/H^n, and the higher the percent of variance explained (i.e., R-squared values), the more accurate an index for estimating %fat.

3. **Misclassification Rates**: Percent of individuals who are misclassified on the basis of overweight status (≥85th percentile in %fat). Misclassifications can come in the form of false positives (normal weight individuals mistakenly classified as overweight) or in the form of false negatives (overweight individuals mistakenly classified as normal weight). Misclassification rates were determined using standard receiver operating characteristic (ROC) curve analysis methods.

4. **Simplicity**: If two or more indices were tied on a criterion, the simplest index would be favored because it would be easier for clinicians, researchers, and the general public to use.

We tested the following six body fat indices of the form M/H^n:

1. BMI (n=2)
2. n=2.5
3. TMI (n=3)
4. n=3.5
5. The sex-specific indices derived in Figure 2 (i.e., n=3.5 for males and n=2.8 for females)
6. The sex- and age-specific scaling powers derived in eFigure 2

**Stability with Age**

Using only the first imputation of the NHANES dataset yielded virtually identical means and significance values as using all five imputations (typically to <0.5% accuracy) for the temporal stability comparisons of BMI and TMI (Figure 3). This has been found to be true for other analyses, so we henceforth used the first imputation for this supplementary analysis comparing all 6 indices. BMI (n=2; Figure 3) and the n=2.5 index were not stable during adolescence in either sex, but rather increased with age. TMI (n=3) was stable across adolescence in both sexes, with the small exception of a slight increase at ages 16-17 years in females (see Figure 3). Interestingly, the sex-specific index (n=3.5 for males and n=2.8 in females) was not stable in either males or females across adolescence. This is despite the fact that polynomial regression analysis indicated a scaling exponent for %fat ∝ M/H^n of n=3.5 for males and of n=2.8 for females. This underscores the important facts that (1) the regression analysis of %fat ∝ M/H^n does not take growth allometric effects into account (i.e., %fat changes with age), and that (2) stability with age, body fat estimation, and misclassification rates are truly distinct criteria for comparing the performance of body fat metrics. We therefore underscore our important conclusion that one cannot blindly take the index derived from the regression %fat ∝ M/H^n as the correct body fat index because of these growth allometric effects. Finally, the age- and sex-specific scaling powers are obviously not stable during adolescence. Thus, TMI was the most stable of the six body fat indices. This stability with age is important because without it, percentiles or z scores must be used and separate thresholds need to be developed for each age and sex group. But BMI z scores are complicated for health care providers and parents/guardians to use, requiring them to navigate multi-page technical documents provided by the national health organizations that set guidelines on appropriate BMI classifications.

**Body Fat Estimation**

As reported in the main text, BMI only explained a paltry 38% of the variance in percent body fat in males, but predicted percent body fat substantially better in females (66% of the variance). By comparison, TMI was far more accurate in males, explaining 64% of the variance in percent body fat—a 70% improvement in body fat estimation. TMI was also slightly better in females, explaining 72% of the variance. Of the remaining indices, the n=2.5 index was intermediate in performance between BMI and TMI for both sexes, and the n=3.5 index explained 4% more of the variance in absolute terms in males in comparison to TMI, but explained 5% less of the variance in absolute terms in females. The sex-specific index (n=3.5 for males and n=2.8 for females) was the best of the non-age-specific indices, but the improvements over TMI were modest: 4% in absolute terms in males and 1% in females. Lastly, the age- and sex-specific scaling powers did estimate percent body fat best as a function of age, but a fair direct comparison against the other five non-age-specific indices is not possible. Thus, of the non-age-specific indices, the sex-specific index was superior at estimating %fat, with TMI being the second best index evaluated on this criterion.

Finally, for completeness, we also performed similar regression analyses without stratifying by sex and instead by adjusting for age, sex, and/or an age×sex interaction, but in all cases, TMI produced higher R-squared values than BMI.
Misclassification Rates

We also compared all indices on the basis of misclassification rates using ROC curve analysis. ROC curve analysis produces a number called Area Under the Curve (AUC), which determines the accuracy of a binary classification scheme. Comparing body fat indices on the basis of their AUC values is convenient because AUC encapsulates accuracy into a single number: the higher the AUC value, the greater the accuracy and the lower the misclassification rates. We therefore compared the 6 indices on the basis of their AUC values.

The differences in AUC values did not quite reach statistical significance due to overlap of the 95% confidence intervals because of the modest sample size. Nonetheless, AUC values were highest for TMI. Shown in eFigure 3 are the AUC values for a body fat index of the form M/H^n for n values of 2 (BMI), 2.5, 2.8, 3 (TMI), 3.5, and 4 for each sex cohort. Of these 6 indices, BMI performed the worst, having a lower AUC value than even the n=4 index. Relative to BMI, AUC values rose as n increased, peaked around n=3 (TMI), and then declined as n increased further—suggesting that values of n close to 3 (TMI) are superior for minimizing misclassification rates. Importantly, neither the sex-specific nor age- and sex-specific indices we mentioned above produced higher AUC values than BMI, illustrating the fact that classification of overweight versus normal weight status (which is a binary measure of body fat and is adjusted for age) is wholly distinct from estimation of body fat levels (which is a continuous measure along the entire body fat spectrum and is not adjusted for age-dependent changes in %fat). Therefore, of the six indices, TMI was best at classifying overweight versus normal weight status.

Simplicity

Finally, on the basis of simplicity, the simplest indices are n=2 (BMI unadjusted for age), n=2.5, n=3 (TMI), and n=3.5 indices, since they are the same for all sexes and ages. If BMI z scores or BMI-for-age is used, then TMI is a simpler index to use.

Overall Assessment

In sum, TMI had the greatest stability with age; the second greatest accuracy in estimating percent body fat among the non-age-specific indices; the lowest misclassification rates, although the differences in AUC values did not quite reach statistical significance; and the best simplicity (tied with 3 other indices). By comparison, BMI performed substantially worse than TMI on all four criteria. Therefore, in aggregate, we choose to pursue TMI as the potential replacement for BMI z scores during adolescent development.

REFERENCES

1. Buffon GLL, Cuvier G. *Œuvres complètes de Buffon avec les supplémens.* Paris; P. Duménil; 1835.
eFigure 1. Percent Fat (Mean and 95% CI) as a Function of Age.
eFigure 2. Height Exponents, $n$ (Mean and 95% CI), From Two Regression analyses: (A) $M \propto H^n$ and (B) $\%\text{fat} \propto M/H^n$.
eFigure 3. Misclassification Rates with 95% CIs for TMI versus BMI Z Scores in Classifying Overweight Status in (A) Males and (B) Females for Each Age Group.
eFigure 4. Area Under the Curves (AUCs; Mean with 95% CI) from Receiver Operating Curve Analysis for Body Fat Indices of the Form M/H^n with n values of 2 (BMI unadjusted for age), 2.5, 2.8, 3 (TMI), 3.5, and 4 for non-adults (ages 8-17 years).

The higher the AUC value, more accurately the index classifies individuals as overweight versus normal weight. The AUC value is highest for 3 (TMI) for both sexes.
eTable 1. Subject Characteristics and Body Composition Measurements (Mean±SE) for NHANES NH Males and Females.

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<thead>
<tr>
<th>Age Group (years)</th>
<th>N</th>
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<th>Body Weight (kg)</th>
<th>FFM (kg)</th>
<th>Fat Mass (kg)</th>
<th>N</th>
<th>Height (cm)</th>
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FFM, fat-free mass; FFM is equal to DXA body weight minus fat mass or the sum of lean soft tissue and bone mineral content. †, differs significantly from preceding age group; ‡, differs significantly from the reference group aged 25-29 years.
eTable 2. Height (Mean±SE) as a Function of Age for Each Quartile of Percent Body Fat.

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