CHAPTER III

Accurate Ultrasound Measurement of Adipose Tissue, and Body Shape Correction of the BMI

(Original Scientific Article)

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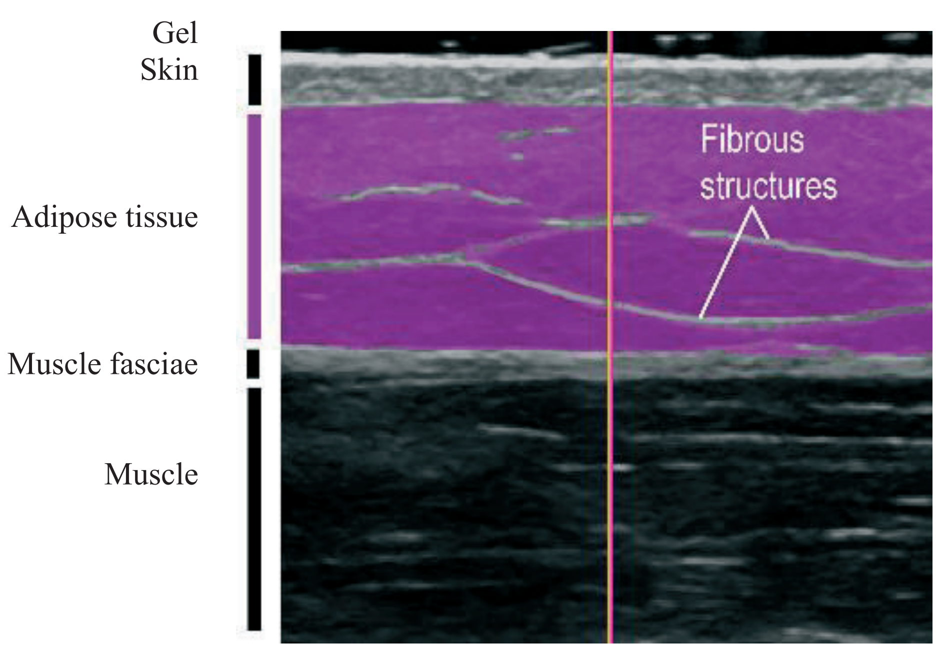

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Abstract

Background

Valid, accurate, and reliable quantification of (i) body mass with respect to body dimensions, and (ii) of adipose tissue are essential for health and performance optimisation in sports, as well as for general medicine and public health. To remove the dependency of body mass *m* on stature *h*, the body mass index, $BMI=m/h^2$, is widely used to assess whether individuals are underweight, of normal weight, or overweight. A classification based on *BMI* can only refer to an individual's body mass, but not to their body composition in terms of lean mass and fat mass, as these variables are not captured by the *BMI* formula. Quetelet, whose data led to the definition of this index, had found that 'the weight is nearly as the square of the stature' – and never intended to use measurements of weight and stature for estimating body fat. Nevertheless, *BMI* is widely used as a surrogate measure for body fat, or as a numerical indicator associated with a person's level of adiposity, despite error ranges that often exceed the values to be measured. In a given population, standard errors of estimate for regression models predicting body-fat percentage from *BMI* are typically around 6%. In other words, approximately 68% of the estimates will fall within ±6% of the true body-fat percentage, while in about 32% of cases, the error will even exceed this range. When applying such a regression function to other populations, error ranges are even large. Such levels of uncertainty disqualify *BMI* as a surrogate measure of body fat because of the large percentage of severely misleading values that may lead to inadequate and potentially harmful behavioural changes in the individuals being observed. Particularly in lean groups - e.g., athletes in weight-sensitive sports or patients with anorexia nervosa – other *indirect* methods used to estimate body fat or adipose tissue also fail to discriminate between individuals at the fine scale required, due to their inherent methodological shortcomings. These *indirect* or *doubly indirect* methods include: dual-energy X-ray absorptiometry (DXA), skinfold measurements, bioelectrical impedance analysis (BIA), hydrodensitometry, air displacement plethysmography, and others.

The standardised (brightness-mode) ultrasound method (SUM) measures subcutaneous adipose tissue (SAT) layers *directly* (using the pulse-echo technique for imaging the SAT), with high validity, accuracy and reliability. This novel method has recently been standardised in cooperation with the Working Group on Body Composition, Health and Performance, under the auspices of the Medical Commission of the International Olympic Committee (IOC). Here, we present the finalised SUM in detail, including reference values of SAT for both athletes and for the general population.

The mass index *MI*, $MI=S_R m/(hs)$ improves the *BMI* by taking body shape in terms of the Cormic index *S* into account ($S=s/h$; *s*: sitting height, $S_{R,M}$: reference value for males, and $S_{R,F}$: reference value for females). It is important to clarify that *MI* is also not designed to quantify adipose tissue or body fat, but represents an improved variable for assessing body weight with respect to body size and shape. The *MI* is presented here in finalised form, taking the sexual differences in body shape into account.

Methods

The *MI* formula is deduced here from a general approach designed to take body shape into account for determination of body mass with respect to body dimensions. Derived from a data set of 1,072 physically active persons, reference values for the Cormic index (S_R) were determined for men and women, and cross-validated with a data set of N=1,006 persons with low physical activity.

The comprehensive description of the SUM presented here includes the approach for SAT mass estimation based on SAT thicknesses at the eight standardised sites. The sum (or mean) of the eight thicknesses is used as a *direct* measure of adipose tissue (AT), and the SAT mass in kilograms and in percent of body mass is computed straightforwardly: body surface area multiplied by the calibrated mean SAT thickness and the density of AT. In persons with low to medium waist circumference, the SAT mass represents the dominant part of the total AT, and thus also the main part of the fat mass (non-polar lipids). Pulse-echo SAT thickness measurement accuracy is 0.1 mm (using an 18 MHz probe and the speed of sound in SAT); for comparison, 0.1 mm is about the size of a single fat cell (or of a few ones – cells vary in size). SAT thickness values are robust median values of typically 100 thickness measurements in each ultrasound image. Reliability is better than 0.2 kg SAT mass (95% limit of agreement in non-obese persons), embedded fibrous structures (fasciae) are quantified, and SAT patterning is derived from three sites on the trunk and five sites on the extremities. The standard sites include lateral thigh – the most pronounced SAT depot site in most women, and lower abdomen, the major SAT depot in most men.

Results

In the physically active adult male group (N = 441), the median of the sums of SAT thicknesses across the eight standardised measurement sites was D_I=24.40 mm, and D_E=19.45 mm. The corresponding medians of the individual means across the eight sites were $d_{I,8,mean}$=3.05 mm and $d_{E,8,mean}$=2.43 mm, respectively. The index 'I' indicates that fibrous structures (fasciae) were included in the measurements, while 'E' denotes that they were excluded. The values for the corresponding female group (N=249) were: D_I=65.14 mm ($d_{I,8,mean}$=8.14 mm), and D_E=58.27 mm ($d_{E,8,mean}$=7.28 mm). In all subgroups of physically active females, the median D_I and D_E values – as well as the values at lower percentiles – were 2 to 4 times higher compared to their male counterparts ($p<0.01$ in all cases). In adult male elite athletes of various sports (N=354), median $d_{I,8,mean}$ was 2.6 mm, and in the female elite group (N=180) $d_{I,8,mean}$ was 7.3 mm. Medians of World-Cup semi-finalists in sport climbing (a typical weight-sensitive sport) were just 1.2 mm in males (N=41) and 4.3 mm in females (N=41), corresponding to about 3% and 8% of SAT mass in relation to body mass; the lowest male value was 1%, and the lowest female value was 3%. A detailed analysis of world class climbers can be found in Chapter II.

Although SAT thicknesses were significantly higher in the female compared to the male climbers, the group medians of *BMI* and *MI* were significantly lower – by 1.4 kgm^{-2} and 1.0 kgm^{-2}, respectively. At lower percentiles, the *BMI* and *MI* differences were even larger – about 2.0 kgm^{-2}. In both the physically active female group (N=429) and in the low physical activity (lifestyle activity) female group (N=512), *BMI* and *MI* medians were also approximately 2.0

kgm^{-2} lower ($p<0.01$) than those of the corresponding male groups (N=643, and N=494, respectively). Similarly large differences of about 2.0 kgm^{-2} in the median – and at all percentiles below the median – were also observed in various subgroups of physically active adults. This also holds true for the lifestyle activity subgroup of individuals with a *BMI* below 25 kgm^{-2} and younger than 50 years, but such pronounced differences in the median values were not observed in the subgroups with a *BMI* above 25 kgm^{-2} and in those older than 50 years.

In this publication, reference values of SAT are presented for athletes and for the general population. These values are based on the comprehensive data sets obtained during several years and replace the preliminary reference values.

Discussion and Conclusions

MI is recommended instead of *BMI* to take the important impact of body shape into account, which is ignored by the *BMI*. For persons with long legs, *MI* is larger than *BMI*, and vice-versa. Furthermore, our data indicate that there are substantial differences in *BMI* (and also in *MI*) values between men and women that should not be ignored when assessing body mass with respect to body dimensions based on empirical evidence, in particular when classifying grades of leanness. The current World Health Organisation (WHO) classification ignores these evidences. Given that these highly significant differences between sexes were found in all groups of physically active individuals, as well as in the group with low physical activity, *BMI* below 25 kgm^{-2}, and age under 50 years, we assume that similarly large differences will also appear in future studies and should be taken into account when assessing grades of underweight.

SUM measures SAT validly (by direct measurements of SAT thicknesses) with high accuracy and reliability, so that also the especially high demands in lean groups like anorectic patients or athletes are met. The percentile-based SAT reference values facilitate the assignment of medical findings with accurately measured AT values that were not hitherto available. We recommend including only accurate AT measurements to prevent erroneous results and confusion arising therefrom, as well as inappropriate reactions from the measured individuals due to misleading feedback.

Key Points

This article presents two methodical improvements

(i) The Mass Index *MI*

- Epidemiological studies have shown that body shape has a large impact on *BMI*, which classifies individuals with unusual leg length inappropriately (WHO).
- The most common bivariate index of body shape is the Cormic index *S*, which is the ratio of sitting height to stature: $S=s/h$.
- The mass index *MI* corrects the *BMI* for body shape by taking *S* into account.
- For individuals with usual leg length, that is a Cormic Index in the middle of the *S*-continuum, *BMI* and *MI* are identical.
- For long-legged individuals, the *MI* value is higher than the *BMI* value (mapping the lower body volume associated with long legs and short upper body), and vice versa.
- The *MI* distinguishes between the significant differences in body shape between men and women (by using sex-specific body shape reference values in the *MI*-equation).
- The *MI* is as easy to determine as the *BMI*: just sitting height needs to be measured in addition.
- The evidences of significantly lower female *BMI* and *MI* medians and percentiles (by typically 2 kgm^{-2}) of the female groups compared to the values of the corresponding male groups are not taken into account in the widely used WHO cut-off values for grades of underweight.

(ii) The Standardised (Brightness-Mode) Ultrasound Method (SUM)

- SUM measures uncompressed subcutaneous adipose tissue (SAT) thicknesses validly: it is a *direct* measurement method that does not need any assumptions.
- The accuracy for thickness measurements of SAT is 0.1 mm (at 18 MHz), which is about the size of a single fat cell.
- Multicentre studies have shown that the reliability of the SUM is better than 0.15 mm for the mean of the eight standardised sites.
- Changes of less than 0.2 kg SAT (0.3%) can reliably be detected by SUM.
- SUM quantifies the SAT, which makes up the predominant part of the body's adipose tissue and contains most of the body fat (non-polar lipids), at least in individuals with medium and low waist circumferences.
- For persons with large waist circumference, we suggest to use the waist-to-stature ratio (W/h) in addition to the SAT measurement for assessing their health risks.
- SUM is the only method that enables the quantification of the fibrous structures (fasciae) embedded in the SAT, which account for typically 10% in women and 20% in men, ranging up to more than 40% in some individuals.
- The high accuracy and reliability of SUM enable SAT patterning analyses and monitoring of intervention effects on SAT on a fine scale that was beyond reach before.

- SUM is applicable across the full spectrum of body composition and age, from extremely lean to severely obese individuals and from preterm neonates (using a simplified SUM; publication is in preparation) to the elderly.
- SUM can easily be applied in the field (reasonable notebook or hand-held B-mode ultrasound systems are available).
- SUM also allows SAT thickness measurements at only four or five sites and estimates the values for all eight sites. This saves time and is still sufficiently reliable for many purposes.
- SUM does not use ionising radiation.
- Training courses for measurers are available to ensure that the high measurement reliability is achieved in a short period.
- Reference values are presented for athletes and for the general population that were obtained from large data sets of physically active persons.

Keywords

Leanness, adiposity, adipose tissue, patterning, body fat, lipids, triglycerides, B-mode ultrasound, fasciae, mass index, MI, body mass index, BMI, anthropometry, body shape, Cormic index, elite athletes, physical activity, anorexia, eating disorders, sex differences, dimorphism