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NARRATIVE REVIEW

How should we assess body fatness? 2. Quantitative field methods available to the epidemiologist and the practitioner.

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Abstract

Objectives: The objectives of this narrative review are to consider and evaluate the simple quantitative field methods available to epidemiologists and clinical practitioners who wish to estimate body fat content. ***Methods.*** Information obtained from Ovid/Medline and Google Scholar through to January 2018 was supplemented by a search of the author's personal files. ***Results.*** Potential options include the calculation of body mass/height ratios, a variety of circumference measurements, determinations of skin-fold thicknesses, measurements of bioelectrical impedance, and photogrammetric determinations of body volume, all of which have significant limitations. ***Conclusions.*** The most widely used approaches are to examine departures from the actuarial ideal body mass, to calculate the body mass index (body mass/height^2), and to measure the thickness of selected skin-folds. Information on the height-adjusted waist circumference is also useful as a means of distinguishing an android from a gynpoid distribution of body fat. **Health & Fitness Journal of Canada 2017;10(4):45-97.**

Keywords: Adiposity; Body mass; Body mass index; Body build; Fat distribution; Impedance; Obesity; Photogrammetry; Skin-fold measurements.

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Introduction

An accompanying article (Shephard, 2017) has described the simple subjective methods that can be used by field workers to determine whether an excess body mass reflects an accumulation of muscle or fat, and if there is an excess of fat, to estimate its regional distribution. This narrative review looks at the relative advantages, disadvantages, and limitations of the objective methods that are currently available to determine body fat content and to assess responses to the treatment of obesity in clinical practice and during epidemiological surveys.

There are now many sophisticated laboratory options for the quantitative determination of body composition, as discussed in detail elsewhere (Shephard, 1991). We may note that the more sophisticated techniques for the determination of body fat, such as underwater weighing, magnetic resonance imaging, computed tomography and dual energy x-ray absorptiometry are generally not suited to the needs of the health practitioner or epidemiologist. The necessary equipment is often expensive, and the findings remain difficult to standardize between laboratories. Issues limiting the reproducibility and validity of each of these sophisticated methodologies are sufficient that some investigators have argued that any "gold standard" assessment of body fat content should be based on a multivariate function that combines data gained from a combination of body density measurements (D), determinations of body water (W) and assessments of body mineral content (B) (Selinger, 1977):

- Body fat (%) = 100(2.747/D) - 0.714W + 1.146B - 2.050

Nevertheless, whether they are used singly or in combination, sophisticated laboratory methods are an important tool in evaluating the validity of commonly used field techniques for the measurement of body fat.

In this narrative review, we focus upon the relatively simple approaches that are commonly applied in epidemiological surveys and obesity clinics, specifically determinations of excess body mass, comparisons of measured body mass with predicted ideal values, examinations of body fat content in relation to height and body mass, calculations of body mass index, the measurement of abdominal circumferences and skin-fold thicknesses, bioelectrical impedance estimates of body fat content, and photogrammetry.

Excess body mass

The simplest objective approach to the estimation of body fat content is to relate an individual's body mass to the population norm for a person of similar height. In the Victorian era, this approach was widely espoused by anthropometrists, particularly André Quetelet in Belgium and John Hutchinson in England.

Adolph Quetelet. Adolph Quetelet (1796-1874 CE, Figure 1) had the varied scientific interests of a typical "Renaissance man." Fluent in at least six languages, Quetelet was best known as an early statistician. One of his assignments was measuring and analyzing the heights and weights of the Belgian armed forces at the time of their recruitment (ages 16 to 20 years, Table 1). Military physicians in other countries collected similar data on their recruits over the latter part of the 19th century, generally with findings similar to those reported by Quetelet.

In 1836, Quetelet constructed a chart listing the average height and body mass from birth to 80 years of age (Table 2). As a statistician, Quetelet was particularly fascinated by recurring patterns in his data, and he emphasized that new knowledge must come from the study of large samples, rather than focusing upon individual peculiarities. Thus, he wrote (Quetelet, 1835): *"l'homme se trouve sous l'influence des causes dont la plupart sont régulières at périodiques" ("humans find themselves under the influence of causes, of which most are regular and periodic."* This viewpoint stimulated his quest for "*L'homme moyen*". His idea of "*L'homme moyen"* was not what we might today consider as an "*average"* or "*mediocre*" person, but rather a perfect example of young manhood, with physical characteristics lying at the apex of a normal distribution curve for the population under study. In his view,

Figure 1: Belgian anthropometrist and statistician Adolph Quetelet (1796-1874 CE). Source: https://en.wikipedia.org/wiki/Adolphe_Quetelet

Table 1: Some figures reported by Adolph Quetelet for the average height and body mass of Belgian army personnel at ages of recruitment that ranged from 16 to 20 yr.

Age at recruitment (yr)	Height (m)	Body Mass (kg)	Quetelet Index (M/H^2)*
16	1.45	49.5	23.5
17	1.63	52.7	19.8
18	1.66	57.2	20.8
19	1.67	60.0	21.5
20	1.68	62.7	22.2

*Index calculated by the present author.

anthropometric measurements and indeed all human data conformed to this normal distribution. Individuals who deviated from the statistical ideal were liable to deformity, disease (Quetelet, 1835), and crime (which he regarded as a defect of moral anatomy). One factor motivating Quetelet's interest in such norms was the hope that their publication would stimulate society to bring all members of the community towards normal, "healthy" values.

Quetelet made an exhaustive analysis of factors linked to the risk of premature death, including an individual's nationality, age, sex, profession, and the season of the year. Interestingly, he underlined a relatively large difference of mortality rates between those who were sedentary (0.140) and those who exercised regularly (0.089). He commented that the English were systematically taller than the French or Italians, but his treatise did not look at the influence of height-adjusted body mass upon prognosis.

The original table of height and body mass (Table 2) presented average, maximum and minimum values at all ages from birth to 80 years, with M/H values expressed as simple ratios. Quetelet noted that the M/H ratio increased rapidly over the period of growth, whereas M/H^2 approximating a relatively stable value throughout much of childhood. He did not include M/H^2 in his publication, but this information has been added to Table 2; the values are similar to those anticipated in healthy modern populations. The body mass index (M/H^2) is still sometimes termed the Quetelet Index, in honour of his observations.

John Hutchinson. John Hutchinson (1811-1861 CE, Figure 2), was a surgeon and master violinist, but today he is best known for his invention of the clinical water-sealed spirometer (Hutchinson, 1846). His initial publication on vital capacity included data on the height, body mass and lung volumes of some 2130 individuals, which (although not entirely randomly selected) covered a wide cross-section of English society. Those whom he examined ranged from "*paupers*" to "*gentlemen*," and included artisans, servicemen,

Figure 2: John Hutchinson, inventor of the clinical, water-filled spirometer, collected much data on the heights and lung capacities of a broad sample of people in Victorian England.
Source: https://www.google.ca/search?q=John+Hutchinson+spirometer+pictures

Table 2. Abbreviated version of average body mass for height tables published by Quetelet (1835). Note: the original table also included values for intervening ages and maximal and minimal values at each age.

	Males			Females		
Age (yr)	Height (m)*	Body mass (kg)+	M/H and M/H2 **	Height (m)*	Body mass (kg)+	M/H and M/H2 **
1	0.696	10.0	14.3 20.5	0.690	9.3	13.5 19.6
5	0.990	16.7	17.0 17.7	0.974	15.5	15.7 16.1
10	1.282	26.1	20.4 15.9	1.248	24.2	19.5 16.0
15	1.559	46.4	29.9 19.2	1.475	41.3	23.1 15.7
20	1.711	65.0	38.0 22.2	1.570	54.5	34.7 22.1
40	1.713	68.8	40.0 23.4	1.555	56.7	36.5 23.5
60	1.639	65.5	40.0 24.4	1.515	56.7	37.3 24.6
80	1.613	61.2	38.0 23.6	1.506	51.5	34.2 22.7

* Stature with shoes +Mass with indoor clothing ** Present author's calculation

pugilists and wrestlers. He demonstrated very clearly that the information on height-adjusted lung volumes was correlated with the risk of various chronic diseases (particularly tuberculosis and cardiac conditions).

Hutchinson also noted that "*weight did influence the vital capacity when it became remarkable or in excess*," but admitted to some difficulty in deciding when the weight of an individual was excessive. He took a binary view of body mass (normal or excessive), ignoring the possibility that a large body mass might be attributable to muscular development. Thus, he assumed that if the norm for height was a mass of 10 stones, but the actual weight was 14 stones, *"every ounce increasing upon 10 stone tends towards corpulency*." His data on height and body mass were for a time used and acclaimed by Actuaries in both England and the U.S., as can be seen in this unqualified endorsement of his research (Bishop, 1977):

> *"we have no hesitation in recording our deliberate opinion, that it forms one of the most valuable contributions to physiologic science that we have met with for some time. In all future investigations into the phenomena of the respiratory process, the name of Mr. Hutchinson must receive honorable notice. "*

Height-adjusted lung volumes were of considerable relevance to prognosis in Victorian times, when tuberculosis was rampant, but as ischaemic heart disease replaced tuberculosis as the major cause of premature death, interest shifted from height-adjusted vital capacity to height-adjusted body mass, with the latter serving as a surrogate of body fat content.

In 1846, Hutchinson (1846) replicated and expanded the work of Quetelet, publishing a table (Table 3) that showed the average body mass of 3000 English men aged 15-40 years, ranging in height from five feet (1.52 m) to six feet (1.83 m).The data are very similar to those reported by Quetelet a decade earlier (Table 2).

H.C. Fish. H.C. Fish of the Mutual Life Insurance Company of New York published an American table of body build in 1867 (Table 4). It again offered data on the average body mass of individuals from a height of five to six feet, drawing upon the English tables of John Hutchinson, as well as information taken from the Carlisle, the Actuaries, Mutual Life and Massachusetts actuarial experience (Fish, 1867). The published data are closely comparable with those found in the two preceding tables (Tables

2 and 3).

Actuarial tables of ideal weight

As the insurance industry began to appreciate the substantial effects of an excessive body mass upon prognosis, it was no longer assumed that the average body mass found at any given height was the "ideal" (or the "desirable" value, as it was termed in the 1959 Build and Blood Pressure study) for the individual concerned. Rather, the focus shifted to values that were associated with the greatest life expectancy. Notice that the focus was strictly upon survival, and no consideration was given to either morbidity or the person's quality of life. The most widely used tables of ideal weights were those published by the Metropolitan Life Insurance Company.

Table 3: Clothed body mass in relation to standing height, as seen in a sample of 3000 Englishmen aged 15-40 years (Hutchinson, 1846).

Height range (in)	Average body mass (lb)	Average height (m)*	Average body mass (kg)*	BMI (kg/m²)*
54-60	92.26	1.45	41.9	20.0
60-61	115.52	1.54	52.5	22.1
61-62	124.33	1.56	56.5	23.2
62-63	127.86	1.59	58.0	22.7
63-64	138.01	1.61	62.7	24.2
64-65	139.17	1.64	63.3	23.5
65-66	144.93	1.66	65.9	23.9
66-67	144.29	1.69	65.6	22.7
67-68	152.59	1.71	69.2	23.9
68-69	157.76	1.74	71.7	23.7
69-70	166.40	1.77	75.6	24.1
70-71	170.86	1.79	77.7	24.0
71-72	177.45	1.82	80.7	24.4
72+	218.66			

*Calculated by present author.

Table 4: Average height and body mass tables for American men (Fish, 1867).

Height (in)	Body mass (lbs)	Height (m)*	Body mass (kg)*	Body Mass Index (kg/m²)*
61	120	1.55	54.5	22.7
62	125	1.57	56.8	23.0
63	130	1.60	59.1	23.1
64	135	1.63	61.4	23.1
65	140	1.65	63.6	23.4
66	143	1.68	65.0	23.0
67	145	1.70	65.9	22.8
68	148	1.73	67.3	22.5
69	155	1.75	70.5	23.0
70	160	1.78	72.7	22.9
71	165	1.80	75.0	23.3
72	170	1.83	77.3	23.1

*Calculated by present author.

Early tables of ideal weights. The Actuarial Society of America was founded in 1889, and their first table of recommended values for body mass, based on longevity, appeared in 1912 (Table 5). The table was developed from information that had been abstracted from life insurance policies purchased (usually by young adults) between the years 1885 and 1908. Further actuarial figures, collected through to the year 1927, were so similar to the original data set that it was not thought necessary to revise life tables during the 1920s.

Dublin and Lotha (1937) extended their data base to a sample of four million policy holders who had been insured by the Metropolitan Life Insurance Company over the period 1911-1935. The ideal body mass for height was classified by subjective estimates of the individual's body frame (rated as large, medium or small). A body mass 20-25% above the recommended value was considered as undesirable, and a 70-100% excess was considered as evidence of morbid obesity. A reworking of Dublin and Lotha's data (Metropolitan Life Insurance, 1942) eliminated age adjustments, and set the ideal body mass for a given height at levels seen in a 25-year old person with the same frame size. The table specified a range of weights rather than a single ideal body mass for a given height, and it placed the threshold of obesity at a body mass 20% above the ideal value.

1959 Build and Blood Pressure Study. Calculations of "*desirable weights*" for the 1959 study (Society of Actuaries, 1959) were based on the experience of 26 life insurance companies in the U.S. and Canada. The data base comprised individuals who had been insured during the years 1935 to 1953. The body frame size was now defined semi-objectively (in terms of elbow breadth relative to the individual's height), although not all study participants included this adjustment when reporting their data (Society of Actuaries, 1959). The main weakness in the 1959 tables is that some 20% of the height and body mass values were self-reported rather than measured. Self-estimates are notoriously inaccurate. In one survey, Hill and Roberts (1998) demonstrated that 84% of people over-reported their standing height, and that 74% under-reported their body mass. Moreover, as in most insurance company data, in those patients where the data were actually measured, the height was distorted by wearing shoes with varying heel heights, and the body mass was sometimes increased by the wearing of heavy clothing; further, in some cases arbitrary corrections were made for both of these factors

Second (1979) Build and Blood Pressure Study. Further modifications to the actuarial tables were introduced in 1983, based on the 1979 body build study (Metropolitan Life Insurance, 1983; Society of Actuaries, 1980). The new standards covered the mortality experience of individuals who were insured from 1950 to 1972, and the "desirable" values were somewhat greater than those adopted in the1959 study. The 1979 data for height and body mass (Table 6) today remain the most widely used reference standards.

Other height and weight norms

Hathaway and Foard. An analysis somewhat similar to that of the insurance companies was carried out by Hathaway and Foard (1960; 1961), based on data for 60,000 U.S. students entering university between 1949 and 1950.

Hathaway and Foard were more precise than other investigators, since their subjects were invariably weighed nude, and height was measured without shoes.

Table 5: Published tables, showing the body mass for a given standing height in terms of life expectancy, based in part on information collected by Komaroff (2016).

Author	Information presented	Population	Adjustments made for clothing	Outcome
Association of Life Insurance Medical Directors (1912)	M & F body mass vs. height tables classified by age,	Insured U.S. population	Arbitrary seasonal adjustments for clothing	Ideal body mass based on longevity
Dublin & Letha (1937)	M & F body mass by height, classified by body frame	4 million people insured by Met. Life 1911 to 1935	Wearing street shoes, indoor clothing	Ideal based on lowest mortality; bad weight if 20-25% excess, morbid obesity if 70-100% excess
Metropolitan Life Insurance (1942)	M & F body mass by height, classified by body frame, norms maintained at level seen at age 25 yr	4 million people insured by Met. Life 1911 to 1935	Wearing street shoes, indoor clothing	Obese if 20% excess over ideal body mass
Build and blood pressure study (Society of Actuaries, 1959)	M & F body mass by height, classified by body frame	Data from 26 life insurance companies in U.S. and Canada 1935 to1954 (20% of data self-reported)	Wearing street shoes, indoor clothing	Ideal is minimum mortality, obese if 20% over ideal body mass
Hathaway and Foard (1960)	M & F body mass by height (low, median and high)	60,000 U.S. university entrants aged 20 to 25 yr, 1949-1950	Weighed nude, without shoes	Authors interested mainly in secular and regional trends in growth
Bray (1975)	Based on 1959 Build and blood pr4essure study data	4 million people insured by Met. Life 1911 to 1935	With street shoes, indoor clothing	Acceptable weights BMI (kg/m^2) of 20.1-25.0 for men, 18.7-23.8 for women
U.S. Department of Agriculture (1980)	Based on 1959 Build and blood pr4essure study data	4 million people insured by Met. Life 1911 to 1935	Without shoes of clothes	Acceptable ranges BMI (kg/m^2) of ~ 20.0-25.2 for men, 18.5-25.2 for women
National Institutes of Health (1985)	NHANES II data			Specified thresholds of BMI (kg/m^2) for overweight/obesity (27.2 M, 26.9 F)
World Health Organisation (1984)	Mortality curve	International data		

Table 6: 1999 Metropolitan Life Insurance table of 1979, relating standing height (when wearing shoes)+ to body mass (when wearing indoor clothing)* for men aged 25-59 yr classified according to the observer's estimate of an individual's body frame.

Height (cm)	Small Frame (kg)	Medium Frame (kg)	Large Frame (kg)
158	58.3 - 61.0	59.6 - 64.2	62.8 - 68.3
159	58.6 - 61.3	59.9 - 64.5	63.1 - 68.8
160	59.0 - 61.7	60.3 - 64.9	63.5 - 69.4
161	59.3 - 62.0	60.6 - 65.2	63.8 - 69.9
162	59.7 - 62.4	61.0 - 65.6	64.2 - 70.5
163	60.0 - 62.7	61.3 - 66.0	64.5 - 71.1
164	60.4 - 63.1	61.7 - 66.5	64.9 - 71.8
165	60.8 - 63.5	62.1 - 67.0	65.3 - 72.5
166	61.1 - 63.8	62.4 - 67.6	65.6 - 73.2
167	61.5 - 64.2	62.8 - 68.2	66.0 - 74.0
168	61.8 - 64.6	63.2 - 68.7	66.4 - 74.7
169	62.2 - 65.2	63.8 - 69.3	67.0 - 75.4
170	62.5 - 65.7	64.3 - 69.8	67.5 - 76.1
171	62.9 - 66.2	64.8 - 70.3	68.0 - 76.8
172	63.2 - 66.7	65.4 - 70.8	68.5 - 77.5
173	63.6 - 67.3	65.9 - 71.4	69.1 - 78.2
174	63.9 - 67.8	66.4 - 71.9	69.6 - 78.9
175	64.3 - 68.3	66.9 - 72.4	70.1 - 79.6
176	64.7 - 68.9	67.5 - 73.0	70.7 - 80.3
177	65.0 - 69.5	68.1 - 73.5	71.3 - 81.0
178	65.4 - 70.0	68.6 - 74.0	71.8 - 81.8
179	65.7 - 70.5	69.2 - 74.6	72.3 - 82.5
180	66.1 - 71.0	69.7 - 75.1	72.8 - 83.3
181	66.6 - 71.6	70.2 - 75.8	73.4 - 84.0
182	67.1 - 72.1	70.7 - 76.5	73.9 - 84.7
183	67.7 - 72.7	71.3 - 77.2	74.5 - 85.4
184	68.2 - 73.4	71.8 - 77.9	75.2 - 86.1
185	68.7 - 74.1	72.4 - 78.6	75.9 - 86.8
186	69.2 - 74.8	73.0 - 79.3	76.6 - 87.6
187	69.8 - 75.5	73.7 - 80.0	77.3 - 88.5
188	70.3 - 76.2	74.4 - 80.7	78.0 - 89.4
189	70.9 - 76.9	74.9 - 81.5	78.7 - 90.3
190	71.4 - 77.6	75.4 - 82.2	79.4 - 91.2
191	72.1 - 78.4	76.1 - 83.0	80.3 - 92.1
192	72.8 - 79.1	76.8 - 83.9	81.2 - 93.0
193	73.5 - 79.8	77.6 - 84.8	82.1 - 93.9

*Indoor clothing weighing 2.3 kilograms; +Shoes with 2.5 cm heels

Source of basic data: Body Build Study, 1979. Society of Actuaries and Association of Life Insurance Medical Directors of America,1980. Courtesy of the Metropolitan Life Insurance Company.

The primary objective of their study was to look at secular and regional trends in growth, and low, median and high values were tabulated in relation to stature. Nevertheless, the final results did not differ greatly from the data collected by the Society of Actuaries (above). For instance, men with a height of 1.73 m had a median body mass of 68.6 kg, compared with a range of 63.2-68. 7 kg for insurance clients rated as having a medium body frame.

Fogarty International Conference Center, 1973. A meeting held at the Fogarty International Conference Center (Bethesda, MD) in 1973 re-examined data from the 1959 Build and Blood Pressure Study, proposing an "acceptable" range of body mass in terms of BMI (20.1-25.0 kg/m^2 for men,18.7-23.8 kg/m^2 for women) (Bray, 1975).

U.S. Department of Agriculture, 1980-2010. In a health promotional booklet for the U.S. population ("*Nutrition and your Health, 3rd ed."),* the U.S. Department of Agricultural published acceptable ranges of body mass in relation to height (without shoes or clothes). For example, with a height of 1.73 m, the suggested acceptable ranges of body mass were 60.1 - 75.5 kg in men and 55.5 - 70 kg in women (corresponding to BMIs of 20.0-25.2 kg/m^2 in men and 18.5-25.2 kg/m^2 in women respectively). The 1995 edition of the same pamphlet (U.S. Department of Agriculture, 1995) lowered the acceptable body mass range slightly (for instance, in men the acceptable range for a height of 1.73 m decreased to 56.8-74.5 kg, and it was emphasized that the upper limits of body mass applied only to men with heavy muscles and bone structure). A further edition of the nutritional guide, published in 2000 (U.S. Department of Agriculture, 2000), presented recommended values in the form of a graph; it specified that a healthy body mass corresponded to a BMI in the range 18.5-25.0 kg/m^2. The most recent edition of this nutritional guide (2010) matched the body mass criteria set by the World Health Organisation, below (U.S. Department of Agriculture, 2010).

U.S. National Institutes of Health, 1985. Guidelines published by the National Institutes of Health (1985) suggested that an individual's body mass should not rise more than 20% above the upper limit of the normal range. Using the 1983 tables, this would correspond to a threshold BMI for overweight/obesity of 27.2 kg/m^2 in men and 26.9 kg/m^2 in women, and based on the NHANES II data, the respective thresholds for overweight would be 27.8 and 27.3 kg/m^2.

World Health Organisation. The World Health Organisation based their recommendations on a sampling of international data for height and body mass (World Health Organisation, 2008). They set the threshold of overweight at a BMI of 25 kg/m^2, and the threshold of obesity at a BMI of 30 kg/m^2 (although subsequently these values were lowered for some specified Asian populations, see below).

Conclusions. The available tabulations of body mass for height suffer from a number of significant limitations. Perhaps most importantly, the majority of tables are not based upon a random sample of the North American population, but rather reflect values reported by people who had the necessary surplus income to purchase life insurance or to enroll in specific universities. Moreover the data in general have been poorly standardized, often reflecting self-reported values for height and body mass (Wing, Epstein, and Ossip, 1979) or, in the case of measured data, values that have been inappropriately adjusted for shoe heights and/or the weight of clothing. Finally, most of the measurements have been made on young adults. It has been assumed that no age adjustments are needed, a point that has been vigorously contested by Andres (1985). In fact, body mass decreases in most elderly people because of a loss of bone mass and lean tissue, and it seems unlikely that the finding of a given BMI in the elderly has the same implications for morbidity and mortality as would a corresponding BMI when found in a young adult. One empirical study noted that in the elderly a low BMI often reflected muscle wasting or cancer, and that quite a broad range of BMIs was compatible with an optimal mortality experience (Heiat, Vaccarino, & Krumholz, 2001).

Nevertheless, height-for-weight tables, particularly Table 6, are still widely used in clinical practice, and in the average healthy adult they continue to provide some guidance to the practitioner who is recommending a healthy body mass.

Pharmacologic predictions of ideal body mass

Because fat is relatively inert from a metabolic point of view, pharmacologists have found that the breakdown of ingested drugs correlates more closely with a person's lean tissue mass or their "pharmacological ideal body mass" than with their actual body mass. Thus, beginning with Devine (1974), equations have been developed to approximate the pharmacological ideal mass from an individual's height, measured in m, for example:

- Men = 50.0 kg + 91 kg/m
- Women = 45.5 kg + 91 kg/m

Note that the pharmacological ideal mass reflects an individual's metabolic capability, and is helpful in optimizing the dosage of medication, but that it bears little relationship to the body mass that is ideal from the viewpoint of minimizing mortality.

Relationship of height and weight indices to measures of an individual's body fat content

Standing height has a major influence upon a person's healthy body mass, and thus over the centuries various ratios have been used over the centuries when interpreting body mass in terms of the individual's stature. Many early investigators focused on the laws of Archimedes (born 287 BCE) for geometrically similar bodies. Thus, Galileo Galilei (1564-1642 CE) suggested that if animals had a generally similar shape, then the mass of their bodies should be proportional to the cube of their principal linear dimension.

Broca's ideal body mass. Broca’s formula for ideal body mass was developed empirically in 1871 by the French army doctor, anatomist and anthropologist Pierre Paul Broca (1824-1880 CE)(Cho, 1983). The normal body mass in kg was given by: (height in cm—100). The ideal body mass (kg) was then calculated as:

- Ideal mass for men = (height in cm—100) - 0.1(height in cm—100)
- Ideal mass for women = (height in cm—100) - 0.15(height in cm—100)

The Broca index has now largely been abandoned, because it only works well in middle-aged people of average height.

Creff's ideal body mass. Creff's formula sought to improve the Broca index by adding information on the individual's age and a subjective assessment of body build, the slimness factor being 0.9 for "gracile" individuals, 1.0 for normal individuals, and 1.1 for those who were judged as "stocky":

- ideal body mass = H -100 + (age/10) x 0.9 x slimness index

Lorentz ideal body mass. The Lorentz formula for ideal body mass first appeared in 1929 (Nahler, 2013). It is another attempt to improve upon Broca's formula. The equations are:

- Men: ideal body mass (kg) = H(cm) - 100 - ([H, cm -150]/4)
- Women: ideal body mass (kg) = H(cm) - 100 - ([H, cm -150]/2)

History records many similar formulae, associated with the names of investigators such as Hamwi, Devine, Monnerot-Dumaine, Robinson and Devine, all yielding slightly different estimates of the ideal body mass, with some formulae (such as those of Robinson and Devine) interpreting the ideal value in a pharmaceutical rather than a prognostic sense (see above).

Rohrer Index. Probably based on Galileo's hypothesis, in 1921 the Swiss physician Fritz Rohrer proposed calculating a "corpulence index" (M/H^3) in order to make inter-individual comparisons of body mass (Rohrer, 1921). This measure is also known as the Rohrer index or the Ponderal index. Sheldon and his associates supported use of the M/H^3 ratio in assessments of obesity, although they commented that it was "*by no means an infallible index*" (Sheldon, 1963). Babar (2015) tested the corpulence index against the BMI as a method of predicting a bioelectrical impedance determination of body fat content in the NHANES III study. On three measures (sensitivity, specificity, and predictive value) the corpulence index performed somewhat better than the BMI relative to the impedance standard (Table 7). It also out-performed the Lorentz index and Broca's estimate of ideal body mass.

Some investigators still argue that body mass should be standardized against the third rather than the second power of linear dimensions, since tall people with an identical body shape and body composition have a larger BMI than those who are short (Taylor, 2010). Certainly, the corpulence index shows little correlation with standing height, giving similar ratios for short and tall people.

The corpulence index has certainly remained a popular method of assessing obesity in children; for example, Hebbelinck et al. (1973) adopted the Rohrer approach in a Belgian study of child growth and development. However, values of the corpulence index for young

Table 7: Comparison of corpulence index vs. body mass index in the prediction of obesity as measured by a bioelectrical impedance technique, based on the analyses of Babar (2015).

Measure	Sensitivity	Specificity	Predictive value
Corpulence index	57.9%	74.6%	72.3%
Body mass index	51.8%	71.1%	67.2%

children are about twice as large as those for adults, because the children have relatively short legs. And as we will see below, body fat content usually shows a closer correlation with M/H^2 than with M/H^3.

Objections to simple obesity indices based on height and body mass. There are several practical objections to any simple manipulation of height and body mass as an index of obesity. These include the rightward skewing of body mass data in the obese, the assumption inherent in the calculation of any ratio that the relationship passes through the origins of both axes, and (perhaps most seriously) the fact that the body is not spherical in shape, but rather consists of a series of truncated cones (Ross et al., 1982; Van der Walt et al., 1986). Some investigators have thus made plots of body mass against the logarithm of standing height, finding exponents of 1.92 to 1.96 for adult males, of 1.45 to 1.95 for adult females and in some instances exponents as high as 2.6 for children (Diverse Populations Collaborative Group, 2005; Levitt et al., 2007).

Theoretical arguments can be advanced for a variety of formulae, and it is thus helpful to look further at empirical relationships between some of the more commonly used potential "objective" indices of body fat content. One analysis of data for 518 Canadian city dwellers found that 72% of the variance in an estimate of body fat content obtained from eight skin-fold measurements was described by a three-term multiple regression equation, using (in order of their contribution to the overall variance) body mass, height, and height^2 (Shephard et al., 1969). Further analyses conducted in a sample of 27 boys and 29 girls aged 10-12 years, used the percentage of body fat determined by underwater weighing as an objective reference value (Shephard et al., 1971). In this sample, the skin-fold measurements proved substantially superior to any of the simpler height/weight indices, but in terms of correlation coefficients there was little to choose between the predictive values of various manipulations of height and body mass (Table 8).

In two U.S. populations (university students and executives), Ancel Keys and his colleagues (Keys et al., 1972) compared various indices with underwater weighing data. They claimed from their results that M/H^2 was superior to other simple indices of obesity, although their data apparently pointed to essentially the same conclusion as that

Table 8: Coefficients of correlation between underwater weighing estimates of body fat content and simpler field methods of estimating body fat, based on data obtained on 27 boys and 29 girls aged 10-12 years (Shephard et al., 1971).

Field measure of obesity	Correlation with underwater weighing data	
	Boys (n = 27)	Girls (n = 29)
Sum of 3 IBP skinfolds	0.55	0.61
M/H	0.41	0.38
M/H^2	0.37	0.51
$H/M^{1/3}$	-0.24	-0.47
Telford index*	0.46	0.47
Excess body mass+	0.29	0.50

* The Telford index is given by M/H (330-age [months]/270) in boys, and by M/H (308-age[months]/235) in girls. + The excess body mass is calculated relative to a pooling of standard growth charts for children in Edinburgh and Iowa.

reached from Table 8, with only marginal (and statistically insignificant) differences in correlation coefficients between the various potential options (Table 9). In a large sample of adults drawn from various countries, the correlations between underwater weighing and skin-fold data (mostly the mean of triceps and subscapular measurements) were greater than those for M, M/H, M/H^2 or M/H^3; in seven of 11 samples the closest of the mass/height correlations was for M/H^2, and in 4 of 11 the closest relationships was for M/H (Table 10).

Conclusions. We may conclude that when comparing people of rather similar heights but with varying degrees of obesity, the choice of mass/height ratio is not a major issue. Empirical data generally support the use of M/H^2, and M/H is also superior to M/H^3, but skin-fold data give a closer prediction of body fat than any manipulation of height and body mass.

Body mass index

Calculation of the body mass index (body mass in kg, divided by the square of standing height in metres) as a means for the height standardization of body mass was first suggested by Quetelet many years ago (above). This ratio was originally known as the Quetelet index; the currently used term of body mass index (BMI) was first introduced in a 1959 report on the somatotypes of dogs (Dimascio, 1959).

Normal values. The data of Quetelet and Hutchinson (Table 2 and 3) and early actuarial data all placed norms for young adults at around 23.5 kg/m^2, but by the 1980s, the average BMI for young U.S. males had increased to around 27.5 kg/m^2. This seemingly shows a secular trend to a substantial increase of body fat content, although longitudinal comparisons of population BMIs are complicated by secular trends to an earlier maturation and an increase of standing height in most people from developed countries (Malina, 2004; Waller and Brooks, 1972).

The World Health Organisation has pushed extensively for use of the body mass index as a method of monitoring the prevalence of obesity since the 1980s (World Health Organisation, 1995), and this has now become the ratio preferred by most epidemiologists The original WHO proposals classed individuals with a BMI > 25 kg/m^2 as overweight, and those with values > 30 kg/m^2 as obese. These norms were based on actuarial data for young (mainly white) American adults, and do not necessarily apply to other populations with a different body build or ethnicity (Levitt et al., 2007). Thus, with the support of the WHO, the threshold of

Table 9: Coefficients of correlation between underwater weighing estimates of body fat content and simpler field methods of estimating body fat, based on data obtained on large samples of U.S. adults (Keys et al., 1972).

Field measure of obesity	Correlation with underwater weighing data	
	U.S. students (n = 180)	U.S. executives (n = 249)
Skin-folds (sum of triceps + subscapular)	0.85	0.82
M	0.78	0.62
M/H	0.83	0.66
M/H^2	0.85	0.67
Ponderal index (M/H^3)	0.79	0.66

overweight for South East Asians living in Hong Kong and Singapore, has more recently been lowered to 23 kg/m^2.

BMI standards for children. It is plain from a number of the tables published above that the adult norms of BMI cannot be applied to children. The U.S. Centers for Disease Control (CDC) calculated BMI standards for children aged 2-20 years using the same M/H^2 formula but evaluating individual status on an age- and sex-specific percentile grid, based on data that the CDC had collected over this age range. Those falling above the sex-specific 85th percentile for their age were arbitrarily considered as overweight, and those over the 95th percentile were rated as obese (Figure 3). In boys aged 12 years, the critical values defining overweight and obesity would, on this basis, correspond to BMIs of 21 and 24 kg/m^2 respectively, and in girls to BMIs of 21.7 and 25.4 kg/m^2. Incidentally, such standards are substantially above the average values noted for children of this age in some early surveys.

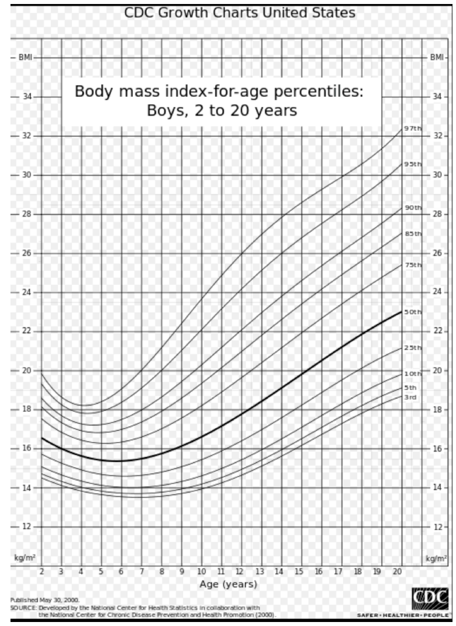

Figure 3: Percentile grid for evaluating the BMI of children, based on CDC data for U.S. boys aged 2-20 years. Source: https://upload.wikimedia.org/wikipedia/commons/c/cd/BMIBoys_1.svg

The International Obesity Task Force proposed the setting of pediatric

Table 10: Correlations between summed skin-folds and various indices of obesity in multiple adult populations (based on the data of Keys et al. (1972). The closest correlations are shown in bold type.

Population & number of subjects	M	M/H	M/H^2	M/H^3
134 University students	0.777	0.833	**0.850**	0.790
248 Executives	0.723	0.771	**0.777**	0.736
116 Bantu	0.724	**0.756**	0.732	0.629
499 Japanese farmers	0.567	**0.613**	0.611	0.521
926 sedentary RR workers	0.679	0.747	**0.757**	0.691
871 RR switchmen	0.700	0.761	**0.774**	0.728
997 E. Finland	0.708	0.773	**0.791**	0.710
836 W. Finland	0.769	**0.804**	0.799	0.718
978 Crev. Italy	0.664	0.706	**0.711**	0.659
636, Monte, Italy	0.750	0.793	**0.797**	0.732
802 Rome, Italy	0.736	**0.768**	0.762	0.705

standards by back-extrapolation of the BMI data observed in six countries (U.K., USA, Netherlands, Brasil, Singapore, and Hong Kong) at the age of 18 years (18 years being the oldest age set available for Hong Kong students) (Cole and Lobstein, 2012). Age and sex-specific standard deviations from the mean and percentiles were calculated at all ages from 2-18 years (Table 11). Thresholds were specified for gross obesity (corresponding to adult values >35 kg/m^2), obesity (adult BMI 30 kg/m^2), overweight (adult BMI 25 kg/m^2), and excessive thinness (grade 1, 18.5 kg/m^2; grade 2, 17 kg/m^2; grade 3, 16 kg/m^2). In general, differences between the Task Force and the WHO standards were minimal. However, it remains debatable whether norms should be reworked for Asian populations, setting the adult threshold of overweight in Asian populations at 23 kg/m^2.

Relationships between an individual's BMI and the risk of disease. People who are overweight or obese are at an increased risk of premature death (World Health Organisation, 1984). They also have an increased risk of developing a wide variety of chronic clinical conditions, including coronary artery disease, hypertension and stroke, dyslipidaemia, type 2 diabetes mellitus, various types of cancer, gall bladder disease, osteoarthritis, and sleep apnoea (Pi-Sunyer, 1998), with the likelihood of some of these outcomes increasing above a BMI as low as 20 kg/m^2 (Table 12).

A study of 900,000 adults found that the optimal range of BMIs in terms of mortality rates was 22.5-25.0 kg/m^2 (Prospective Studies Collaboration, 2009), but a more controversial analysis found no substantial increase of risk with a BMI <29 kg/m^2 (Campos, Saguiy, & Ernsberger, 2006). The latter point of

Table 11: International Obesity Task Force cut-offs on age and sex specific distribution curves corresponding to the BMI reached by specified percentiles at an age of 18 years (Cole & Lobstein, 2012).

	Boys		Girls	
BMI at age 18 yr (kg/m^2)	Standard deviation	Percentile	Standard deviation	Percentile
>35 (gross obesity)	2.93	99.8	2.82	99.8
>30 (obese)	2.29	98.9	2.19	98.6
>25 (overweight)	1.31	90.5	1.24	89.3
<18.5 (underweight 1)	-1.01	15.5	-0.98	16.5
<17 (underweight 2	-1.88	3.0	-1.79	3.7
<16 (underweight 3)	-2.57	0.5	-2.44	0.7

Table 12: Relationship between body mass index and cardiac risk factors, as seen in cross-sectional data from the NHANES III study.

	Men				Women			
BMI (kg/m^2)	<25	25-26	27-29	>30	<25	25-26	27-29	>30
Hypertension[1]	18.2	22.5	25.2	38.4	16.5	21.9	24.0	32.2
Cholesterol[2]	14.7	17.5	20.4	20.2	15.7	27.9	28.2	24.7
Low LDL cholesterol[3]	9.1	17.2	23.1	31.4	16.5	27.0	27.2	41.5

[1]NHANES III data, systolic >140 mmHg, diastolic > 90 mm Hg or taking antihypertensive medication.
[2.]NHANES III data, serum cholesterol >240 mg/dL
[3]NHANES III data, LDL cholesterol <35 mg/dl (M), <45 mg/dL (F)

view was seemingly supported in a meta-analysis of 97 studies embracing 2.88 million individuals and 270,000 deaths (Flegal et al., 2013). Hazard ratios for all-cause deaths were 0.94 for those with a BMI in the range 25.0-29.9 kg/m^2, and 0.95 for grade I obesity (BMI <35 kg/m^2), only rising to 1.29 for grades 2 and 3 obesity (BMI > 35 kg/m^2). One difficulty in accepting such risk estimates is that several conditions associated with a reduced life-expectancy, such as existing chronic disease or a history of smoking, tend to be associated with a below average body mass, skewing optimal population survival values in an upward direction. A subsequent investigation of data for 9.98 million people participating in 230 cohort studies (Aune, Sen, and Prasad, 2016) recognized this issue, suggesting that calculations should be limited to studies with a long follow-up period (to avoid issues of pre-existing disease), and should be confined to people who had never smoked (Table 13). Using this more cautious approach, one reaches the generally accepted conclusion that the optimal BMI lies in the range 22-23 kg/m^2.

Limitations of BMI as a measure of body fat content. The use of the BMI to assess body fat content is open to a number of specific criticisms. It has proven a helpful simple measure to use in epidemiological studies of middle-aged adults, where the usual cause of an increase in body mass is an accumulation of fat, but unadjusted values are generally inappropriate for children, for athletes (where excess weight may reflect muscle rather than fat), and the elderly and those with various types of chronic disease (where a decrease of body mass due to a loss of lean tissue and osteoporosis may mask an accumulation of fat).

Although the BMI has quite a high specificity as a means of identifying obesity, it has a poor sensitivity relative to bioelectrical impedance measures of body fat content. Thus, in the NHANES III survey of 13,601 U.S. adults aged 20-79.9 years, the specificity of BMI for those with values > 30 kg/m^2 was 95% for men and 99% for women; however, the sensitivity of this same threshold was only 36% for men and 49% for women (Romero-Corral et al., 2008), implying that the use of BMI leads to a substantial under-diagnosis of the prevalence of obesity. Interestingly, the correlation of BMI with lean tissue mass in the NHANES III survey (r = 0.50 in men, 0.55 in women) was similar to the correlation seen with body fat content (r = 0.44 in men, 0.71 in women); this in itself seems a major limitation to the use of the BMI, except in people who are grossly obese. Further, the diagnostic performance relative to measurements with a simple bioelectrical impedance

Table 13: Relationships between BMI and mortality relative to that observed at a BMI of 23 kg/m^2, showing the need to limit data to non-smokers (based on the analysis of Aune et al. (2016).

BMI (kg/m2)	All subjects	Non-smokers	Healthy non-smokers	Smokers
20	1.15	1.10	1.03	1.19
23	1.00	1.00	1.00	1.00
25	0.97	1.01	1.03	0.96
27.5	0.98	1.07	1.11	0.99
30	1.04	1.20	1.24	1.08
35	1.29	1.65	1.66	1.48
40	1.74	2.50	2.37	2.32

device was even poorer in the elderly than in middle-aged adults. Finally, the BMI does not differentiate between a gynecoid distribution of accumulated fat and the metabolically more harmful android type of obesity.

In looking at individual rather than grouped values, it seems likely that the "ideal" body mass should differ by 10 kg or more between small- and large-framed people, yet most interpretations of BMI makes no allowance for frame size. Further, the BMI fails to take account of decreases in stature associated with the normal aging process, and the values designated as minimizing the risk of various chronic conditions fail to take account of sex differences in the magnitude of these risks. Finally, a change of lifestyle can improve health prospects even if there is no change in a person's BMI; if the body fat content remains fairly high, an active person who is overweight still has a lower metabolic risk and better survival prospects than a sedentary person who is overweight (Lee et al., 2005). A sample of 297 men aged 45-50 years receiving a comprehensive medical examination were categorized in terms of their treadmill endurance times (corresponding to maximal oxygen intakes of 29.7, 36.2 and 44. 3 ml/[kg.min]. Multiple regression equations linked their metabolic risk factors to a magnetic resonance image of visceral fat (V, cm^2) and age (A, years) as follows:

Triglycerides (mg/dL):

- Low fitness = 183.1 - 1.21 (A) + 0.48 (V)
- Moderate fitness = 156.5 - 1.21 (A) + 0.48 (V)
- High fitness = 129.5 - 1.21 (A) + 0.48 (V)

HDL cholesterol (mg/dL)

- Low fitness = 30.1 + 0.33 (A) - 0.06 (V)
- Moderate fitness = 35.9 + 0.33 (A) - 0.06 (V)
- High fitness = 37.4+ 0.33 (A) - 0.06 (V)

Systolic blood pressure (mm Hg)

- Low fitness = 85.7 + 0.28 (A) + 0.14 (V)
- Moderate fitness = 97.3 + 0.28 (A) + 0.07 (V)
- High fitness = 106.0 + 0.28 (aA) + 0.02 (V)

Further, an eight-year follow-up of 21,925 men attending the Cooper Clinic in Dallas, TX, found that after adjusting for age, examination year, smoking habits, alcohol use, and parental history of ischaemic heart disease, the all-cause mortality for a given level of obesity was 2.07 times greater in those who were unfit than in those who were fit (Avicenna, 1999).

Conclusions. Although the various height/body mass relationships have the attraction of simplicity for use in large-scale epidemiological obesity surveys, they all suffer from important limitations.

We have already noted the problem that fat is not distinguished from muscle (causing problems when assessing both muscular athletes and elderly individuals with sarcopaenia or osteoporosis). Another significant issue is that many aspects of body build (including the relationship of leg to trunk length) differ significantly from one population to another. Thus, a short leg length and substantial muscularity have caused Inuit and other indigenous groups to be classed incorrectly as having an "excessive" body mass relative to the height-based norms of U.S. urban populations, leading to the erroneous inference that the indigenous groups concerned were obese (Nutrition Canada, 1973). In fact, the average skin-fold readings for traditional Inuit are much smaller than those seen in healthy "white" populations. On the basis that they had a BMI >30 kg/m^{2,} Young (1994) classified the prevalence of obesity in Inuit men from various Arctic coastal settlements as 24% in those aged <35 years and 43% in those aged 35-49 years. However, this high BMI has existed from the earliest historical records (1901-1923), when the Inuit populations concerned were highly active and had limited access to food, with little likelihood that they were obese.

Finally, if an obesity treatment programme is assessed on the basis of changes in body mass, and if a programme of vigorous exercise has replaced body fat by an equal mass of muscle and the water associated with increased glycogen storage, then the incorrect conclusion may be drawn that there has been little fat loss in response to therapy.

Circumference measurements

An alternative simple field method of estimating obesity is to look at specific body circumference measurements. To allow for inter-individual differences in body size, waist circumferences are usually assessed relative to standing height, chest and/or hip circumferences. When making such measurements, substantial errors can arise if tape measures are not placed at carefully designated sites (Daniell et al., 2010).

Waist circumference-height ratios. In adults, the highest waist circumference-height ratio corresponding to a good health prognosis is 0.50. Typically, a ratio of 0.51 corresponds to a BMI of 25 kg/m^2 (the generally accepted threshold of overweight), and a value of 0.57 corresponds to a BMI of 30 kg/m^2 (the usual threshold of obesity). Combining data from a 3.3 year follow-up of 6,355 participants and an 8.5-year follow-up of 4297 participants, one study demonstrated that interpretation of the waist circumference-height ratio gave a much better prediction of future cardiac incidents than use of the BMI (Schneider et al., 2010). Comparing the lowest versus the highest quartiles, the relative risks of future cardiovascular events were 2.75 and 1.35 in terms of circumference ratios and BMIs, respectively, and the corresponding relative risks for all-cause mortality were 1.86 and 1.30. In this data series, after adjusting for multiple confounders, the waist/height ratio also out-performed the waist circumference and the waist-hip ratio, with BMI having substantially less prognostic value than any of the circumference-based indices, presumably because the BMI does not distinguish either the abdominal component of obesity, or an increase of body mass due to muscular development (Table 14).

A substantial number of other reports have commended abdominal fat as a preferred predictor of cardiovascular risk factors, cardiovascular events and all-cause death (for example (Bennasar-Veny et al., 2013; Cox and Whichelow, 1996;

Table 14: Relative risk of future cardiovascular events and all-cause mortality in highest vs. lowest quartile with respect to selected obesity indices (based on data of Schneider et al. (2010).

Health problem	Waist/height ratio	Waist circumference	Waist/hip ratio	1/BMI
Future cardiovascular disease	2.75	1.74	1.71	1.35
All-cause mortality	1.86	1.62	1.36	1.30

Gelber et al., 2008; Ho et al, 2003; Lapidus et al., 1984; Larsson et al., 1984; Lee et al., 2008). Ho et al. (2003) reported that in terms of predicting 11 cardiovascular risk factors and related conditions, the waist circumference-stature ratio had greater diagnostic value than waist-hip ratio or waist circumference, with the first of these three potential indices having an optimal upper limit of 0.48 in both men and women. Gelber et al. (2008) followed 16,332 older men for 14.2 years, and 32,700 older women for 5.5 years, using the same indices as Schneider et al. (2010). All four of these measures predicted future cardiovascular disease, but the most precise indication was again given by the waist circumference/height ratio. After adjusting for confounders, the relative risks of cardiovascular disease for the lowest and the highest waist/height ratios were 0.58 vs. 2.36 in men, and 0.65 vs. 2.33 in women. A meta-analysis of studies reporting receiver operating characteristics and areas under the curve for various indices of abdominal obesity further underlined that the waist circumference/height ratio provided the best discrimination of the risks of hypertension, diabetes and dyslipidaemia in both sexes (Lee et al., 2008).

In a study of various North American Indian populations, Young (1994) noted that the highest waist circumference/height ratios were seen in Cree and Ojibway samples (0.94-0.99 in men and 0.90-0.93 in women). Young commented that these two indigenous groups had undergone the greatest acculturation to a sedentary "western" lifestyle during recent years.

Waist-hip ratios. One report suggested that the prognostic value of the waist-hip ratio surpassed that of the waist circumference/height ratio in terms of predicting mortality from ischaemic heart disease, particularly if data were adjusted for BMI, and thus combined information on both general obesity and abdominal obesity (Mørkedal et al., 2011). However, the experience of most other investigators has been that the waist circumference/height ratio provides a slightly better identification of those at risk than does the waist-hip ratio (Lee et al., 2008).

The waist-hip ratio is correlated with age, total body fat, and abdominal fat content, but unlike circumference measurements, values do not always decrease with weight loss programmes. The waist-hip ratio has sometimes been considered as an indicator of abdominal fat, but again this is not always the case. The WHO considers a waist-hip ratio > 0.85 in men and 0.90 in women as evidence of obesity (World Health Organisation, 2008), while the U.S. National Institutes of Diabetes, Digestive and Kidney Diseases have set the male and female obesity thresholds at 0.80 and 1.00 respectively.

Waist circumferences. The simplest measure of abdominal obesity is the unadjusted abdominal circumference. It is closely correlated with BMI and total body fat content. It also shows a limited relationship to height (Felson et al., 1997), although the influence of height increases if the data is adjusted for age, and as seen above height-adjusted values generally provide a better indication of metabolic risk than the unadjusted data. Most investigations have shown that circumference alone has a poorer discriminatory value than size-adjusted ratios. Nevertheless, the NHANES III survey found a better prediction of metabolic risk factors from the waist circumference than from the BMI (Zhu et al., 2002).

A consensus report from the WHO

pointed to an increase of metabolic complications if the unadjusted waist circumference exceeded 102 cm in men, or 88 cm in women (Deurenberg-Yap and Seidell, 2003). Janssen et al. (2004) emphasized that waist circumference rather than body mass index explains the health risk that is associated with obesity. Thus, BMI data have shown no relationship to the risk of hypertension, dyslipidaemia or the metabolic syndrome after statistical adjustment of data for inter-individual differences in waist circumference.

Hip circumferences and adiposity indices. Although less useful than the waist circumference or the waist-circumference-height ratio, the hip circumference alone shows a moderate relationship to overall body fat content (coefficient of correlation r = 0.60). Some authors have also calculated an adiposity index as:

- Adiposity Index = 100 [(hip circumference, m)/height$^{3/2,}$ m] - 18

The relationship between the adiposity index and body fat content as estimated by dual energy absorptiometry is quite close (coefficient of correlation r = 0.85). However, a large study of Spanish adults confirmed that cardiovascular risk factors showed the largest correlation with waist-circumference/height ratios, and that the correlation of risk with the adiposity index was lower than with either the BMI or the waist circumference (Bennasar-Veny et al., 2013).

Waist-to-chest circumference ratios. The waist-to-chest circumference ratio is commonly used to determine the sexual attractiveness of appearance rather than a person's risk of ill-health. Ideal values for men are in the range 0.74-0.77, with low ratios usually implying a predominance of sexually desirable chest muscle relative to abdominal fat. Ratios are also moderated by ethnic origin. Values for Inuit men aged 20-40 years averaged 0.85, and for nGnassan men, the ratio was 0.86. Both of these groups had relatively little abdominal fat when they were first evaluated (around 1970) (Rode and Shephard, 1994), but they have subsequently tended to replace muscle by a masculine distribution of body fat, as they had become acculturated to an "urban" lifestyle.

Conclusions. There seems good evidence that waist circumference measurements provide a preferential simple estimate of obesity. Although the WHO still recommends BMI as the universal field criterion of overweight and obesity, it also encourages supplementing this information by measurements of waist circumference or waist-to-hip ratio.

Skin-fold measurements

Any skin-fold necessarily comprises a double layer of skin and subcutaneous fat. Despite this composite nature of the information that is obtained, measurements of skin-fold thickness provide a simple and popular method of evaluating body fat content.

The concept of measuring skinfolds was first suggested in the early 1920s, and the technique became popular from the early 1950s, when John Durnin and his colleagues at the University of Glasgow developed equations for the prediction of body density based on large samples of the Scottish population. The method is well-suited to epidemiological studies and clinical practice, and if the calipers are used carefully and appropriate prediction equations are chosen, it has been claimed that skinfold data are as valid as information obtained by more sophisticated laboratory techniques, whether assessing the absolute body fat content (Fuller et al., 1992) or examining the changes in body fat resulting from a weight-loss regimen (Jebb et al., 1993).

After noting the nature of skin-fold data and making a brief survey of the history of such measurements, we will look here at details of possible instrumentation and measuring techniques and consider the various options for interpretation of the resulting data.

Nature of skinfold data. One factor affecting the relationship between skin-fold measurements and body fat content is the water content of the adipose tissue (Bliznak and Staple, 1975). Other important issues include the relative proportions of sub-cutaneous and visceral fat, and regional differences in thickness of the overlying skin and the compressibility of individual skin-folds.

The water content of a skin-fold may increase with malnutrition (Grant, Custer, and Thurlaw, 1981), but surprisingly it does not seem to change over the menstrual cycle (Womersley and Durnin, 1973). Depending on water content (Bliznak and Staple, 1975), the fat content of a skin-fold can range all the way from 5% (in very active and/or poorly nourished populations) to 94% in those who are grossly obese. However, the usual range is 60-85% (Pawan and Clode, 1960; Thomas, 1962).

A standard correction of two mm is sometimes applied to allow for the inclusion of an overlying double layer of skin in the total thickness of the fold. On the back of the hand, where there is almost no fat, skin-fold readings are 1-3 mm in young adults but are lower in the elderly and those with wasting diseases (Edwards et al., 1955; Lee, 1957; Lee and Ng, 1965; Roberts et al., 1975). However, there are substantial differences with body region, skin thicknesses for men and women averaging 0.8 and 0.5 mm over the biceps and 2.1 and 1.7 mm over the trunk, but with much higher values on the soles of the feet (Clarys et al., 1987). Values may be increased in some parts of the body, such as the palms of the hands among those who engage in hard physical labour, and there are varying decreases of average skin thickness with aging and dehydration. O'Hare et al. (1979) also found decreases in skin thickness with vigorous exercise and cold exposure.

History of skinfold measurements. The idea of using skin-fold data to determine body fat content can be traced back to the Czecoslovakian anthropologist Jindřich Matiegka (Brozek and Prokopec, 2001; Škerlj and Brozek, 1952). As a part of a system for examining physical overall efficiency, Matiegka divided the gross body mass into four components (bone, muscle, skin + fat and the remaining tissues). He formulated an equation for calculating the mass of body fat from estimates of body surface area and six skin-fold measurements (upper arm, forearm, thigh, calf, thorax and umbilical region), making measurements by means of a sliding compass with blunt points (Matiegka, 1921). His proposed formula was:

- 0.13 (surface area) x 0.5 (average skin-fold at 6 sites)

In the example that he cited, a half of the average skin-fold reading for a young man was 4.1 mm, and the body surface area was 2.14 m^2. The total mass of skin and subcutaneous fat was given by the product of these two numbers and an arbitrary constant of 0.13:

- Mass of skin + fat = (4.1 x 21,400 x 0.13) = 11,300 g (15.6% of total body mass).

An evaluation of this formula on a small sample of young and athletic men found it to over-estimate body fat by 4.1% (Damon and Goldman, 1964).

In more recent years, Edwards (1950) and Martin et al. (1985) studied the distribution of subcutaneous fat in small groups of cadavers. Further post-mortem studies on a larger sample of 71 adults showed an average correlation of 0.83 between caliper readings and such direct measurements of fat thickness (Lee & Ng, 1965).

Brozek and Keys (1951) used the relationship between skin-fold thicknesses (abdomen, chest, back, arm, and thigh) and body density to assess the fat content in 255 healthy men. Correlations of individual folds with specific gravity ranged from 0.75 to 0.86 in young men and 0.54 to 0.65 in older men, the closest correlations being yielded by the chest skin-folds. However, Brozek's formulae were never widely used, perhaps because of the practical difficulties in obtaining the required chest and back skinfold measurements under field conditions.

Skin-fold formulae. What is the optimal choice of skin-folds to predict an individual's body fat content? Pascale et al. (1956) developed their equations on military personnel, so that they had no problems in making measurements on the torso. They suggested that the optimal equation for the prediction of body density was based on readings taken from the mid-axillary region (X_1), juxta-nipple (X_2) and the dorsum of the arm (X_3):

- Body density = $1.0885 - 0.00712\ X_1 - 0.00483\ X_2 - 0.00513\ X_3$

A correlation coefficient of 0.85 was reported for this equation, although the estimate may be criticized since the folds were not summed prior to calculating the regression. A few years later, the Czech pediatric physiologist Jana Parizková (1961) developed a sex-specific nomogram for predicting the body fat content of children from either two (triceps + subscapular) or five (biceps, triceps, subscapular, suprailiac, and calf) skin-folds. The corresponding equations were:

- Body fat = 35.567 Log S2 folds - 25.330
- Body fat = 32.689 Log S5 folds - 33.108

Steinkamp et al. (1965) based their predictive equations on a combination of body circumferences and skin-fold thicknesses taken on 167 healthy Californian adults. They validated their equations against helium dilution and total body water (tritium) estimates of body fat content; correlations of around 0.90 were claimed.

In theory, it is advisable to sum the skin-fold readings before calculating prediction equations, since readings for individual folds are closely related with each other. However, the objection then arises that equal weight is commonly given to arm measurements (representing a small total quantity of fat) and trunk measurements (representing a much larger fat mass) (Déspres et al., 1985). Durnin and Rahaman (1967) compared data from four skin-fold measurements (biceps, triceps, subscapular and suprailiac) with hydrostatic estimates of body fat in 105 adults and 86 adolescent children. Single or multiple correlations were around 0.80. Both linear and logarithmic regressions were evaluated, and the standard error of predictions from the curvilinear (logarithmic) regression equations was 3.0 to 3.5%, a level that was judged acceptable for clinical purposes Summing linear values for the 4 folds, a table was developed that allowed the calculation of percentage body fat (Table 15). The corresponding equations for the prediction of body density were:

- Men = 1.161 -0.0632 S4
- Women = 1.158 - 0.072 S4
- Boys = 1.153 - 0.643 S4
- Girls = 1.137 - 0.0508 S4

where S4 is the sum of the four skin-folds. It seems likely that this combination of folds would have a closer correlation with abdominal type of fatness than many subsequent options. Assessments made by this approach also agreed quite well with subjective assessments of "plumpness" for the study participants (Table 16), and a comparison of estimates with total body water estimates of body composition in children also yielded a close correlation (r = 0.98)(Brook, 1971).

Durnin and Womersley (1974) developed a more recent equation for the International Biological Programme Human Adaptability Project. This used a larger subject pool, and focused upon the logarithms of the same four summed skin-folds:

- For men aged 20-69 yr: $D = 1.1765 - 0.0744 (\log_{10} S_4S)$
- For women aged 20-69 yr: $D = 1.1567 - 0.0717 (\log_{10} S_4S)$

where D is the predicted body density and S_4S is the sum of biceps, triceps, subscapular and suprailiac skin-folds (mm). Note that because the newer formulae used logarithmic skin-fold data, the coefficients changed relative to those initially proposed by Durnin and Rahaman (1967).

The slope of the relationship between density and skinfolds decreases with age,

Table 15: Abbreviation of a table developed by Durnin and Rahaman (1967) for the calculation of percentage body fat from the sum of 4 skin-fold measurements (abdomen, chest, back, arm and thigh).

Sum of 4 skin-folds (mm)	Body fat content (%)			
	Men	Women	Boys	Girls
20	9.0	15.5	12.5	16.0
30	13.5	21.0	17.5	21.5
40	17.0	24.5	21.5	25.0
50	20.0	27.5	24.0	28.5
60	22.0	30.0	26.5	30.5
70	24.0	32.5	28.5	33.0

Table 16: Relationship between the sum of 4 skinfolds as shown in Table 15, and subjective assessments of body build. Based on the data of Durnin and Rahaman (1967).

Subjective assessment	Sum of 4 skin-folds (mm)			
	Men	Women	Boys	Girls
Thin	24.0	31.2	22.4	33.3
Intermediate	35.7	39.9	29.7	36.2
Plump	57.2	66.0	43.2	40.0

pointing the need for age-specific equations. More than 100 potential prediction equations have now been advanced, using from two to seven skin-folds. The appropriate choice of equation for any given study depends in part on the nature of the population to be tested (sedentary or athletic), the age and sex of the participants, their state of nutrition and their ethnic group (Norgan and Ferro-Luzzi, 1985)(Table 17). Usually, the equations have estimated body density, but in a few cases a direct prediction of body fat content has been made. Notice also that problems have arisen from the use of stepwise regression analyses (which develop a highly specific formula, accounting for much of the variance in a unique population, but lack generalizability), that the close-inter-correlation of individual skin-fold readings tends to invalidate multivariate analyses where the thickness of folds has not been summed, and that many of the proposed equations have not used logarithms or power functions to allow for a possible curvilinearity in relationships (Mukherjee and Roche, 1984).

Jackson and Pollock (1978) presented a variety of equations for adults, using either three or seven skin-folds, squared or treated as logarithms, and with the option of adding waist and forearm circumferences to the formulae. These options were cross-validated against a second sample of men drawn from the same pool; there were only minor differences between options, with no apparent benefit from measuring more than 3 folds to the prediction. All of their prediction equations showed correlations of >0.90 with data from a second sample of the same population. Critics have found these equations very effective in evaluating athletes, but population-specific (Davies, 1982); thus, they have lacked precision relative to a "gold standard" of dual energy X-ray absorptiometry when applied to racially divergent groups (Jackson et al., 2009), with under-estimations of body fat for Hispanics, and over-estimation for groups of African origin. Dioum et al. (2005) also emphasized that the distribution of body fat was different in women of African origin, and thus specific equations were needed for such populations.

Leahy et al. (2013) presented equations for a population of Irish adults (including an abdominal circumference term in the women), claiming a standard error of 2.5-3.0% relative to dual energy x-ray absorptiometry. Other equations for adults, based on skin-folds alone or combinations with other anthropometric data, have been proposed by Heitman (1990), Noppa et al. (1979) and Pascale et al. (1956) (Table 17). In terms of the number of skin-folds to be included in equations, Roche (1984) argued that the proportion of variance described did not decrease alarmingly if observers relied simply on the triceps fold, and Lohman (1981, 1984) also commented that the use of three folds offered no great advantage over two. Nevertheless, there may be an advantage in including additional folds if there is a substantial component of visceral fat to be measured. Arguing from observations on cadavers, Müeller and Stallones (1981) specifically recommended the inclusion of information from the lower limbs (for instance, a skinfold on the front of the thigh).

Table 17: Potential equations for the prediction of body density or percent body fat from skin-fold data.

Skin-folds	Population & age group	Equation to predict body density or body fat %	Author
Biceps, triceps, subscapular. suprailiac,	114 Dutch boys, 98 girls aged 10.5-11 yr	Boys D = 1.1133 -0.561Log S4 +1.7A Girls D = 1.1187 - 0.063Log S4 + 1.9A	Deurenberg et al. (1990)
Biceps, triceps, subscapular. suprailiac,	208 girls, 130 boys aged 7-20 yr	Boys DPr = 1.1133 - 0.0561Log S4 +1.7A DP = 1.0555 - 0.0352 Log S4 + 3.8A DPp = 1.1324 - 0.0429 Log S4 Girls DPr = 1.1187 - 0.0630Log S4 +1.9A DP = 1.1074 - 0.0504 Log S4 + 1.6A DPp = 1.1830 - 0.0813 Log S4	Deurenberg et al. (1990)
Biceps, triceps	208 girls, 130 boys aged 7-20 yr	Boys DPr = 1.0963 - 0.0432Log S2 +1.8A DP = 1.0691 - 0.0352 Log S2 + 3.8A DPp = 1.1132 - 0.0410 Log S2 Girls DPr = 1.0984 - 0.0633Log S2 +2.2A DP = 1.1103 - 0.552 Log S2 + 1.4A DPp = 1.1547 - 0.0796 Log S2	Deurenberg et al. (1990)
Triceps, subscapular	50 boys, 16 girls aged ~ 10 yr	S2 <35 mm Boys F = 1.21 S2 - 0.008 $(S2)^2$ -1.7 Girls F = 1.33 S2 - 0.013 $(S2)^2$ -2.5 S2 >35 mm Boys F = 0.783 S2 - 1.7 Girls F = 0.546 S2 + 9.7	Slaughter et al. (1988)
Biceps, triceps, subscapular, suoprailiac	140 boys, 168 girls, aged 8-14 yr	Boys D = 1.1660 - 0.0070 Log S4 Girls D = 1.144 - 0.060 Log S4	Johnston et al. (1988)
Biceps, triceps, subscapular, suoprailiac	13 obese, 10 short children	Boys D = 1.1690 - 0.0788 Log S4 Girls D = 1.2063 - 0.0999 Log S4	Brook (1971)
Chest, axilla, triceps, subscapular, abdomen, suprailiac, thigh (waist C)	403 adult men aged 18-61 yr	D = 1.1120 - 0.000435(S7) + 0.00000055$(S7)^2$ - 0.0002868 A D= 1.1020 - 0.000412(S7) + 0.00000069$(S7)^2$ - 0.000263A - 0.00592C + 0.0191F D = 1.1239 - 0.03101(LogS7) - 0.00029 A D= 1.1762 - 0.02394(LogS7) - 0.00022A - 0.0070C + 0.02120F	Jackson and Pollock (1978)
Chest, abdomen and thigh	403 adult men aged 18-61 yr	D = 1.1094 - 0.000827(S3) + 0.0000016$(S3)^2$ - 0.0002574 A D= 1.10991 - 0.000821(S3) + 0.0000026$(S3)^2$ - 0.0002017 A - 0.00568C + 0.0186F D = 1.12886 - 0.03049(LogS3) - 0.00027 A D= 1.1574 - 0.02288(LogS3) - 0.00019A - 0.0075C + 0.0223F	Jackson and Pollock (1978)
Abdominal girth (Ag), biceps (B), triceps (T), mid-axilla (MA), medial calf (MC), supraspinal (SS)	736 Irish men and women aged 18-81 yr	Men F = 0.1A + LogTx7.6 + LogMA x8.8 + LogSS x11.9 - 11.3 Women F = 0.1A + Log Ag x 39.4 + Log MA x4.9 + Log B x11.0 + Log MC x9.1 -73.5	Leahy et al. (2013)
Chest (nipple)(Cn), chest xiphoid (x) and arm (Ar),	100 healthy young American soldiers	D = 1-0885 - 0.007123Cn - 0.004834Cx - 0.005513Ar	Pascale et al. (1956)
Biceps, triceps, subscapular, suprailiac	196 African women	Age <20 yr D = 1.1549 - 0.0678 Log S4 20-29 D = 1.1599 - 0.0717 Log S4 30-39 D = 1.1423 - 0.0632 Log S4 40-49 D = 1.1333 - 0.0612 Log S4 >49 D = 1.1339 - 0.0645 Log S4	Dioum et al. (2005)

D = density; F = %fat; Pr + prepubertal; P = pubertal; Pp = post-pubertal; A = age in years; S = sum of specified number of skinfolds; C = waist circumference (cm); F = forearm circumference (cm); RM = relative body mass.

Dauncey et al. (1977) compared skin-fold readings with cadaver estimates in young children, and a number of authors have offered specific equations for the prediction of body fat content in boys and girls (Brook, 1971; Deurenberg et al., 1990; Durnin and Rahaman, 1967; Johnston et al., 1988; Lohman et al., 1975; Nelson and Nelson, 1986; Slaughter et al., 1988). Deurenberg et al. (1990) underlined the necessity to allow for an increase in the density of a child's fat-free mass from 1.080 at the age of seven years to 1.010 at 20 years; they thus proposed the introduction of differing equations for predictions in prepubertal, pubertal and post-pubertal children, with their maturity-specific equations showing a prediction error of 3-5% relative to underwater weighing. Reilly et al. (1995) compared skin-fold estimates of body fat obtained from five potential prediction equations in a sample of 98 children against values obtained by hydro-densitometry. Perhaps because of difficulties in carrying out the underwater weighing in youngsters, correlations with hydrostatic estimates of body fat have proven only moderate (Corbin and Zuti, 1982), with substantial apparent errors (Table 18). Reilly et al. (1995) suggested that because of the relatively large errors, skin-fold predictions in children should be regarded as indices rather than definitive measures of fatness. However, this conclusion perhaps needs to be checked, using an alternative "gold standard" measures that require less cooperation from study participants than that needed for underwater weighing.

Specific equations have been developed for athletes in general and for participants in specific sports (Forsyth and Sinning, 1973; Meleski et al., 1982; Sinning, 1974, 1978). The current consensus seems that the equations of Jackson and Pollock (1978) remain a viable basis for the prediction of body fat in most athletic populations (Thorland et al., 1984).

The option of height scaling. Ectomorphy is commonly linked with tallness, and perhaps for this reason some investigators have found little correlation between skin-fold readings and stature, at least in adults (Benn, 1971; Brozek and Mori, 1958). Nevertheless, a few authors (Behnke and Wilmore, 1974; Katch and Katch, 1984; Mazess et al., 1984) have argued the advantages of scaling skin-fold data for standing height. Behnke and Wilmore (1974) proposed the formula:

- $F\% = SS\,[3(M/H)^{1/2}\,K)$

where SS was the sum of triceps, suprailiac, abdominal and thigh skin-folds, and K was a constant equal to:

- $K = SS_r\,[3(M_r/H_r)^{1/2}\,F_r)$

with the subscript $_r$ signifying the corresponding values for a reference person. Notice that if M is assumed proportional to H^3, then the equation simplifies to:

- $F\% = SS/3/H\ (K)$

Plyley et al. (1988) found the overall correlation of Behnke and Wilmore (1974) estimates with hydrostatic measures of body fat was rather similar to that obtained by the use of traditional equations (r = 0.78 in men, r = 0.76 in women). Moreover, the scaled approach tended to introduce positive errors with thin subjects, and negative errors with those who were obese. Height scaling of obesity data thus has not found wide acceptance.

Conclusions. In average healthy adults, adequate skin-fold predictions of body density and thus body fat content can be obtained, using the equations proposed by Durnin and Womersley (1974). However, when evaluating athletes, the equations of Jackson and Pollock (1978) may give more accurate predictions. Moreover, unless age specific equations are used, substantial errors can occur in both children (Parizkova, 1977) and the elderly (Chumlea, Roche, and Roger, 1984).

Instrumentation. There are a multitude of calipers on the market, ranging in cost from $10 to $400 each (Anderson and Ross, 1986; Schmidt and Lindsay-Carter, 1990). The accuracy of the data collected depends in part on the quality of the instruments and their calibration, but the main constraint is the adoption of an impeccable measurement technique by the investigator. Ideally, the design should exert a consistent pressure on the underlying skin, with the jaw surfaces remaining parallel to each other, irrespective of the size of the skin-fold. Some early calipers exerted pressures as great as 30 g/mm^2 (Parizkova and Goldstein, 1970; Parizkova and Roth, 1972). The International Biological Programme Human Adaptability Project called for a device that exerted a constant jaw pressure of 10 g/mm^2, and provided dial readings that were accurate to 0.2-0.5 mm (Tanner et al., 1969). Leger et al. (1982) found that some Harpenden calipers exerted pressures as low as 7.6 g/mm^2, and they suggested that instruments should be checked periodically against a calibration block to ensure that the desired compression pressure was maintained. Skin-fold readings do not seem to change greatly over the pressure range 9-20 mm^2 (Keys and Brozek, 1953; Leger et al., 1982; Sloan and Shapiro, 1972), but readings become less consistent and clients may complain of discomfort if pressures are greater than 15 g/mm^2 (Behnke and Wilmore, 1974; Keys and Brozek, 1953). Differences in jaw area (over the range 25-40 mm^2) do not seem to affect the results greatly (Edwards et al., 1955; Pascale et al., 1956).

Commercial calipers that are currently the most widely used in scientific investigations include the Harpenden, Holtain and Lange devices.

Harpenden caliper. The Harpenden Caliper (Edwards et al., 1955; Tanner and Whitehouse, 1955) is generally regarded as the "gold standard" instrument for making skin-fold measurements, and is the device recommended by the International Society for the Advancement of Kinanthropometry (Figure 4). Calipers of this type are capable of measuring skin-folds accurately up to jaw widths of some 50 mm. The equipment is sturdy and well made, and its accuracy is maintained over at least 100,000 cycles of opening and closing (Gore et al., 2000). The cost is substantial for large-scale epidemiological work (~$400 per unit), but this make of caliper has nevertheless been the instrument of choice in Canadian epidemiological surveys (Tremblay et al.,

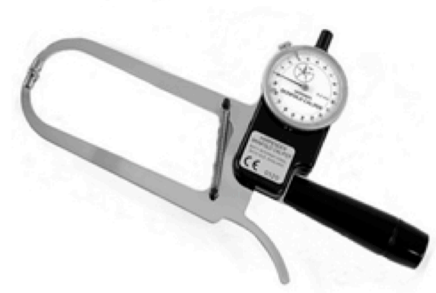

Figure 4: Harpenden skinfold caliper.
Source:
https://www.healthprofessionalsolutions.com.au/Harpenden_Skinfold_Calipers_p/harpenden.htm

2009).

Holtain calipers. The Holtain caliper (Figure 5) was developed from the original Harpenden caliper by the English anthropometrist J.M. Tanner and his technical colleague R.H. Whitehouse (Tanner & Whitehouse, 1975). It has a maximum jaw width of 46 mm, and provides estimates of skin-fold thickness to an accuracy of 0.1 mm. The current price of the instrument is ~ $600 per unit. Holtain calipers have been used extensively to study the development of skin-folds in children and adolescents, and were adopted in the NHANES III study (Westat, 1988).

Figure 5: Holtain skin-fold caliper. Source: https://www.google.ca/search?q=Holtain+calipers

Lange caliper. The Lange caliper was developed by Karl O Lange at the University of Kentucky aeronautical laboratory (Lange and Brozek, 1961). This instrument became commercially available in 1962 (Figure 6). It features spring-loaded arms that exert a constant pressure of 10 gm./mm^2 over an operating range of 60 mm, and floating tips that rotate to enable parallel measurement of skin-folds. The unit cost is ~$250. The Lange caliper has been selected for a number of large-scale North American studies, including the AAHPERD survey (Morrow et al., 1986).

Figure 6: Lange skin-fold calipers.
Source: https://nutriactiva.com/blogs/body-fat/history-of-the-lange-skinfold-caliper

Slim-Guide caliper. The Slim Guide (Ross) caliper is a relatively reliable cheap plastic product that may prove useful in large field studies, particularly if it is checked biologically against readings taken by a Harpenden caliper. It is claimed to exert the appropriate jaw pressure and to produce readings that are closely comparable to those obtained from more expensive calipers, despite a low unit price (~$20). It can be read over jaw widths to 80 mm, with an accuracy of 0.5 mm being claimed.

McGaw caliper. The McGaw caliper is a lightweight plastic device which has sometimes been distributed cost-free. Several studies have compared readings from this instrument with data obtained from Harpenden or Lange calipers. Rombeau et al. (1977) found that in about a half of 107 surgical patients, the McGaw readings matched the Lange data to within one mm, although in general the McGaw device gave slightly higher readings. On the other hand, Burgert and Anderson (1979) found the McGaw caliper to yield 8% lower reading than the Lange calipers. Leger et al. (1982) pointed out that differences arising from use of either the McGaw or the Ross calipers, although statistically detectable, were usually not of clinical significance. Moreover, the McGaw device stood up well to various types of physical abuse. Jung et al. (1984) made a comparison in 240 children; they found that on average readings with the McGaw instrument were 12.6% lower than with the Lange calipers, but they argued that this was a clinically acceptable bias, since inter-observer differences were as large as 20.4% for the Lange calipers, and 17.6% for the McGaw instruments.

Accuracy of skinfold calipers. The early studies of Durnin and Rahaman (1967) suggested that skin-fold data had an accuracy of 3.0-3.5% relative to hydrostatic estimates of body density, and that this was adequate for most clinical assessments. Schmidt and Lyndsay Carter (1990) undertook a systematic comparison of the information yielded by 38 calipers of five different types (Harpenden, Lange, Skyndex, Lafayette, and Slim Guide). Ratings were made of dial accuracy, caliper force, surface area compressed, and pressure exerted, as well as the dynamic performance in determining the thickness of pads of foam rubber. We will look at each of these aspects of performance.

Dial accuracy. The dial of the Harpenden caliper could be read to 0.1 mm relative to the actual jaw separation as measured by a Vernier scale; for the other four instruments, the precision was 0.5 mm.

Surface area. The surface area that was compressed varied substantially among calipers: from 30 mm^2 (for Lange and Lafayette instruments), to 90 mm^2 (Harpenden and Slim Guide), and 100 mm^2 (Syndex).

Caliper Force. Most instruments showed little variation from the intended compression force of 8-10 g/mm^2 over the jaw width of 10-50 mm, although average values were slightly higher for Harpenden and Lange instruments (8.3-8.4 g/mm^2) than for the other types (7.3-7.5g/mm^2). Moreover, the caliper force was most consistent for the Harpenden calipers (coefficient of variation 1.7%), with figures for the other instruments of 2.2% (Skyndex), 2.4% (Lange), 3.1% (Slim Guide) and 5.9% (LaFayette). The Slim Guide caliper also tended to impose an increased force as jaw width increased, and with the Lafayette instrument it decreased.

Despite the relative consistency of these numbers, there have been reports of compression varying from 2.6-15.9 g/mm^2 when using older Ross calipers.

Dynamic measurements. The greatest inter-instrument differences were seen with dynamic tests when measuring the thickness of pads of foam rubber. Here, the Harpenden calipers consistently gave the highest compressed readings at any uncompressed thickness, values for the Lange calipers were four to five mm less, and those for the three other devices were yet smaller. This may reflect in part the presence (or otherwise) of pivoting jaws and inter-instrumental differences in friction between the jaws and the rubber, but the main explanation is likely differences in jaw area, and thus the total pressure applied to the surface under examination.

Comparisons on human subjects. An early study from Italy compared skin-fold readings for the upper arm and subscapular regions in a large sample of 848 middle-aged men, finding no systematic differences between the results obtained from Harpenden, Lange and Rizzolo calipers (Imbibo et al., cited by Womersley and Durnin, 1973). Sloan and Shapiro (1972) also found no systematic difference of the summed data for four skinfold sites between Harpenden, Lange and MNL calipers in a small sample of 28 men. However, several more recent observers have found the Lange calipers to give systematically higher skin-fold readings than the Harpenden instruments. Lohman et al.

(1984) measured five skin-folds in 16 female athletes, using four types of caliper; they found average values of 15.6 mm (Harpenden), and 14.4 mm (Holtain) but 16.1 mm (Adipometer) and 19.8 mm (Lange); they also commented that the standard deviation of data was greater for the Lange than for Harpenden or Holtain calipers.

Morrow et al. (1986) measured triceps and subscapular folds in 90 boys, and triceps folds in 90 girls, using Lange, Layfayette and Slim Guide calipers. In both sexes, there were substantial systematic differences in average data for the three types of caliper: Lange 10.9, 15.0 mm; Lafayette 12.2, 15.9 mm; and Slim Guide 9.1, 12.5 mm.

A further empirical comparison of the results given by the Harpenden and Lange calipers was made in young adults (31 M, 29 F) over a total of seven skinfolds (Gruber et al., 1990); this study confirmed that higher readings were given by the Lange than by the Harpenden calipers (in men, an average reading of 104.5 vs. 93.8 mm, in women, 113.5 vs. 103.7 mm).

It remains a little unclear why some observers have found substantial differences between calipers and others have not. Probably, differences of measuring technique are involved. Any such differences are not of great importance when using the same design of calipers to evaluate changes of body fat content within a given individual, but on the other hand the equations used to compare absolute values of body fat should be specific not only to the populations concerned, but also to the type of caliper that is used.

Comparisons of skin-fold data with gold standard measurements. Some authors have noted substantial systematic differences between skin-fold data and alternative (gold standard) methods of measuring sub-cutaneous fat. Thus, Walia et al. (1992) found 21-45% higher readings from a CAT scan film of the arm than from use of a Holtain caliper. Müller et al. (2013) also found systematic differences between caliper readings and the data for uncompressed skinfolds as measured by ultra-sound; discrepancies in their study ranged from 2.6 to 8.6 mm, and (in part because the skin-folds included skin), the regression equations did not pass through their origins. However, others have found close correlations between skin-fold values and those obtained by alternative techniques, with no systematic differences. For example, Nolte et al. (2016) reported strong correlations between ultrasound data and estimates from six of seven skin-fold sites, the exception being data from the abdomen. Likewise, Durnin and Rahaman (1967) found single or multiple correlations with underwater weighing of around 0.80, and the standard error of their skinfold predictions was only 3.0 to 3.5%. Estin et al. (2005) examined correlations with dual energy x-ray absorptiometry in young adults, finding closer correlations for lower limb (thigh and calf) than for upper limb skin-folds; the thigh fold alone yielded a correlation of 0.91 with total body fat.

In children, Parker et al. (2003) found a 1.4% bias in estimates of body fat percentage from the Slaughter equations relative to their gold standard; however, this was substantially better than the 2.4-4.1% bias seen with bioelectric impedance methods.

Conclusions. The error of a given type of caliper appears to increase with the thickness of the skin-fold that is being measured, thus remaining a relatively consistent 10% fraction of the reported thickness. However, the systematic difference of at least 10% between the various caliper options remains a significant concern.

Measurement techniques. The learning of correct technique is important to obtaining accurate skin-fold data, since the critical variables of both compressibility and the ultimate thickness of the fold are site dependent (Brozek and Kinsey, 1960; Clegg and Kent, 1967; Edwards et al., 1955; Hammond, 1955; Hines et al., 1979; Lee and Ng, 1965). Precision is necessary in locating the measurement site, determining the direction in which the skin is picked up, and in standardizing the duration of compression of the skin-fold.

Location. The precise location of skin-folds used for any given equation must be described in relation to anatomical landmarks and/or clear photographs, with appropriate surface markings (Jackson and Pollock, 1985; Katch and Katch, 1984; McNair et al., 1984). Detailed locations for commonly used folds have been provided by Weiner and Lourie (1981) and by Marfell-Jones et al. (2006). Ruiz et al. (1971) emphasized the importance of locating the correct measurement site; a lateral error of one inch (2.5 cm) could change the recorded thickness of the triceps skin-fold by two mm. Hume and Marfell-Jones (2008) tested the effect of a one cm displacement of the calipers at eight skinfold sites; differences from readings at the correct location were in the range 0.5-1.5 mm, with effects least for the subscapular site and greatest for abdominal readings. Durnin et al. (1995) tested the effect of measuring their four chosen sites at distances of up to 20 mm from the correct placements; they did not comment on the article of Ruiz et al. (1971); in their study, the resulting errors were trivial for vertical displacement of the calipers, usually less than 1%, but again errors of up to two mm were seen with a lateral displacement of the calipers on the triceps

Compression. It was soon recognized that the duration of skin-fold compression had an important bearing on the readings that were obtained (Booth, Goddard, and Paton, 1966; Fletcher, 1962; Orpin and Scott, 1984). There are regional, sex, and age-related differences in skin-fold compressibility (Brozek, 1965; Clarys et al.,1987; Clegg and Kent,1967; Lee and Ng, 1965), and changes in tissue hydration can also be an issue (Laven, 1983). Moreover, the process of compression continues exponentially over a period as long as 60 s (Brans et al., 1974). Becque et al. (1986) recommended a compression time of four seconds, but two seconds is the usual standard allowance (Le Bideau and Rivolier, 1958; Schmidt and Lindsay-Carter, 1990). Even if a standard compression time is adopted, inferences from skin-fold readings are limited by differences in the compressibility of folds from one site to another and from one person to another (Müller et al., 2013).

Training of observers. Most of the tests of validity relative to underwater weighing have been conducted by experienced investigators, using relatively small population samples. In such circumstances, inter-tester correlations are commonly in the range 0.92-0.98 (Keys and Brozek, 1953). Further, it has been suggested that a tester with 17 years of experience can, in half an hour, train inexperienced assistants to take readings that show a good correlation (r = 0.90-0.97) with the values obtained by the tutor, suggesting that large teams of observers can collect useful epidemiological data if they are given minimal training (Kerr, Wilkerson, and Bandy, 1994). Lohman and Pollock

(1981) noted substantial improvements in the accuracy of data collected by neophytes after they had received 20 minutes of instruction in the location of measurement sites, how to hold the skin-fold, and how to apply the calipers. Burkinshaw et al. (1973) compared three observers (one experienced and two relatively inexperienced); when the measurement sites (biceps, triceps, subscapular and suprailiac) had been marked by the experienced observer, data agreed well between the three workers, but when the inexperienced observers found the measurement sites for themselves, values were on average about two mm greater for those who were inexperienced. Some training in technique is plainly needed to make reproducible and valid measures of skin-fold thickness at appropriate body sites, and Arroyo et al. (2010) have suggested the importance of maintaining an acceptable level of accuracy by periodic retraining. Even after training, substantial inter-laboratory differences may remain- as high as seven mm for the triceps fold (Lohman et al., 1984).

Edwards et al. (1955) found small but statistically significant inter-observer differences of readings. Sloan and Shapiro (1972) commented that although systematic inter-observer differences were generally small, they were nevertheless less with Harpenden than with Lange calipers (an average of 0.56 vs. 1.06 mm). Lohman et al. (1984) also found less inter-observer discrepancies with the Harpenden and Holtain than with the Lange and Adipometer calipers; moreover, inter-observer differences were smaller for triceps and subscapular sites than for abdominal, suprailiac and thigh sites in both sexes and the for the biceps (in women) (Lohman et al., 1984; Womersley and Durnin, 1973). Problems of reproducibility increase when measurements are made on the obese (Ashwell, Cole, and Dixon, 1985). In a comparison with ultrasound data, Selkow et al. (2011) found that Lange calipers yielded erroneously high readings at large jaw widths. Erroneous readings also seem more likely with cheaper calipers that do not exert the required pressure; the observer must then learn to exert a consistent tension at the measurement site (Lohman & Pollock, 1981).

Ideal skinfold readings and body fat percentages*.* In using skin-fold data to predict future health, it might seem logical to examine the directly measured skin-fold data rather than to estimate body fat (Table 18), but measurements are commonly converted first to estimates of body density and then to percentage body fat, using population-specific prediction equations. The setting of "ideal" values for sub-cutaneous or total body fat is even more controversial than the specification of an ideal body mass. Commonly, the 85th percentile of skin-fold thickness has been considered as the threshold of obesity. In the NHANES population, the 85th percentile of triceps readings was around 18 mm in

Table 18: Average skin-fold predictions of percentage body fat in children, relative to hydro-densitometric measurements (based on data of Reilly et al., 1995).

Method	Boys	Girls
Hydrodensitometry	13.2%	19.8%
Brook equation	13.1%	13.3%
Deurenberg equation	16.2%	19.3%
Durnin & Rahaman equation	10.4%	16.6%
Johnston et al. equation	8.2%	13.1%
Slaughter et al. equation	15.5%	19.9%

men and 29 mm in women at age 20, rising to 20 mm in men and 37 mm in women at an age of 60 years (Must et al., 1991).

Marshall et al. (1991) undertook a formal analysis of skin-fold data relative to measures of body mass, arbitrarily setting the threshold of obesity at a value >1.5 SD above the mean for a particular measure (Table 19). Perhaps the most telling statistic is the accuracy (the percentage of correct classifications). This was relatively high for all four methods of examination, but favoured the O-scale skin-fold technique (the age- and sex-based norms for a given stature, rated on a 1-9 scale, Ward, 1981).

perhaps because there are substantial measurement errors for the skin-fold data, and skin-fold data provide no evidence concerning the relative amount of visceral fat. A British military study proposed an arbitrary ideal body fat content of 14% for men and 18% for women (Amor, 1978). Against this proposal, endurance athletes often carry much less fat (5% in men, 10% in women), apparently without any adverse impact upon their health.

A further possible option in the direct interpretation of skin-fold data is to compare findings with the skin-fold predictions of body fat seen in young adults of "ideal" body mass. According to one group of health professionals (the American Council for Exercise, ACE, https://www.acefitness.org/acefit/healthy-living-article/60/112/what-are-the-guidelines-for-percentage-of-body-fat), respective values for healthy, overweight and obese individuals are fat percentages of 14-17%, 18-24% and >25% in men and 21-24%, 25-31% and >32% in women. However, the basis for these figures remains unclear. Some charts (although not those proposed by ACE) allow increases in obesity thresholds for older adults. A comparison with bioelectrical impedance data for 23,627 U.K. adults found substantially higher percentages of body fat at the thresholds for overweight

Table 19: Data on sensitivity, specificity, accuracy and positive and negative predictive value of 4 methods of defining obesity in adolescents. Based on data of Marshall et al. (1990).

Measure	Relative body mass	CSTF skin-folds	O-scale skin-folds	Relative BMI
Sensitivity	78.6%	92.9%	78.6%	100.0%
Specificity	96.1%	93.4%	98.1%	92.0%
Accuracy	94.7%	93.3%	96.6%	93.5%
Positive predictive value	0.64	0.55	0.78	0.55
Negative predictive value	0.98	0.99	0.98	1.00

An alternative approach to defining the fatness threshold is to consider individuals as falling into two groups: those who are healthy and those who are obese. Using this approach, a probit plot of the distribution of body fat for children aged 12 years showed a marked discontinuity in the normal distribution curve, beginning at 16% body fat in boys and 22% body fat in girls (Shephard, 1991).

Skin-fold predictions of body fat percentages show a j-shaped relationship to the risk of death, much as for BMI, although the relationship seems to be less close for skin-folds than for the BMI (Kalmijn, Curb, and Rodriguez, 1999),

Table 20: Percentages of body fat corresponding to BMIs of 25, 30, and 35 kg/m² in subjects aged 20 years*, based on a bioelectrical impedance-derived multiple regression equation (Meeuwsen, et al., 2010).

BMI (kg/m²)	Body fat (women%)	Body fat (men%)
25	28.8%	17.5%
30	34.4%	23.1%
35	40.0%	28.7%

* An age coefficient adds 5.6% fat at age 60 years.

and obesity, particularly in women (Table 20), as did a U.S. plotting of BMI against a precise, four-compartment assessment of body fat content in 202 "black" and 504 "white" subjects ((Gallagher et al., 1996), Table 21). Likewise, estimates of body fat in a large sample of Canadians who had dual x-ray measurements of body fat content found values in line with those reported by Gallagher and associates (Pawal, Leslie, and Lix, 2016). However, relationships between BMI and estimated body fat were not very close in any of these investigations (correlation coefficients were around 0.50, with considerable variation between studies, depending in part on subject selection). Age corrections would seem to be required in future studies, because the lean tissue component of overall body mass (bone and muscle) is necessarily quite a bit smaller in older adults.

Conversion of body density predictions to estimates of body fat content. Shephard et al. (1969) noted that in a simple, two-compartment model, the overall body density D was given by the equation:

- $D = 1.100 - 0.2\ F/M$

where F was the mass of body fat, and M was the total body mass. The fat mass appropriate to this equation could be calculated as:

- $F = [(S - k)/2]Ar$

where S was the skinfold reading, k the thickness of the double layer of skin, A was the body surface area, and r was the ratio of body fat to subcutaneous fat. A in turn was approximated from standing height H and body mass M:

- $A = 50 \times H^{0.75} \times M^{0.5} \times 10\text{-}4\ m^2$

Thus, the percentage of body fat was given by:

- $F\% = [(S - k)/2]50 \times H^{0.75} \times M^{0.5} \times 10\text{-}4\ m^2] \times r/M$,

and putting $M = H^3$,

- $F\% = [(S - k)/2]50 \times 10\text{-}4\ r/H^{0.75}$

These calculations underline the need for a height scaling of skin-fold data.

The percentage of body fat is

Table 21: Body fat for subjects aged 20 years. * Estimates based on multiple regression equations of Gallagher et al. (1996) corresponding to BMI values of 25, 30 and 35 kg/m².

BMI (kg/m²)	Body fat			
	"Black" women	"White" women	"Black" men	"White" men
25	30.5%	30.0%	17.7%	17.2%
30	37.6%	38.0%	24.5%	24.2%
35	44.7%	46.%	31.3%	31.2%

* For age 60 years, increase the listed body fat percentages for the 3 BMI categories by 2.9, 3.8, 4.2 and 7.1% respectively.

commonly calculated from hydrostatic estimates or skinfold predictions of body density D as proposed by Brozek:

- Body fat % = (457/D) - 414.2

The error of this estimate of body fat content relative to hydrostatic data is substantial (± 5% in men, ± 3.5% in women). Accuracy of the prediction does not seem to be improved by measuring more than three or four skin-folds. One difficulty arises from inter-individual differences in the average density of lean tissue between athletes, sedentary individuals and those with osteoporosis. There are also issues arising from differences in the regional distribution of subcutaneous fat, as well as technical factors limiting the precision of predictions.

Conclusions. Some authors have considered the errors of body fat predictions are too large to permit the use of skin-fold data in scientific research. Comparisons between skin-folds and body fat content plainly have limited reliability in the individual, but in large epidemiological surveys such errors tend to cancel one another out. Skin-fold readings can also have practical value when looking for time-related changes of body fat content within an individual as the consequence of participation in a weight-reduction intervention.

Regional distribution of body fat

A regional accumulation of subcutaneous fat seems encouraged by a lack of local body movement, for instance with paresis of a body part (Lee, 1959). The converse also appears to be true: if a body part is unusually active, as in the arms of a canoeist (Shephard, 1991), then skin-folds in that body region are unusually thin.

From the clinical standpoint, a more important distinction is between the android and the gynoid distribution of body fat. Skin-fold measurements are not well-adapted to making this distinction, but the best differentiation is probably obtained by the subscapular/thigh skin-fold ratio. Unfortunately, it is not always practicable to remove enough clothing to make such measurements, particularly under the conditions of a field survey, and subscapular/suprailiac and/or subscapular/triceps ratios have sometimes been substituted. The ratio of (triceps + subscapular) to subscapular readings can make a correct classification of a person's fat distribution in 72% of subjects (Kaplowitz et al., 1987). Even for a person with an ideal body mass, this skinfold ratio averages 1.66 in men, but 2.33 in women. Data for men of the Inuit community of Igloolik showed a progressive transition to a more masculine fat distribution between 1970 and 1990, as the local population became acculturated to a Westernized, sedentary lifestyle (Table 22).

Imeson et al. (1989) looked at the value of four individual skin-folds in predicting fatal and all ischaemic heart disease (Table 23). No skin-fold measurements were as helpful as the body mass index, but the optimal of the four skin-fold options was the subscapular reading, suggesting that this gave the best impression of central fat deposition. Interestingly, the lowest cardiovascular risk was seen where a low waist/hip ratio of body fat was coupled with a muscular body build, and thus a seemingly unfavourable BMI (Jarrett, 1986).

Table 22: Secular changes in skin-fold ratios in men from the Inuit community of Igloolik as they became acculturated to a westernized lifestyle between the years 1970 and 1990.

Age (yr)	SS/SI		SS/T	
	1970	1990	1970	1990
20-29	0.99	0.91	1.39	1.74
30-39	1.04	0.97	1.48	1.60
40-49	1.15	0.83	1.36	1.68
50-59	1.23	0.91	1.49	1.58

SS = subscapular, SI = suprailiac, T = triceps skin-folds

Table 23: Tertiles for four individual skin-folds and body mass index, showing relationships to the risk of fatal and all categories of ischaemic heart disease (based on the data of Imeson et al., 1989).

Tertile	Forearm	Triceps	Subscapular	Suprailiac	BMI
Fatal ischaemic heart disease					
Low	1	1	1	1	1
Medium	1.29	1.36	1.90	1.29	2.03
High	1.08	1.72	1.99	0.89	3.02
All categories of ischaemic heart disease					
Low	1	1	1	1	1
Medium	1.41	1.23	1.54	1.10	2.11
High	1.33	1.42	1.65	1.00	2.84

Total skin-fold readings are not necessarily related to the amount of deep body fat, which typically amounts to only 200 g per kg of superficial fat (Clarys et al., 1987). Edwards et al. (1955) suggested that thin people had a higher proportion of deep fat than those who were obese, and this view was substantiated in our studies of unacculturated Inuit. Despite very low subcutaneous skin-fold readings, measurements of total body fat based on the doubly-labeled water technique and underwater weighing suggested that the Inuit population had a substantial quantity of internal body fat (Rode and Shephard, 1994). We hypothesized that in terms of thermal regulation for those living an active lifestyle in a cold climate, it was better to store fat internally than externally, Removable layers of clothing provided a more practical protection against cold than a thick layer of subcutaneous fat, since much less insulation was needed when the Inuit were engaged in heavy physical activity than when they were, for example, watching a hole in the ice for a seal to emerge.

Impedance measurements

The biological use of bioelectrical impedance measurements first came to prominence through the investigations of Jan Nyboer (1970). Among other applications, the bioelectrical impedance reflects the individual's body composition. The impedance to passage of an electrical current through the body comprises both resistance and reactance terms, but the reactance is often sufficiently small that attention can be focused simply upon the resistance component. If paired electrodes are placed on the body, the impedance to a weak (100-800 mA) alternating current in the frequency range 25-100 Hz is proportional to the distance separating the detecting electrodes (and thus height and limb length) and is inversely proportional to the average cross-section of interposed lean tissue.

Because the applied current is small, there have been no reports of any untoward effects of bioelectrical impedance equipment (BIA) upon cardiac rhythm, although there is at least some theoretical possibility of interference with implanted devices such as pacemakers and defibrillators (Buchet al., 2012), and patients with such devices are generally advised to avoid BIA measurements.

Impedance is usually measured from hands to feet (Nyboer, 1970), but hand to hand or foot to foot values are determined by some types of equipment. in the leg-to-leg approach, the subject simply stands with bare feet on stainless steel pads that have both current application and impedance measuring positions, and likewise simply grasp hand-to hand devices with both hands. Segmental measurements of impedance are sometimes made to assess the local development of muscle tissue.

Fat, with a water content of only 14-22% offers a much higher impedance to transmission of the electrical signal than does lean tissue, and in some analyses, it has been considered as a non-conductor. Thus, there is a possibility of estimating a person's body fat and/or lean tissue mass from inter-individual differences in impedance. The water that is mainly responsible for transmission of the electrical signal comprises an extracellular component of about 75% (vulnerable to changes in body hydration), and an intracellular component of about 25%.

The resistance and reactance can both be measured with considerable accuracy (0.1-0.2%), but the biological significance of the information is more controversial. With the usual electrode techniques, problems arise from a substantial and temperature-dependent impedance at the skin contacts. Moreover, the overall accuracy of the method is limited by systematic errors that can arise from inter-individual differences in the relative proportions of the trunk and limbs, and intra-individual changes in fat-free mass and tissue hydration over time.

Choice of equipment. The BIA measuring apparatus is often portable, with a relatively low cost (for example, the hand-held OMRON HBF-306CN (Figure 7) retails for about $50), but some models such as the leg-to-leg InBody 570 can cost more than $10,000 per unit (Figure 8). Instruments can be classified as single frequency, multiple frequency and spectroscopic analyzers.

Figure 7: Omron hand-held BIA analyzer.

Single frequency analyzers. The earliest BIA equipment measured impedance to a single frequency (50 KHz) current (Kyle et al., 2004; Lukaskiet al., 1986); this remains the most commonly used type of instrument, particularly for field work. The four-electrode system is helpful in minimizing skin-electrode interactions (Lukaski et al., 1986; Nyboer, 1970).

Multiple frequency analyzers. Multiple frequency analyzers (for

Figure 8: The InBody 570 BIA body fat analyzer has a high unit cost (>$10,000). Source: http://inbody.net.au/machines/inbody-570/

example, 100 and 1 kHz) attempt to distinguish extracellular fluid from total body water (Thommaset, 1962). In one study, 17 differing frequencies were applied, with extrapolation of impedance readings to zero frequency (corresponding to extracellular resistance) and infinite frequency (corresponding to total body water resistance)(Deurenberg, Andreoli, and de Lorenzo, 1996).

Bioimpedance spectroscopy. BIA spectroscopy uses a broad band of frequencies, with the same objective as multiple frequency analysis, the determination of impedance corresponding to zero and infinite frequencies.

Technical issues. Irrespective of the unit cost of BIA equipment, difficulties inevitably arise from the influence upon impedance of complex body shapes and changes in the individual's state of hydration. In terms of body shape, since impedance is related to the reciprocal of tissue cross-section, the observed values are heavily influenced by the composition and form of the arms relative to the form of other body segments. Attempts have been made to allow for this problem by considering the body as an approximation to five cylinders (Kyle et al., 2004). However, any such analysis is very complicated, since the five cylinders each have a varying cross-section, and any given cross-segment has a far from uniform impedance.

The recent ingestion of a meal usually changes the water content of the extracellular fluid, and this can modify impedance estimates of body fat by as much as 2% (Slinde and Rossander-Hulthén, 2001). Fasting is recommended for at least eight hours before measurement, along with recent emptying of the bladder, conditions that immediately limit field use of the BIA technique. Substantial apparent increases in lean tissue mass have also been calculated following 90-120 minutes of exercise, because of a combination of vasodilatation, increases of limb temperature and an increased fluid content in the peripheral tissues (Abu et al., 1988; Liang and Norris, 1993), again an important variable that is difficult to avoid by those undertaking field studies. Results can even be influenced by the conductivity of the examining table.

The observed impedance is influenced not only by the individual's height, age, sex and ethnic group, but also by the precise site of electrode contact, as well as menstrual rhythms, recent posture, skin temperature, and ambient air temperature. Many BIA measuring devices include undisclosed proprietary equations to correct for some of these variables. The equations incorporated into the instruments have usually been determined on a small and specific population, and their generalizability may thus be quite limited.

The information obtained from the

BIA is heavily biased by the composition of the arms, which account for 45% of the arm-to-leg impedance, but only 4% of body mass; in contrast, data depend much less on the composition of the chest, which accounts for 45% of the total mass, but only 10% of the total impedance. Further, BIA measurements provide no information on the distribution of fat within the body.

Validity. In essence, BIA measurements estimate body water, and a number of assumptions about body hydration and the density of fat must be made when converting impedance data to estimates of body fat content (total body water is first translated to fat free mass, and this is then converted to fat mass).

Most empirical validation studies have been conducted on adults of white European ancestry, commonly with hydrostatic weighing or isotope dilution as the "gold standard" criterion method. Note that both impedance and hydrostatic measurements are vulnerable to changes in body hydration, potentially over-estimating the true validity of the BIA technique in terms of normal body fat content. One investigation checking a single frequency tetra-electrode BIA system against hydrostatic weighing in 114 adults 18-50 years suggested a close correlation for the two estimates of lean tissue mass in both men (r = 0.98) and in women (r = 0.95), with a lower standard error than anthropometry as a means of predicting body fat content (2.7% vs. 3.9%) (Lukaski et al., 1986). However, in another study, the correlation between bioelectrical impedance and hydrostatic estimates of body fat was only 0.88 in men and 0.82 in women (Lawlor, Crisman, and Hodgson, 1985). Further, Diaz et al. (1989) concluded that BIA techniques offered a poor prediction of body fat, explaining only 0-21% of the variation in body fat content. Segal et al. (1985) also found that the standard error of determinations relative to hydrostatic weighing was as large as 6% body fat. Further, the error of BIA measurements relative to "gold standard" techniques was even greater in obese than in lean individuals (Ling, de Green, and Slagboom, 2011). In obese adolescents, Hofsteenge et al. (2015) evaluated various BIA equations in terms of their ability to predict fat-free mass to within 5% of the value obtained by dual energy x-ray absorptiometry. Accuracy of the available equations ranged from 1% to 68%, with none achieving the desired level of precision. Use of a multi-frequency BIA analyser in 40 obese adolescents yielded an average systematic error of 7.7 kg in the estimate of fat mass relative to deuterium oxide dilution, with a range from 16.4 kg to -1.3 kg (Resende et al., 2011). Parker et al. (2003) used the three component gold standard estimate of body fat (above) in 42 adolescent boys; they found the hand to foot impedance to over-estimate a fat mass of 8.7 kg by an average of 1.4 kg, and the leg to leg impedance had an even larger systematic error (2.3 kg), with both methods showing very wide ranges of error (+/- 7.6 and +/- 7.8 kg respectively).Validity of six field and laboratory methods for measurement of body composition in boys.

The errors of BIA analysis, often alarmingly large in healthy individuals, have a potential to become even larger in patients with clinical disorders. Thus, in children with HIV infections, errors relative to dual x-ray absorptiometry ranged from -2.8 to + 3.0 kg for total body water, and from -2.3 to + 3.4 kg for various prediction equations (Arpadi et al., 1996). In a group of 56 children with cystic fibrosis, the BIA equipment under-estimated total body water by an average of 1.1 L, with a range from -3.5 to + 9.5 L (Puiman et al., 2004).

In practical terms BIA data had no advantage over BMI in terms of predicting cardiovascular risk factors in children and adolescents (Bohn et al., 2015).

Despite these evident problems, NHANES III introduced BIA measurements into their survey, using the Valhalla 1990B analyzer apparently because of frustration at problems in skin-fold measurement. However, they found difficulty in interpreting the data because of a lack of generalizable, reliable and valid predictions appropriate to various age, sex, and racial-ethnic groups (Kuczmarski, 1996). The BIUA 450 BIA analyzer was used in recent iterations of the Framingham study (Motta et al., 2016), although no critical evaluation of the results has yet appeared.

In the clinical context, it is particularly disturbing that because of changes in the water content of the body, the impedance technique often under-estimates the fat loss occurring in exercise and dieting programmes (Carr, Davies, and Dressendorfer, 1985; Frisard, Greenway, and DeLany, 2005). Carr et al. (1985) noted an average 1.6 kg under-estimation of fat loss when obese men lost a total of 13.0 kg of fat.

Conclusions. Despite the technical improvements introduced by multi-frequency and spectroscopic BIA analyzers, both systematic errors and the scatter of data about mean errors can be very large with the BIA technique. Other objective methods of examining body fat content, particularly skin-fold and circumference measurements, are generally preferred for epidemiological surveys.

Photogrammetry

The term photogrammetry commonly denotes the use of photography in surveying distances between objects, a technique that was developed extensively by photo-mappers following World War II. Anthropologists have adopted this approach as one means of introducing objectivity into anthropometry and somatography (Gheoghegan, 1953; Parnell, 1954; Sheldon et al., 1940; Shephard, 2018; Tanner and Weiner, 1949). Attempts were made to determine body surface area, volume and body fat content from 2-D or 3-D photographs of subjects. Advantages of a photographic technique for the determination of surface area and volume are readily apparent; in particular, measurement does not change the shape of the subject, there is little inconvenience to the subject other than the removal of clothing, and detailed measurements can be completed at leisure, without regard to changes in the physical status of the subject. For the purposes of anthropometry, two overlapping pictures are commonly taken, much as for an old-fashioned stereoscope (Hertzberg et al., 1957). Linear measurements obtained from the photographs generally agree with direct anthropometry to 0.25 mm (Hertzberg et al., 1957).

Against these potential advantages, good quality photographic prints are expensive, it is difficult to obtain a good spatial image from the monochromatic surface of the body, the underlying mathematics are complicated, findings depend on the posture of the subject, and evaluation requires skilled personnel (Dupertuis and Tanner, 1950; Pierson, 1963).

In an effort to overcome these drawbacks, Pierson (1963) introduced a monophotogrammetric method, where the body was illuminated from both sides, with light passing between coloured translucent strips of equal width. When using this technique, it was claimed that the body volume could be estimated to 0.01%. Thus, if lung volumes were also measured, it was possible to estimate body density and body fat content. Expert raters could determine body volumes from such images with an error of less than 2% relative to volume displacement techniques (Pierson, 1963).

More recent research developments include three-dimensional digital imaging, laser scanning and cone beam computed tomography (Fourie, Damstra, and Ren, 2011). To date, the photogrammetric technique and its offshoots have been used to study the characteristics of sea-lions and the cranial features of criminals, but it has not become popular in human epidemiological studies, probably because of the need for skilled photography of nude subjects and expert rating of the resulting pictures.

Discussion and conclusions

Although body composition can be rated in qualitative terms, quantitative data are required for epidemiological surveys and assessments of the response to weight-reduction regimens. The most common approach is to relate body mass to some function of standing height, but even if the accuracy of the ratio is improved by removing the shoes and making an appropriate allowance for the weight of any residual clothing, such ratios cannot determine whether a change in body mass reflects a change in the fat, muscle or water content of the body.

In particular, determinations based upon excess body weight and body mass indices can lead to incorrect perceptions of the prevalence of obesity in both muscular individuals and some indigenous populations with unusual limb lengths. Further, a failure of body mass to decrease over the course of an exercise-based rehabilitation programme does not necessarily prove the ineffectiveness of regular physical activity as a means of reducing body fat content.

Skin-fold measurements generally correlate better than height/weight ratios with gold-standard measures of body fat such as those obtained by underwater weighing, and they provide a simple preferred alternative option for determining both the total amount and the distribution of body fat. The accuracy of individual estimates is relatively limited, and there can be substantial inter-laboratory differences between estimates, depending on the skin-folds that are measured. Nevertheless, experience has shown that skin-fold data can be used quite effectively in large epidemiological surveys and in assessing intra-individual changes during weight-loss treatment.

Waist/hip circumference ratios provide a useful addition to skin-fold data, allowing a more precise estimate of the distribution of body fat. Bioelectrical impedance data are less accurate than careful skin-fold readings, and although they have formed a part of NHANES surveys, they are not generally recommended for studies of obesity. Photogrammetry also has yet to prove its worth in field studies of body fat content.

Even the better options for field studies often have substantial systematic errors and a large scatter relative to laboratory, "gold standard" estimates. Marshall et al. (1990) compared five simple field methods of identifying obesity in a sample of 533 male and female ostensibly healthy adolescents aged 11.8-15.9 years (Table 24). The

Table 24: Percentage of obesity in adolescents as judged by 5 field measures (based on recalculated data of Marshall et al., 1990).

Measure	Percent obese (males)	Percent obese (females)	Percent obese (M + F)
Relative weight	12.1	11.0	11.6
Relative BMI	15.8	19.3	17.5
CSTF skin-folds	27.4	18.9	23.2
0-scale skin-folds	13.0	5.4	9.3
Visual inspection	6.1	4.1	5.1

lowest percentage of obesity (5.1%) was found by simple inspection, but even when using skin-fold estimates, estimates ranged widely from 9.3% (O-scale geometrically scaled skin-folds) to 23.2% (using CSTF recommended skin-folds). Nevertheless, such techniques may provide useful within-individual comparisons of body fat content. Moreover, even if errors in assessments are substantial when determining absolute values for an individual, the average values from large-scale epidemiological surveys may reach an acceptable level of accuracy.

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Author's qualifications

The author's qualifications are as follows: Roy J. Shephard, C.M., Ph.D., M.B.B.S., M.D. [Lond.], D.P.E., LL.D., D.Sc., FACSM, FFIMS.

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