Research Article

International Journal of Diabetes & Metabolic Disorders

The Body Mass Index BMI Should be Abandoned in Favour of the Body-Shape Index BSI for Controlling Body Weight in Adults

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Submitted: 11 Nov 2016; **Accepted**: 19 Nov 2016; **Published**: 24 Nov 2016

Abstract

Objective: *This paper aims at optimal metrology for defining healthy weights in humans using weight-height ratios.*

Study Design: *Normal appearing Caucasian males and females of any age and height were stochastically selected individually and grouped into cohorts of gender, different heights and ages, in order to apply rigorous statistical analyses, using the least squares method of Gauss.*

Methods: *246 Caucasian males and 258 Caucasian females of "normal" appearance represent an unbiased stochastically selected cohort sufficiently large to analyse statistically individual and cohort values for Body-Mass-Index, kg/m^2, and Body-Shape-Index, kg/m^3, relating to gender, height, and age.*

Results: *For Caucasians taller than ~1.2m the BMI is largely inferior to the BSI. In adults, the single average normal weight BSI value is 12.54 for males and 12.36 for females, with standard deviations of 1.67 and 1.95, respectively. For children smaller than ~1.2m the BMI is superior showing at normal weight an average value of ~16.0 for males and ~15.2 for females, with standard deviations of 1.70 for males and 1.66 for females. The difference between BMI and BSI applicability lies in the proportionality of body shapes changing with growth from childhood to adults.*

Conclusions: *The BMI is the choice for weight control only of children of <1.2m. In individuals taller than 1.7m, a single BMI value introduces serious errors and should not be used. The BSI provides a stable value with height >1.2m and should replace the BMI. - BSI and BMI cut-off values are given for severe underweight, overweight and obesity for males and females for clinical guidance and use in public health.*

Keywords: Body-mass index, Body-shape index, Controlling healthy weight.

Pathogenesis of Metabolic Syndrome

This paper takes a new look at the old issue of optimal metrology for defining healthy weight and its relevant deviations in the attempt to guide individual weight control, decisions in clinical medicine and serving Public Health. Of course, healthy weight varies between individuals and average weight values in populations are defined with their statistical constraints. Various metrological approaches aim at optimal precision. For more than a century physicians tried to quantify the degree of obesity by checking skin-folding on physical examination of the patient, or ratios of body weight (W) and body height (H) in various ways have been proposed, such as W/Hp, the "Benn Index", or W/H^2, which was early on also named Quetelet Index [1,2]. Particularly for babies and small children the radio W/H^3, called Ponderal Index, appeared to be better than birth weight for predicting the course of a number of pediatric illnesses [3]. Within limited ranges of age and heights, all these indices seemed to be reasonably accurate. The ratios W/H^2, now conventionally termed "Body-Mass-Index" (BMI), and the W/H^3, here termed the "Body Shape Index" (BSI), appeared both especially useful for estimating the "Ideal Body Weight" [4]. However, an extended study on the degree of correlation between the various weight/height indices concluded that the BMI and the "Benn index" were not correlated with height; yet they still showed the strongest correlation with skin fold measurements [5]. Lack of a constant correlation between weight and height also derives from a large cohort study showing the BMI value to increase with age between ~6 and 20 years [6].

Objective quantification of normal weight and its deviation demands a body-mass index which allows the calculation of the mass of a healthy individual from its height reliably and with reasonable accuracy for self-control in public health, and for clinical medicine in patients at risk especially of obesity and its related clinical diseases [7-14]. Also underweight persons have an increased risk of premature death and those with moderate overweight appear to have a lower mortality risk [15,16]. Obviously, the most accurate and reliable body-mass-ratio should be preferred for guidance in public health, clinical medicine and research.

To-day, commonly used is the BMI, (weight in kg/square-height in m^2) and its average value in adults 21.7 despite severe criticisms regarding its reliability [17]. Thus, the BMI tends to make small normal weight persons appear underweight, and tall normal individuals appear overweight [18]. A single BMI value in adults only applies within a narrow height region from ~1.6 to 1.7 m [18]. Moreover, in normal-weight children BMI values are significantly lower than for adults [6,13,14,18]. Alternatively to the BMI, the ratio kg/m^3, the BSI; shows fair constancy irrespective of height in people taller than ~1.2m, but it is not constant in children [19]. Here we report on data on normal-weight persons from birth up to 94 years in order to determine which of the two indices is most practical, covers best large ranges of human heights and ages for males and females, and yields sufficiently precise cut-offs for defining underweight, overweight and obesity. While BMI data on large cohorts of children and young adults up to 20 years old are available a broad population based comparison between the BMI and BSI for all age groups has not yet been reported [6]. This current study shows the inferiority of the BMI against the BSI for most individuals taller than ~1.2m. Below the height of 1,2m, the BMI is superior to the BSI.

Methods

Body Mass Indices

The BMI has been defined by Kuczmarski and Flegal [17]. “The most recent transition is a … single body mass index (BMI; in kg/m^2 …) ... applicable to all adults… independent of age … internationally.” Healthy weight average BMI was defined to be 21.7 and ranges between 18.5 and 25.0 kg/m^2, for overweight it is between 25 and 29.9 and for obesity above 30.0. The dimension of the BMI, mass/m^2, is an area density. Using kg as weight yields a pressure that is relevant clinically.

The Ponderal Index (kg/m^3) was considered by Quetelet [1], Florey [20], and Fayyaz [21]. For this ratio, the term Body-Shape Index, BSI, is an appropriate expression, because it is intimately related to the shape of the human body. It is defined as: human body mass / (cube of its height) (kg/m^3). The human body has a nearly constant volume density with an average value being within about +/- 2% that of water.

Data Sources

The data for this study comprise individual values from each of 246 Caucasian males and 258 Caucasian females with “normal” weight, providing cohorts sufficiently large for statistical analyses. The data were collected at random, i.e., stochastically, in order to avoid bias. The individually measured subjects stem from local physicians, schools, circles of family, friends, colleagues, co-workers, and their family members, and cover ages from birth to 94 years. Persons with a BMI value larger than 30, indicative of obesity, or appearing outright skinny indicative of severe underweight, were not included in our data sets so that representative cohort sizes encompassed “normal weight” individuals.

Statistical Analysis

The size of the cohort in this study permits plotting the individual values and thus allows appreciating the individual data scatter and formation of data clouds [22]. Note that individual values and the degree of data scatter around the mean are inversely proportional to the value of the index denominator height in terms of m, m^2 or m^3, as further discussed under results.

We analysed all BMI and BSI values that fall into regions of approximate constancy, as shown below in figures 1 to 3 using the rigorous least squares method of Gauss [23]. From n individual BMI values a_{Mi} their mean value a_M is obtained, with its uncertainty u (a_M) and its standard deviation d(a_M). The standard deviation (SD) is proportional to the width of the BMI distribution, the accuracy of its centre equals u(a_M). For the BSI the calculations of a_S, u (a_S) and d (a_S) were performed similarly from individual BSI values a_{Si}. Because body shapes naturally vary individually, our statistical description is only approximate, so that the chi-square fit yields a number larger than 1; note that chi-square is close to 1 only for a fully random, stochastic sample.

The distributions of the individual BMI and BSI values and their comparison with the Gaussian distribution serve to define “healthy weight”. The centre of the Gaussian distribution is the BMI or BSI mean value a_M or a_S. The distribution is bell shaped with the characteristic parameter sigma, which in our comparison is equal to the respective SD value. This is validated by the good agreement between the measured distributions of BMI and BSI and the Gaussian distribution, except that the BMI and BSI distributions are slightly skewed. This, again, is due to individual variations of body shapes precluding true stochastic distribution. This is the main reason for the chi-square numbers being larger than 1. In fact, the chi square values are about a factor of 2.5 smaller for the BSI than for the BMI fits, indicative of the greater precision of the BSI.

The area between a_M (or a_S) – 2SD (a_M (or a_S)) and a_M (or a_S) + 2SD (a_M (or a_S)) in the Gaussian distribution contains 95.4% of the total values. We define members of our cohort to have “healthy weight”, if they fall into that interval, even if this cohort includes, as referred to below, underweight and overweight individuals. For instance, this male BMI distribution interval covers 94% and the female BSI distribution interval 94.7% of the values. For both males and females only 2.3% are below a_M (or a_S) – 2SD (a_M (or a_S)) or above a_M (or a_S) + 2SD(a_M (or a_S)); and for the male BMI distribution ~3.4% of the values are below and ~1.7% above, and for the female BSI distribution ~1.0% of the values are below and ~3.6% above.

Cut-offs to severe underweight (SU), underweight (UW), overweight (OW) and obesity (OB) for males and females are to be – 2 SD, -1 SD, + 1 SD and +2 SD away from the mean values respectively. We consider individuals who are less than 2 SD away from the mean to be healthy.

Results

Figure 1 summarizes body masses in kg as a function of body heights in m, for females and males separately. Inserted are curves representing BMI and BSI values. In addition to the conventional BMI curve of 21.7, the BMI curve of 15.96 is shown for 63 males and of 15.22 is for 66 females with heights up to ~1.2m. These curves fit in crude approximation a constant BMI value for this group and roughly agree with corresponding data reported by Cole et al. who in their larger cohort observe BMI variations as function of age also during the first years of life [6].

The figure also shows that the data points of the male cohort taller than ~1.8m lie above the BMI of 21.7. Persons shorter than ~1.2m are well below the BMI of 21.7. The BSI curve of 12.54 is for 183 males and that of 12.36 for 192 females taller than ~1.2m. Clearly, all persons with a height above ~1.2m are better fitted by the BSI than the BMI, whereas shorter individuals conform better to the BMI. The BMI and BSI lines intersect at 1.27m for males, and 1.23m for females. This justifies separating the BMI and BSI cohorts at ~1.2m for assessing “normal” weights versus heights.

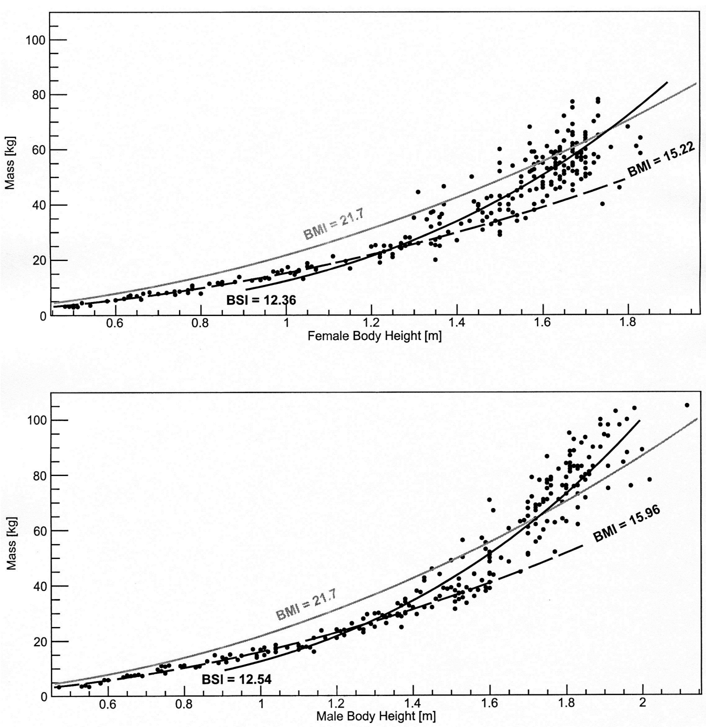

Figure 1: Body masses plotted as function of body heights for 246 males and 258 females.

Figure 1 shows curves for BMI=21.7, and 15.96 and 15.22 for males and females, the latter two being fitted to our data for heights under ~1.2 m and roughly taking the BMI values as constants. The BSI values of 12.54 and 12.36 have been obtained on the basis of our data, again taking the BSI values as constants. The scatter of the points reveals the degree of difference between individuals.

Figure 2 shows for males and females the BM and BSI fits as a function of height. The line of the BMI of 21.7 is incompatibly far above the points for body heights up to ~1.3m for females and ~1.4m for males, but it cuts through the data cloud for females at a body height of ~1.6m and ~1.7m for males. The fitted BMI and BSI lines are placed below and above the height of ~1.2m for both males and females. The BSI is reasonably constant for people taller than ~1.2m, but does not at all cover the data of people shorter than ~1.2m. On the other hand, the BMI appears roughly constant in males, 16.0, and females, 15.2, below ~1.2m.

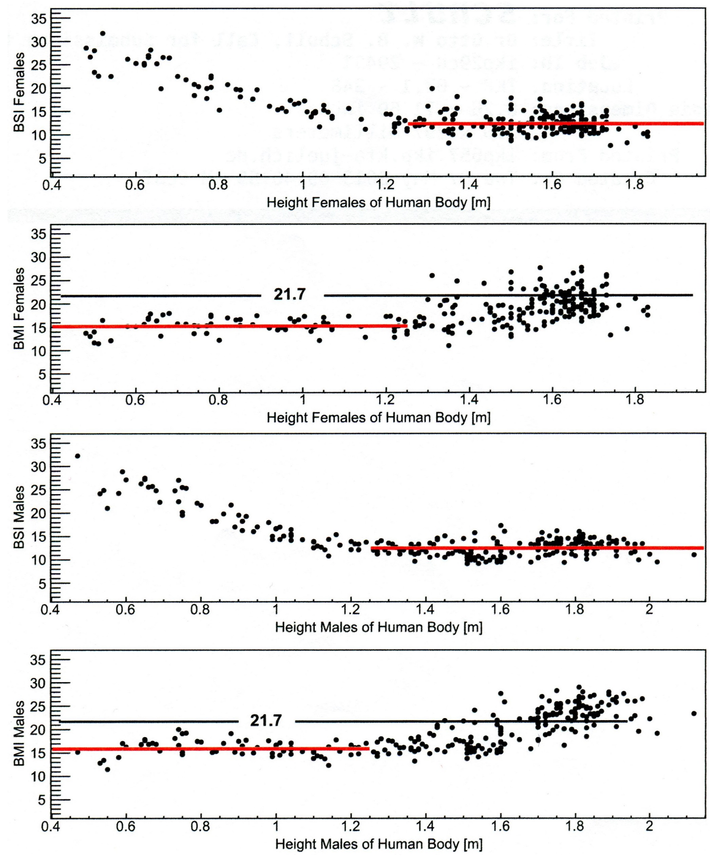

Figure 2: BMI and BSI values as function of body heights for males and females.

In figure 2, BMI lines are fitted to our data of BMI for individuals smaller than ~1.2m, and BSI lines for individuals taller than ~1.2m, separately for males and females.

Figure 3 gives the individual data on the BMI and BSI as a function of age. Compatible with the data in figure 2 the BSI shows approximate constancy for males and females older than 6.2 years and there is not a single BSI value that fits all data below 6.2 years. The BSI values for individuals older than 6.2 years are in good agreement with those taller than ~1.2m. The data points for the BMI from individuals younger than 6.2 years are approximately consistent with the corresponding findings of Cole et al. [6].

There is, independent of gender, a transition zone of BMI data between the ages of ~6 and 14 years. At older age, the BSI data spread less than the BMI and provide the better data fit.

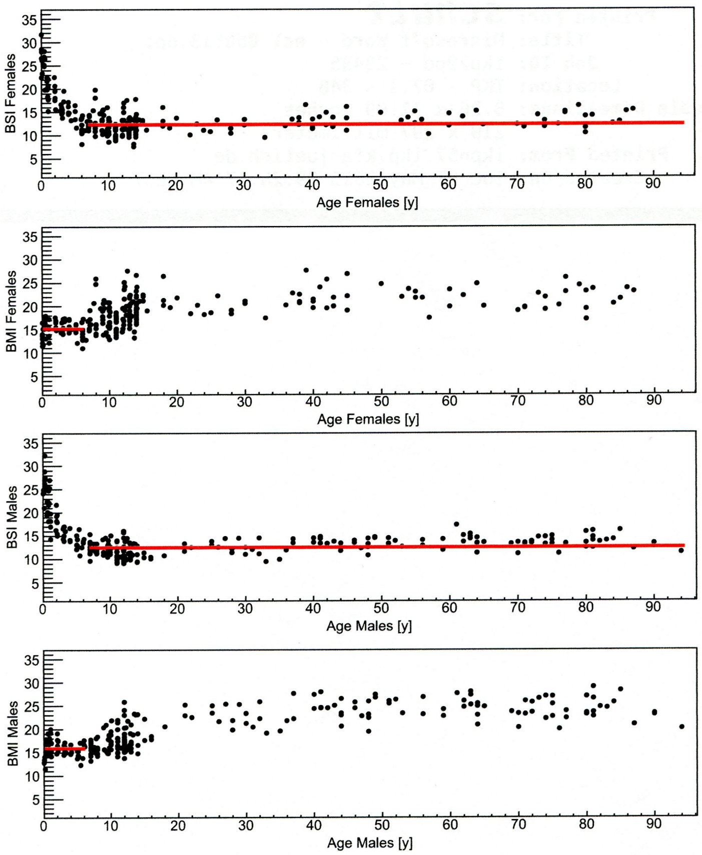

Figure 3: BMI and BSI values as function of age for males and females.

In figure 3, BMI lines are fitted to our data of BMI for individuals younger than 6.2 years. The BSI lines are for persons older than 6.2 years, separately for males and females.

Least-Squares Fits

The best least-squares fits of individual BSI values at heights above 1.2m and ages above 6.2 years yielded the following results for males and females for the mean body shape indices a_S, their uncertainties $u(a_S)$, the SD values $d(a_S)$, and chi-square values.

For males: a_S= 12.54 kg/m^3, u (a_S) = 0.12 kg/m^3, d (a_S) = 1.67 kg/m^3, chi-square = 2.8.

For females: a_S= 12.36 kg/m^3, u (a_S) = 0.14 kg/m^3, d (a_S) = 1.95 kg/m^3, chi-square = 3.7.

In order to check on the influence of age on the BSI in older children and adults, the whole cohort was divided into three sub-cohorts: 1) ages between 6.4 - 20.5, 2) ages between 20.5 - 45.5, and 3) ages above 45.5 years. The BSI values of the youngest cohort are 5.4% for males (2.3% for females) below the mean BSI values of 12.54 for males and 12.36 for females, whereas these deviations are plus 2.4% (1.4%) in the middle cohort and plus 8.5% (8.4%) in the oldest cohort above the mean BSI.

This corresponds to an increase of the BSI of 14% for males and 11% for females over ~50 years, or ~0.25% per year. Note that the degree of precision is limited by individual variations with growth and advancing age in the studied cohorts.

A second test of age-dependence observes the mean ratios of BMIs and of BSIs from the age groups older than 45.5 years and between 6.4 and 20.5 years. These ratios are:
For males: BMI (>45.5)/BMI (6.4-20.5) = 1.40 BSI (>45.5)/BSI (6.4-20.5) = 1.18.
For females: BMI (>45.5)/BMI (6.4-20.5) = 1.15, BSI (>45.5)/BSI (6.4-20.5) = 1.11.

Both tests agree with a slight increase of the indices with age.

Discussion

The current literature on obesity and its consequences to health and economy conventionally uses the BMI with the value of 21.7 for healthy weight [17]. This is done on the assumption of applicability of the conventional average value of the BMI to cohorts of people over wide ranges of heights and ages. The validity of this assumption has been put to question repeatedly and has been considered even to be misleading [24]. In fact, the caveats with the BMI are such that the suggestion arose to abandon this ratio all-together. The results of the present analysis illuminate how misleading the conventional BMI may be. Two aspects need attention. One involves the range limits of its applicability in practice and the other is the concept of the BMI as such. Both aspects are intertwined.

Regarding range limits of applicability, the BMI curve for 21.7 in figure 1 intersects with the BSI curves at the height of ~1.7m. Below and above this range of heights, see also figure 2, the BMI of 21.7 is either too high or too low, respectively. Thus, by applying a single BMI value in Public Health and for clinical guidance one misleads recommendations to obtain a healthy weight [24]. Yet, the BMI is useful for people shorter than ~1.2m or younger than ~6.2 years. However, the conventionally used BMI of 21.7 is much too high for children. On the other hand, the BSI is inapplicable for or persons younger than ~6.2 years.

The reason for the age-dependence and height-dependence of the BMI-BSI discrepancy lies in the very significant difference between body shapes of children younger than ~6.2 years and adults. As children grow and gain weight, the proportions between their body parts change. The near constant BSI in adults relies on the fact that the adult body parts are proportional to each other, with near constancy of their mass ratios largely independent of body height. The uniqueness of the relationship between various body part sizes and masses in adults complies with the "golden cut" [25,26]. The golden cut is not only well known in monumental architecture but also holds for the architecture of the human body. Famous examples are the Sistine Madonna or Mona Lisa by Leonardo da Vinci. For instance, the ratio of body height to naval height is about equal to the ratio of shoulder width to thorax depth. This ratio amounts to about 1.618, the" golden cut". Because of the common mass density of the human body one may explain the BSI as follows: Take a cube with height H of 1 m, filled with water.

Its weight is then one ton and its BSI is 1 ton/m^3. The adult human body with height H does not fill the cube with height H completely, but only to the fraction of it. Thus, on average 12.54 kg/m^3 out of 1ton/m3 is 1.254 per cent of 1 ton. Indeed, the BSI reveals about the fraction of 1 ton of water, actually of tissue, that presents the mass of the body.

Regarding the concept of the BMI, its definition expresses an area density, not a volume density of the human body. This distinction appears numerically (BMI versus BSI) irrelevant for people with heights around 1.7m as shown in figure 1, and has been discussed above.

The age-dependent BMI values of children and young adults up to 20 years have been obtained by Cole at al. for large cohorts out of six nations [6]. For 8 girls and 10 boys up to 1 year old, our BMI values are 15.6 and 16.6, respectively, somewhat but not much smaller than the values that Cole et al. found for the British individuals. For 11 girls and 11 boys with ages between 2 and 5.4 years we find an average BMI of 15.8, in very good agreement with the figures 1 and 2 of Cole et al. Our BMI results are within our statistical uncertainties in agreement with the results of Cole et al. and are considered sufficiently precise for clinical application.

The increase of the BMI with age between ~6 and 20 years reported by Cole et al. is also the finding of the Copenhagen group [6,10]. They show a BMI increase of 15.5% for males and 18.8% for females for an age difference of 6 years which corresponds to about 2.8% per year [7-13]. The BMI values of Cole et al. change from ~15.6 at 7 years to ~21 at 18 years, an increase of ~2.7% per year [6]. These increases are similar to what we find for the BMI in our study, as seen in figure 3. But this figure also shows that there is no increase if one uses the BSI as body mass index for ages above ~6.2 years.

Conclusion

On the basis of the data analysed and reported here, we recommend to use the following indices for healthy weight individuals: Mean values, cut-offs to severe underweight (SU), underweight (UW), overweight (OW) and obesity (OB) for males and females for the BMI and BSI.

For males (M)/females (F) >1,2m, we recommend to abandon the BMI in favour of the BSI. Here, the following values apply for 3 age cohorts:

M, 6.4 to 20.5 y: BSI mean =11.9, SU=8.6, UW=10.2, OW=13.5, OB=15.1
20.5 to 45.5y: BSI mean =12.8, SU=10.1, UW=11.5, OW=14.2, OB=15.6
>45.5y: BSI mean =13.6, SU=11.1, UW=12.3, OW=14.9, OB=16.1

F, 6.4 to 20.5 y: BSI mean =12.1, SU=8.1, UW=10.1, OW=14.1, OB=16.1
20.5 to 45.5y: BSI mean =12.5, SU=9.2, UW=10.9, OW=14.2, OB=15.9
>45.5y: BSI mean =13.4, SU=10.2, UW=11.8, OW=15.0, OB=16.6

For people <6.2 years and <1.2m, we recommend to evaluate proper weight in kg as function of height in m using the BMI, with reference to Cole et al. for higher precision as function if age at the first years of life [6]. As BMI cut-off points the following values arise:
Males: BMI mean = 16.0, SU=12.6, UW=14.3, OW=17.7, OB=19.4
Females: BMI mean = 15.2, SU=11.9, UW=13.6, OW=16.9, OB=18.5

More detailed investigations are beyond the scope of this study. They could reveal a slight age dependence of the BSI and ethnic differences.

Our intention was to find a simple, reliable and easy-to-use body mass relationship for healthy weight individuals from birth until high ages, for everyone to apply and for easy orientation in public health. This goal has been reached in this paper and should motivate to a life and consumer style commensurate with optimal health [27].

Appendix

Individual (i) masses Mi and heights Hi served to calculate individual BMI values a_{Mi} =Mi/Hi^2, and correspondingly BSI values a_{Si}=Mi/Hi^3.

BMI cohorts

From n individual BMI values a_{Mi} the mean value a_M is obtained by summing all a_{Mi} values from i=1 to i=n, the cohort size and dividing this sum through n. The uncertainty u(a_M) of the mean value a_M is given by the square root of the sum, from i=1 to i=n, of $(a_M-a_{Mi})^2/[(n-1)\bullet n]$. The standard deviation d(a_M), or SD, the mean difference between the individual values a_{Mi} and the mean value a_M is the square root of the sum, from i=1 to i=n, of $(a_M-a_{Mi})^2/(n-1)$. This is also u(a_M) times the square root of n.

BSI cohorts

Calculations for the BSI cohorts are carried out in analogy to the above calculations, from individual BSI values a_{Si} and the relevant cohort size number. The results are a_S, u(a_S), and d(a_S).

Chi-Square

Regarding the meaning of the χ^2 (chi-square) value the reader is referred to Bevington [23].

Acknowledgements

The authors deeply acknowledge the profound discussions with Dr. Walton W. Shreeve. We are very grateful to Prof. Dr. Berthold Schoch for reminding us of the importance of the application of the golden section to the human body. We gratefully acknowledge the invaluable help of the paediatricians Dr. G. Klughardt, Drs. St. Bannig, St. Klein, E Janas-Schroeteler, Dr. St. Zaum, and the directors M. Bardenheuer, A. Lafos, M. Gutberlet, and H. Rombach for providing us with many data on school children. Dr. Irakli Keshelashvili deserves our special thanks for his invaluable help with the data analysis. We are most grateful to Prof. Dr. Mult HC. Hans Ströher for his support of our work.

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