Review Article
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Historical review of developing body weight indices: meaning and purpose

Abstract

Rationale: The last century was blossoming with the development of multiple indices to measure body weight. Many researchers aimed to explore the association of extra body weight with various diseases using different approaches of body weight measures. However, there is no summary of developed body mass indices highlighting their strengths and/or weaknesses.

Objective: This paper reviews and compares the existing body weight indexes that were developed particularly to define overweight and obesity in relation to adverse health outcomes.

Methods: A systematic literature review was performed to chronologically summarize the development of body weight measures from the first index developed by Quetelet (BMI) in 1832 to Body Adiposity Index (BAI) in 2011.

Conclusion: The paper provides summary of the development and validation of existing body weight indexes. Knowledge of the historical approaches to the measurements of obesity will help researchers to utilize the appropriate body weight assessments to address their objectives. Latin Proverb: "A good beginning ensures a good ending".

Keywords: body weight index, overweight, obesity, epidemic, chronic, body weight

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Abbreviations: FFM, fat-free-mass; BFM, body fat mass; PBF, percent body fat; SAD, sagittal abdominal diameter; BMI, body mass index

Introduction

In the beginning of the 20th century the association of obesity and increased mortality became documented by insurance companies. After the World War II, the interest shifted to the association between body weight and morbidity with a question how to classify the excess of body weight that can adversely affect health. This paper reviews the process of development and validation of different body weight indexes. The major milestones of this process are presented in Table 1.

Table 1 Development of indexes to measure body weight

Date [Ref]	Who	Index	Technique used	Population	Purpose	Conclusion
1832[1]	Adolphe Quetelet	Quatelet Index=weight/ height^2 W/H^2	Anthropometric methods - Direct measure	Belgium men and women	Define a "Normal man"	Quetelet suggested first anthropological Index based on observation that weight increases proportionally to height squared.
1897[2]	Livi	Ponderal Index: Height divided by cube root of weight H/W$^{1/3}$	Anthropometric methods - Direct measure	UK	Measure of Obesity	Proposed to measure adiposity or obesity
1962[5]	W. Z. Billewicz, W. F. F. Kemsley, and A. M. Thomson	W/H W/H^2 H/W$^{1/3}$ (PI)	Anthropometric methods - Direct measure	English	Compare 3 indexes to measure obesity	1. All three indexes highly correlate with adiposity 2. W/H^2 is less biased (each index selects different proportions of individuals according to their height)

Table Continued....

Date [Ref]	Who	Index	Technique used	Population	Purpose	Conclusion
1967[6]	T. Khosla and C. R. Lowe	I_1=W/H I_2=W/H^2 H/W$^{1/3}$ (PI)	Anthropometric methods - Direct measure	UK, Birmingham study of the distribution of arterial pressure in an industrial population N=5000 men employed	Compare 3 indexes to measure obesity by 2 criteria: 1) Correlate with weight (r_1) 2) Independent of height (r_2)	I_1 : r_1=0.97 r_2 = .3 I_2 : r_1=0.85 r_2~ 0 I_3 : r_1=0.6 r_2 =-0.3 I_2 is the most appropriate for epidemiological studies (at least for British pop.)
1970[3]	Charles du V. Florey	I_1=W/H I_2=W/H^2 I_3=W/H^3= (Rohrer Index-as variation of H/W$^{1/3}$ (PI)) Triceps skinfold & Intrascapullar skinfold (as best adiposity measurements)	Anthropometric methods - Direct measure	US, Framingham Study, Massachusetts N=5127 free from coronary disease at first exam N=4541 persons were reexamined during Exam IV	Compare 3 indexes to measure obesity and adiposity	1. Western male population was Quetelet Index (W/H^2), probable in Western female population was W/H; and the least likely for both sexes was Ponderal Index. 2. All indexes are poor measurements of Adiposity
1972[7]	A. Keys, F. Fidanza, M. J. Karvonen N. Kimura And H. L. Taylor	W/H W/H^2 PI %W (%from weight standard at given height)	Anthropometric methods - Direct measure	Several countries in Europe, Japan, men in South Africa, white men in the United States 7424 'healthy' men in 12 cohorts in five countries. Body density in N=180 young men and in 248 men aged 49-59.	Criteria of correlation with height (lowest is best) and to measures of body fatness (highest is best)	PI is the poorest W/H^2 – is the best Body Mass Index (BMI) which is W/H^2 is preferable measure to "all populations in all times"
1990[18]	Theodore B Vanltaiie, Mei-Uih Yang, Steven B Heymsfield, Robert C Funk, and Richard A Boileau	FFMI = FFM (kg)/H(m)^2, BFMI = BFM (kg)/H(m)^2	TOBEC by electromagnetic scanning instrument (EM-SCAN, model HA-2, Springfield, IL) - FFM Hydrodensitometry in all 32 subjects for Body Composition	124 healthy and 32 Non-obese young men (from the Minnesota Study) before, during, and after experimental semi-starvation.	To demonstrate the clinical value of the FFMI and the BFMI (can be helpful in the nutritional assessment of patients).	Defined FFMI and BFMI that may be used in nutritional assessment (cutoff points should be chosen in more representative population
1991[15]	Paul Deurenberg, Jan A. Weststrate, and Jaap C. Seidell	%Body Fat %BF Formula for children and adult using BMI	%BF - densitometry (underwater weight + Siri's formula) BMI-anthropometry	In 1229 subjects, 521 males and 708 females, with a wide range in body mass index (BMI; 13.9-40.9kg/m2), and an age range of 7-83years	Compare BMI and %BF	Child %BF = (1.51 x BMI) – (0.70 x Age) – (3.6 x Sex)+1.4; Adult %BF = (1.20 x BMI) + (0.23 x Age) – (10.8 x Sex) – 54.

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Table Continued....

Date [Ref]	Who	Index	Technique used	Population	Purpose	Conclusion
2002[19]	Y Schutz, UUG Kyle and C Pichard	FFMI (fat-free mass=height squared) and FMI (fat mass=height squared).	Bioelectrical impedance analysis (50 kHz) was measured (using tetrapolar electrodes and cross- validated formulae by dual-energy X- ray absorptiometry	5635 apparently healthy adults from a mixed non-randomly selected Caucasian population in Switzerland (2986 men and 2649 women), at age from 24 to 98y.	To determine reference values for fat-free mass index (FFMI) and fat mass index (FMI) as a function of age and gender and to develop percentile distribution for them.	Reference intervals for FFMI and FMI (BMI international criteria was used as cutoff points for calculation of corresponding FFMI and FMI values)
2006[22]	Iribarren, Carlos; Darbinian, Jeanne A.; Lo, Joan C.; Fireman, Bruce H.; Go, Alan S	Association between visceral obesity measured by SAD and coronary heart disease (CHD)	Anthropometric measure: Standing SAD (cm)	101,765 adult members of Kaiser Permanente of Northern California	Association between visceral obesity measured by SAD and coronary heart disease (CHD)	SAD was a strong predictor of CHD independently of BMI; the joint consideration of BMI/SAD categories as better assessment risk of CHD compared with use of BMI alone
2008[26]	Whitmer, R. A.; Gustafson, D. R.; Barrett-Connor, E.; Haan, M. N.; Gunderson, E. P.; Yaffe, K	Association between visceral obesity measured by SAD and dementia	Anthropometric measure: Standing SAD (cm) - distance between the back surface and the top of the abdomen at the level of the iliac crest after gentle expiration with the patient in a standing position using an anthropometer; High SAD ≥25 cm Low SAD <25 cm	A longitudinal study included 6,583 members of Kaiser Permanente of Northern California; (SAD) measured in 1964 to 1973, 1,049 participants (15.9%) were diagnosed with dementia 36years later	Association between visceral obesity measured by SAD and dimensia	Visceral obesity increases risk of dementia independent of diabetes and cardiovascular co-morbidities among mid-aged population
2008[17]	Abel Romero-Corral, Virend K. Somers, Justo Sierra-Johnson,, Randal J. Thomas, Kent R. Bailey, Maria L Collazo-Clavell, Thomas G. Allison, Josef Korinek, John A. Batsis, and Francisco Lopez-Jimenez	Accuracy of BMI≥30kg/m^2 to detect excess in body adiposity compared to Body Fat% BMI-defined obesity (≥30kg/m^2) was present in 21% of men and 31% of women, while BF %-defined obesity was present in 50% and 62%, respectively	Bioelectrical impedance analysis was used to estimate body fat percent (BF %).	13,601 subjects (age 20–79.9years; 48% men) from the Third National Health and Nutrition Examination Survey. NHANES III	Using the World Health Organization reference standard for obesity (based on BMI cut offs): Obesity of BF % > 25% in men and > 35% in women. Correlation between BMI and both, BF % and lean mass by sex and age groups.	Diagnostic accuracy of BMI to diagnose obesity is limited (for individuals in the intermediate BMI ranges). A BMI cut-off of ≥30kg/m^2 has a good specificity but misses more than half of people with excess fat. May explain differences in shapes (U or J) of association between BMI and Health Outcomes.

Table Continued....

Date [Ref]	Who	Index	Technique used	Population	Purpose	Conclusion
2008[37]	The WHO Expert Consultation	WC =waist circumf. HC=hip circumf. WHR = the waist circumference divided by the hip circumference Or WHR=WC/HC	Waist circumference (WC)- measured at the midpoint between the lower margin of the least palpable rib and the top of the iliac crest, using a stretch-resistant tape that provides a constant 100 g tension. Hip circumference (HC) should be measured around the widest portion of the buttocks, with the tape parallel to floor.	US and global Summarizes issues to define cutoffs globally	Report of a Waist Circumference and Waist-Hip Ratio	Defines and summarizes the techniques of measurements WC, HC, and WHR
2009[20]	Thomas L. Kelly, Kevin E. Wilson, Steven B. Heymsfield	%BF, fat mass/ height^2, lean mass/height^2, appendicular lean mass/height^2, %fat trunk/%fat legs ratio, trunk/limb fat mass ratio of fat, bone mineral content (BMC) and bone mineral density (BMD)	Dual energy x-ray absorptiometry (DXA)	NHANES III 15 counties across the United States from 1999 through 2004	Developed Classification thresholds for Fat Mass Index (FMI; fat mass/height^2). (by using BMI classification thresholds and prevalence in young adults)	These reference values should be helpful in establishing entry criteria into clinical trials, and for other medical, research, and epidemiological uses.
2010[21]	Gerson Peltz, Maria Teresa Aguirre, Maureen Sanderson And Mary K. Fadden	Compare BMI, PBF, and FMI; and to investigate the accuracy of FMI as a convenient tool for assessing obesity	Anthropometric measurements and bioelectrical impedance analyses (BIA)	538 Mexican American college students (373 women and 165 men) from the University of Texas at Brownsville and Texas Southmost College (UTB/ TSC); recruited from September 2004 through December 2005.	Correlation between FMI and PBF in men ($r=0.975$; $P<0.0001$) and women ($r=0.992$; $P<0.0001$) while misclassification of obesity between FMI and PBF categories was observed in only 5.4% of men and 7.8% of women.	Limitation of BMI: High correlation b/w BMI and PBF in men ($r=0.877$; $P < 0.0001$) and women ($r=0.966$; $P<0.0001$); however, 67.2% of the men and 84.2% of women were miss-classified as normal weight and overweight by BMI while diagnosed as obese by PBF. FMI accurately assessed obesity in this study of Mexican Americans
2010[27–31]	The Body Benchmark Study; US and EU	Development and Validation of Body Volume Index BVI	3-dimensional photonic scanner 3DPS	US and Europe	Development of new Anthropometric index: BVI is accurate, easy to measure, no variability between evaluators.	Definition and Validation of BVI

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Table Continued....

Date [Ref]	Who	Index	Technique used	Population	Purpose	Conclusion
2011[32]	Richard N. Bergman, Darko Stefanovski, Thomas A. Buchanan, Anne E. Sumner, James C. Reynolds, Nancy G. Sebring, Anny H. Xiang and Richard M. Watanabe	Development and Validation of Body Adiposity Index BAI = (hipcircumference)/((height)$^{1.5}$)–18)).	%Body fat, as measured by the dual-energy X-ray absorptiometry (DXA), was used as a "gold standard" for validation;	The population study "BetaGene" with 1,733 Mexican American participants. "Triglyceride and Cardiovascular Risk in African-Americans (TARA)" study of 223 African Americans.	BAI is that measures %adiposity directly for adult men and women.	Development and Validation of Body Adiposity Index BAI = (hipcircumference)/((height)$^{1.5}$)–18)).

Note: W, weight; H, height

Weight-to-height indexes

In 1832, the Quetelet index (later was renamed into the Body Mass Index or BMI) was defined as body weight divided by height squared: BMI=Weight/Height^2,[1] and in 1897, the Ponderal Index was introduced by Rudolfo Livi[2] as height divided by the cube root of weight PI=Height/(Weight)$^{1/3}$.[2,3] In 1921, Roher proposed the Corpulence Index as a measure of leanness of a person where body weight was normalized by the third power of body height rather than the second power RI=Weight/Height.[3,4] By the mid of 20th century, the most popular indexes became: W/H, W/H^2, and H/W$^{1/3}$ (Table 1). Quetelet index was less "biased" in terms of independence from height (coefficients of correlation $r \leq 0.16$) and from this point of view Quetelet index was considered the best.[5]

Khosla and Lowe[6] also had an objective to compare the three indexes: I_1=W/H, I_2=W/H^2, and I_3=W/H^3 using the data from Birmingham survey and two criteria for the best index:

i. The highest correlation with the weight; and

ii. Independence from the height.[6]

The results demonstrated that I_2 was highly correlated with weight (r_1=0.85) and consistently independent from height.[6] The authors concluded that Quetelet index I_2=W/H^2 was the best choice for epidemiological purposes.[6] Both studies by Charles du V Florey focused on the meaning of indexes as the measure of obesity and how to choose the most appropriate index for the particular population.[3] The author used Framingham Heart Study (FHS) data that included subjects free of coronary heart disease at the first examination (N=5127); then 4541 of them were reexamined during Exam IV (6-years follow-up, and 88.6 percent of the original respondents).[3] Height, weight, triceps, and skinfold thickness data were collected with a goal to compare the properties of three weight to height indexes: W/H, W/ H^2, and PI=H/(W)$^{1/3}$.[3] The authors suggested that regression model should be developed for the particular population and the best of the three proposed ratios will depend on the value of the intercept and the coefficient of the regression of weight on height.[3] For example, index W/H is the best when the coefficient b=2 because of most independence from height; and W/ H^2 is least dependent on height when b=5. Based on this approach, the authors concluded that the "most likely" best ratio in Western male population was Quetelet Index (W/ H^2), "probable" in Western female population was W/H; and the "least likely" for both sexes was Ponderal Index.[3] All three indexes were poor measures of adiposity because of low correlation with triceps (<0.5) and infra-scapular skinfold (<0.7) for both males and females.[3]

Keys et al.,[7] decided to repeat analyses on "calibrated" data, in the other words to compare the various indices of relative weight as applied to data on weight, height and body fatness of men in several countries in Europe, Japan, South Africa, as well as white men in the United States.[7] The criteria for the best index was independence from height, and the highest correlation with the body fatness.[7] The Quetelet Index was named as Body Mass Index (BMI) first time and it was pronounced preferable over other indices of relative weight (%W, W/H, W/ H^2, W/ H^3, and PI) judged by the criteria of correlation with height (lowest is best) and body fatness (highest is best) as well as "on the simplicity of the calculation and, in contrast to percentage of average weight, the applicability to all populations at all times".[7]

BMI became the most common index to measure weight status in adults. BMI is a continuous variable and the threshold for overweight and obesity was not an easy task for many years. Currently, World Health Organization international classification of BMI based on association with mortality is used (Table 2). Nevertheless, BMI has a few serious limitations. Assessment of BMI in epidemiological studies assumes an average person with the average physical activity (presumably: not athletes, not elderly) and with an average body composition.[7] BMI is not a good proxy for fat distribution and cannot separate lean fat from body fat mass while the difference how the same amount of extra fat is distributed in the bodies can substantially modify the risk associated with obesity.[4,8–14] Those limitations promoted search for the other measurements of obesity.

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Table 2 Fat mass index (kg/m²) classification ranges

FMI	Fat deficit			Normal	Excess fat	Obese class		
Class	Severe	Moderate	Mild			I	II	III
Male	<2	2 to <2.3	2.3 to <3	3-Jun	>6 to 9	>9 to 12	>12 to 15	>15
Female	<3.5	3.5 to < 4	4 to < 5	5-Sep	>9 to 13	>13 to 17	>17 to 21	>21

Percent body fat (PBF or %BF)

Percent body fat (%BF) is the total mass of fat (or fat accumulated in adipose tissue) divided by total weight: %BF=Body Fat Mass/ Body Weight. Percent body fat can be calculated from skinfolds or other anthropometric methods such as bioelectrical Impedance. The relationship between body fat percentage (%BF) and BMI adjusted for age and sex was investigated by Deurenberg et al.,[15] %BF was calculated from the body density using Siri's[16] formula where the body density was measured by underwater weighing (UWW).[15] The authors estimated that %BF could be derived by the following formulas: *Child %BF=*(1.51 x BMI)–(0.70 x Age)–(3.6 x Sex)+1.4; and *Adult %BF=*(1.20 x BMI)+(0.23 x Age)–(10.8xSex)–54 (males=1, females=0). Deurenberg et al.,[15] concluded that the use of prediction formulas is inexpensive method that does not rely on well-trained observers; moreover, the prediction error is comparable with other methods such as skin-fold thickness measurements or bioelectrical impedance.[15]

The accuracy of BMI to detect excess in body adiposity was assessed by comparing the prevalence of BMI-defined obesity (≥30kg/m²) versus to reference standard for BF%-defined obesity of BF% >25% in men and >35% in women in 13,601 subjects from the United States' third National Health and Nutrition Examination Survey (NHANES III).[17] It was estimated that presence of obesity based on BMI-defined obesity (≥30kg/m²) was 21% for men and 31% for women, versus 50% and 62%, respectively by BF %-defined obesity (>25% in men and >35% in women).[17] High specificity (95% in men and 99% in women) and poor sensitivity (36% and 49%, respectively) was demonstrated by BMI ≥30kg/m² to detect %BF-defined obesity.[17] BMI had a good correlation with %BF in men (R^2=0.44) and women (R^2=0.71), but in spite of that the accuracy to diagnose obesity by BMI was limited, and using BMI cut-off as ≥30kg/m² missed more than half of people with excess fat.[17]

Fat-Free-Mass (FFM) and Body Fat Mass (BFM)

In 1990, Vanltallie et al.,[18] proposed height-normalized indices like Fat Free Mass Index: FFMI=Fat-Free-Mass(kg)/Height(m)², and Body Fat Mass Index: BFMI=Body-Fat-Mass(kg)/Height(m)² as a possible alternative to BMI (it can be noticed that mathematically BMI(kg/ m²)=FFMI(kg/ m²)+BFMI(kg/ m²)).[18] The objective of the Vanltallie et al.,[18] study was to demonstrate the clinical value of FFMI and BFMI in terms of the nutritional assessment, because tall subjects with protein-energy malnutrition (PEM) and short well-nourished individuals may have the same FFM and BFM values.[18] The authors calculated FFMI=FFM(kg)/H(m)² and BFMI=BFM(kg)/ H(m)² before, during, and after experimental semi-starvation for subjects from Minnesota Study.[18] The criteria for PEM was set up as FFMI and BFMI fall below the 5th percentile in reference cohort of 124 healthy men, and 32 non- obese young men.[18] Based on this criteria, 27 out of 32 Minnesota subjects were diagnosed in PEM after 12weeks of semi-starvation.[18] Vanltallie et al.,[18] concluded that FFMI and BFMI may be useful in nutritional assessment.[18] In 2002, Schultz et al.,[19] conducted a cross-sectional study to determine reference values for fat-free mass index (FFMI) and fat mass index (FMI) in a large Caucasian group of healthy subjects from Switzerland (2986 men and 2649 women, 24-98years of age) as a function of age and gender, with the additional goal to develop percentile distribution for these two indexes.[19] The authors used the classical BMI cut-off points as of 18.5, 20 and 25kg/m² to determine the corresponding values for FFMIs and FMIs by means of regression analysis of BMI vs. FFMI, then vs. FMI, and demonstrated that the 25 and 75-percentiles for FFMI and FMI distribution corresponded well to the cut-off of BMI's as 20 and 25kg/m² respectively.[19] It was observed (especially in women): at a BMI of 20kg/m² the corresponding FFMI was 15.1kg/m², and at 25 percentile=15.0kg/ m²; similarly, at a BMI of 25kg/m², the corresponding value of FFMI was 16.7kg/m², and 75-percentile=16.6.[19] Schultz et al.,[19] underscored the advantage of FMI as being a function of age and gender comparing to BMI.[19] The authors stated that the FFM index has a clinical value "for assessing static and dynamic nutritional status and energy reserves endpoints" compared to BMI and%BF.[19]

In 1999, The National Health and Nutrition Examination Survey (NHANES) started collecting DXA whole body measurements of %BF, fat mass/height², lean mass/height², appendicular lean mass/ height²,% fat trunk/%fat legs ratio, trunk/limb fat mass ratio of fat, bone mineral content (BMC) and bone mineral density (BMD) on survey subjects ≥8years old in three mobile examination centers.[17–20] Based on data collected in NHANES from 1999 to 2004, Kelly et al.,[20] developed an obesity classification for Fat Mass Index (FMI: fat mass/ height²) by using prevalence of BMI through established cut-offs and matching thresholds for FMI.[20] The FMI classification is presented in Table 2.[20]

Peltz et al.,[21] assessed body mass index (BMI), percent body fat (%BF), and fat mass index (FMI) by anthropometric methods and bioelectrical impedance analyses (BIA) on 538 Mexican Americans (373 women and 165 men) with the objective to investigate the accuracy of FMI as a convenient tool for assessing obesity.[21] High correlation was observed between BMI and %BF in men (r=0.877; P<0.0001) and women (r=0.966; P<.0001); however, 67.2% of the men and 84.2% of women were miss-classified as normal weight and overweight by BMI while diagnosed as obese by%BF.[21] Correlation between FMI and %BF was also high in men (r=0.975; P<.0001) and women (r=0.992; P<.0001) while misclassification of obesity between FMI and %BF categories was observed in only 5.4% of men and 7.8% of women.[21] The authors concluded that FMI can accurately assess obesity at least in considered population (Mexican Americans).[21]

Sagittal abdominal diameter (SAD)

Sagittal Abdominal Diameter (SAD) is assessment of visceral obesity by measuring the distance from the narrowest point between the last rib and the iliac crests to the mid-point of the iliac crests.[22–24] In the supine position, it is measured to the nearest 0.1cm after a normal expiration with bent knees on a firm examination table

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and without clothes at the level of iliac crest (L4-5). It has been shown that SAD correlates with insulin resistance and hyper-proinsulinemia (i.e. cardiovascular risk factors) in obese men better than other anthropometric measures (BMI, waist girth, and Waist-to-Hip ratio).[25]

A cohort study was conducted by Iribarren et al.,[22] to estimate if visceral obesity measured by SAD predicts coronary heart disease (CHD) above and beyond overall fatness. 101,765 adult members of Kaiser Permanente of Northern California who underwent multiple health checkups between 1965 and 1970, participated in the study.[22] The results demonstrated that the upper quartile of standing SAD (relative to the lowest quartile) was associated with the increased hazard of CHD in men as 1.42-fold (95% confidence interval: 1.30,1.55), and in women as 1.44-fold (95% confidence interval: 1.30,1.59), after adjustment for age, race, body mass index (BMI), educational level, smoking, alcohol consumption, and hormone replacement therapy (in women).[22] The authors recommended the consideration of joint indices BMI/SAD as better assessment risk of CHD compared with use of BMI alone because SAD was a strong predictor of CHD independently of BMI.[22]

Whitmer et al.,[26] conducted a study to evaluate the association between midlife central obesity and risk of dementia three decades later.[26] A longitudinal study included 6,583 members of Kaiser Permanente of Northern California who had their sagittal abdominal diameter (SAD) measured in 1964 to 1973.[26] A total of 1,049 participants (15.9%) were diagnosed with dementia 36years later.[26] The SAD was measured as distance between the back surface and the top of the abdomen at the level of the iliac crest after gentle expiration with the patient in a standing position using an anthropometer; and high SAD was categorized as ≥25cm.[26] Participants with the highest quintile of SAD (vs the lowest) had three-fold increased risk of dementia (hazard ratio=2.72; 95% CI: 2.33, 3.33), and almost two-fold after adding body mass index (BMI) to the model (hazard ratio=1.92; 95% CI: 1.58, 2.35).[26] The authors concluded that visceral obesity increases risk of dementia independent of diabetes and cardiovascular co-morbidities among mid-aged population and further research is needed to understand the underlying mechanism.[26]

Body volume index (BVI)

The Body Volume Index (BVI) is a new anthropometric measure of overweight and obesity where 3-dimensional (3D) body scanner with the help of appropriate software performs the assessments of individual's body shape by measuring the total body volume, and eight body segment volumes including the abdomen (central obesity).[27–29] Basically, the new index automatically measures BMI, waist circumference, and waist-hip ratio in addition to highly sophisticated 3D volumetric and body composition analysis which can differentiate people by body shape and weight distribution with the same BMI level e.g. differentiate muscular/athletic people from those with extra weight around the abdomen.[27–29]

The Body Benchmark Study was a collaborative project conducted by the US and European colleagues that examined BVI through multiple clinical trials.[29] The results were presented in October 2010, and that time point was considered a formal launch of new anthropometric index.[29] Currently, BVI is under evaluation by government agencies in the UK as a possible long-term replacement for BMI; nevertheless, the research still continues and the further studies to assess cut-off values to define overweight/obesity using BVI and the correlation between BVI and obesity-related health outcomes are needed.[29,30]

Body adiposity index (BAI)

Body adiposity index (BAI) was defined by Bergmen et al.,[31] as BAI=((hip circumference)/((height)$^{1.5}$)–18)) with the idea that it can be used to reflect percent body fat (%BF) for adult men and women of different ethnicities.[32] The population study "BetaGene" with 1,733 Mexican American participants focused on the development and validation of this new index of body adiposity.[32] The percent body fat (%BF) was measured by the dual-energy X-ray absorptiometry (DXA) as a "gold standard" for validation.[32] The authors choose hip circumference and height as the two components of the BAI formula because of their strong correlation with%BF (correlation coefficient r=0.602 and r=−0.524, respectively).[32] After developing formula on "BetaGene" data, the "Triglyceride and Cardiovascular Risk in African-Americans (TARA)" study of African Americans was used to validate the BAI measure.[32] The results demonstrated strong correlation between DXA-derived%BF and the BAI (r=0.85).[32] Bergman et al.,[31] concluded that BAI might be useful in settings where accurate assessment of body weight is problematic, and BAI measures percent of adiposity directly from the hip circumference and height (without weight) for adult men or women.[32,33]

Freedman et al.,[34] had an objective to evaluate if the prediction of $\%BF_{DXA}$ by BAI is more accurate than that achieved by other anthropometric measures: BMI, hip circumference, or waist circumference.[33] The sample of 1151 participants at the Body Composition Unit of the New York Obesity Nutrition Research Center between 1993 and 2003 was used with %BF assessed by dual-energy x-ray absorptiometry ($\%BF_{DXA}$).[33] The results demonstrated that BAI overestimated $\%BF_{DXA}$ among men (3.9%) and underestimated among women (2.5%) with the magnitudes that varied with the level of body fatness.[33] The authors concluded that BAI was not more accurate than BMI, waist circumference, or hip circumference.[33]

Lopez et al.,[33] conducted a study with a goal to compare BAI and BMI measurements in a Caucasian population from a European Mediterranean area and particularly to assess the BAI by gender.[34] 1,726 women and 1,474 men (mean age=39.2years, SD=0.8) from Mallorca (Spain) participated in the study.[34] Tetra-polar Bioelectrical Impedance Analysis (BIA) system was used for assess % BF; and the body adiposity index (BAI) was calculated using the equation suggested by Bergman et al.[32,34] The results demonstrated a good correlation of BAI and BMI (r= 0.64, p<.001), and a strong correlation between BAI and the %BF (r=0.74, p<.001), which was even stronger than the one between BMI and %BF (r=0.54, p<.001).[34] The authors concluded that the BAI is a good tool to measure adiposity; however, BAI does not seems overcome the limitations of BMI.[34]

A cross-sectional study was conducted in 29.214 men and 21.040 women (aged 20-68years) who were Spanish Caucasian workers. The aim was to evaluate the correlations between Body Adiposity Index (BAI), BMI, waist circumference (WC), waist-to-hip ratio (WHR), and waist-to-height ratio (WtHR) with cardiovascular and metabolic risk factors.[35] The results demonstrated that BAI was less, and WtHR the best correlated with cardiovascular risk factors and metabolic risk factors than other adiposity indexes (BMI, WC and WtHR).[35] The authors concluded that WtHR and/or WC are better versus BAI and BMI to estimate metabolic and cardiovascular risk

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in both clinical practice and research.[35] Waist circumference (WC), waist-to-hip (WHR), and waist-to-height (WtHR) ratios became the most acceptable alternatives for measuring central and visceral adiposity.[8,9]

Waist circumference, waist-to-hip and waist-to-height ratio

The NIH Clinical Guidelines on the Identification, Evaluation, and Treatment of Overweight and Obesity in Adults (September 1998) recommended to use BMI to assess patient's status of overweight and obesity when the goal is to estimate relative risk to disease (use normal weight as a reference); to use body Weight (W) alone if the goal is to monitor weight loss and to determine efficacy of treatments; and to use Weight Circumference (WC) to access abdominal fat content.[36] In the United States the following WC cut offs are commonly used as a risk factor for obesity-related diseases: >35 inches (or >88cm) for women, and >40 inches (or >102cm) for men.[4,8] Yet, there are differences in risk among ethnic groups that became an obstacle for development a global grading system for WC.[4,8] Multiple studies with a goal to estimate the efficacy of therapies based on the changes in WC and BMI assessments faced methodological problems.[37] BMI is a measure of total adiposity, WC and WHR are assessments of central adiposity and to find interrelations of these three measures of obesity was impossible. Cardiovascular Health study on 5200 men and women aged 65 and older demonstrated that BMI was a negative predictor of mortality (mortality risk decreased 21% for every standard deviation increase in BMI after controlling for WC), whereas WC was a positive one (mortality risk increased 13% for every standard deviation increase in WC after controlling for BMI).[38] The difficulty of this issue was later explained by Walls et al.,[38] demonstrated that percent change in WC and BMI cannot be directly compared because of the nature of their relationships; or it must account for their association described by the regression equation.[38] In summary, BMI (kg/m^2) and WC (cm) should be viewed as complimentary measurements. BMI (kg/m^2) is the most useful measure of overweight and obesity status to identify individuals at increased risk from obesity-related diseases. Waist circumference WC (cm) is the best practical measure of abdominal fatness, and to identify individuals at increased risk of obesity-related diseases due to abdominal fat distribution.[36] In addition, WC was the most practical anthropometric measurement for assessing a patient's abdominal fat before and during weight loss treatment.[36] The NIH Clinical Guidelines on the Identification, Evaluation, and Treatment of Overweight and Obesity in Adults summarized this fact in the Table ES-4[36] that was further adopted by the WHO Expert Consultation on Waist Circumference and Waist–Hip Ratio.[37] The table from guidance is presented in Table 3.[36]

Table 3 Classification of overweight and obesity by BMI, waist circumference and associated disease risk (type 2 diabetes, hypertension and cardiovascular diseases)

Status	BMI (kg/m^2)	Obesity class	Men≤102cm (≤40 in) Women ≤88cm (≤35 in)	>102cm (>40) >88cm (> 35 in)
Underweight	<18.5		-	-
Normal#	18.5-14.9		-	-
Overweight	25.0-29.9		Increased	High
Obesity	30.0-34.9	I	High	Very High
	35.0-39.9	II	Very High	Very High
Extreme Obesity	≥40	III	Extremely High	Extremely High

Note, that increase waist circumference can also be a marker for increased risk even in persons of normal weight persons of normal weight persons of normal weight

Conclusion

This paper is a brief review on development of multiple indices measuring body weight. The history and purpose of each index, as well as their weaknesses and advantages is summarized. This review will help researchers to choose the best body weight measurements to address objectives. On the other hand, this paper may motivate researchers to develop and validate a new index because each measurement has limitations and work on the perfect one is still ongoing.

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Conflict of interest

The author declares no conflict of interest.

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