

Invited Review

Exposed Body Surface Area—A Determinate for UV Radiant Energy in Human UV Exposure Studies

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ABSTRACT

Solar ultraviolet (UV) exposure of people and related health risk is mainly examined by estimating the received UV radiant exposure. However, for several effects such as DNA damage, vitamin D photosynthesis or the probability of developing skin cancer, UV radiant energy is important and with that the size of exposed skin area. There is also a complex interaction between body shape and behavior like sun exposure habits, so that careful analysis is necessary when estimating health effects from UV exposure. In this paper, knowledge on body shape and methods of calculating the total body surface area (BSA) are summarized. BSA depends mainly on the height and weight of a person as well as on gender, ethnicity and body shape. BSA and body shape differ significantly between different populations and both change during life. This paper proposes formulas for BSA that consider height, weight, gender, ethnicity and body shape. As the exposed BSA depends on clothing, finally an approach is presented which aims to calculate the size of body parts released by real garments. In summary, this paper will enable future researchers to quantify the exposed BSA by best matching their study population and consequently investigate risks caused by solar UV exposure.

INTRODUCTION

The quantification of personal UV exposure is carried out with different measures in dependence of the biological endpoint. A first approximation can be done by using the biologically effective irradiance E_{eff} , which gives the radiant flux (or radiant power) received by a flat surface. In detail, the biologically effective irradiance E_{eff} is the spectral irradiance $E(\lambda)$ weighted by the spectral biologically effectiveness $s_{\text{eff}}(\lambda)$ (called action spectrum) and summed up over the corresponding wavelength range:

$$E_{\text{eff}} = \int s_{\text{eff}}(\lambda) \cdot E(\lambda) d\lambda \quad (1)$$

It is expressed in units of W m^{-2} . Preferably, both the symbol for irradiance E as well as its unit can be marked with a subscript to indicate the considered effect like E_{ery} or $W_{\text{ery}} \text{ m}^{-2}$ for the erythemally effective irradiance. This avoids mismatch. For example, solar erythemally weighted irradiance of $1 W_{\text{ery}} \text{ m}^{-2}$ (with $s_{\text{ery}}(\lambda)$ according to the CIE 2019 [1]) can correspond to Vitamin D weighted irradiance (with $s_{\text{VitD}}(\lambda)$ according to the CIE [2]) between 2.11 (SZA = 27.5°, 275DU) and 0.66 $W_{\text{VitD}} \text{ m}^{-2}$ (SZA = 82.5°, 395 DU) (e.g. ref. [3], Schmalwieser 2020 [4,5]).

Accumulation of this irradiance over time leads to the biologically effective radiant exposure H_{eff} , which is the sum of incident irradiance over a certain period. It is expressed in $J_{\text{eff}} \text{ m}^{-2}$.

$$H_{\text{eff}} = \int E_{\text{eff}}(t) dt \quad (2)$$

Radiant exposure is often mixed with the term “dose,” which describes the radiant energy absorbed by a certain volume or mass (and is therefore expressed in W m^{-3} or W kg^{-1}). In rare cases, the radiant exposure can be used as a surrogate for dose, for example, when its relation (influenced by surface reflection, overlying pre-absorption, density and location of target molecules and others) to dose is known (4). For example, an erythemally weighted radiant exposure of $250 J_{\text{ery}} \text{ m}^{-2}$ may correspond to the minimal erythema dose (MED) in previously unexposed skin at the back of a light-skinned individual. It does not correspond to the MED on another body part of the same individual because of differences in skin thickness, pigmentation or others. As another example, $2500 J_{\text{ery}} \text{ m}^{-2}$ may not be equalized to 10 MED (or 10 times the MED) because the dose–response relationship of erythema is not linear, and this radiant exposure does not cause 10 times the Reddening from $250 J_{\text{ery}} \text{ m}^{-2}$.

Biologically effective radiant exposure is the most frequently used quantity when estimating the UV exposure of people, respectively, when estimating the health risk resulting from UV exposure. In some cases, the biologically effective UV radiant energy Q_{eff} (expressed in unit of J) is the measure of relevance, like for DNA damage (6), Vitamin D photosynthesis (7) or the risk to develop non-melanoma skin cancer (8). It is the cumulated irradiance over time and area A :

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$$Q_{\text{eff}} = \int \int E_{\text{eff}}(A, t) \, dA \, dt \quad (3)$$

In certain cases, Q_{eff} corresponds to H_{eff} multiplied by the size of the area.

The quantification of the exposed area A in humans is a difficult issue. The size of the exposed area depends on the stature as well as on the clothing of a person. Human stature, respectively, body size and body shape, became adapted during human evolution. Stature differs by gender and ethnicity (9), it is influenced by nutrition and personal habits, which have both strongly altered during the past hundred years, and changes during an individual's lifetime (10). In the following chapters, we will assess the human body shape and the calculation of the body surface area (BSA).

BODY SHAPE

Body shape, stature and figure of a person

The shape of a body exerts a considerable influence on the surface area of the body (11,12) and on the size of the areas exposed to the sun by style and or by lack of clothing. It is commonly acknowledged, that the surface of a cube is smaller than the surface of a cuboid at the same volume (or weight, if density is the same). Therefore, we can expect that the ratio of weight (=volume) and height will influence the BSA of a human. However, in humans this relation is more sophisticated than in geometrical bodies. The body shape, stature or figure of a person is determined by the combination of skeletal structures and the distribution of muscles and fat. The skeletal structure grows until adulthood and exhibits sexual dimorphism. This is also true for the distribution of muscles and fat, but both may change throughout adulthood. The quantitative description of the body shape is a rather complex issue and results from a variety of different measures (see Fig. 1) (13).

Body mass index, ponderal (Rohrer) index and Broca-Weight

Maybe the most well-known parameter, that can be considered as descriptor of the body shape, is the body mass index (BMI). Called Quételet Index until 1972 (14), it was defined in 1832 by

Adolphe Quételet (15,16) and relates an individual's body mass to their height:

$$\text{BMI} = \text{mass (kg)} / \text{height}^2 \text{ (m}^2\text{)} \quad (4)$$

The BMI is frequently used to estimate health risks from underweight (BMI < 18.5), overweight (BMI ≥ 25) or obesity (BMI > 30) (17). Reliable data on the average BMI from most countries in the world are available (18,19). However, it is only a raw guide value, because the BMI has a several shortcomings. It does not distinguish between muscle and fat, between different fat locations and does not distinguish for gender and ethnicity. A worldwide overview of the BMI is given in Fig. 2 for both sexes. It can be seen that BMI values differ by gender. Clear geographical differences can be recognized, which may indicate differences by ethnicity as well as by nutrition. The BMI itself does not provide any information on the origin of these differences. The highest BMI occurs in south pacific islands with mean values up to 33.1 in males and 35.2 in females (both American Samoa). During the past decades, the BMI has increased in many parts of the world and has become a matter of concern (19).

In comparison with the BMI, the so-called Rohrer Index or Ponderal Index (20,21) is less popular among non-scientific audiences:

$$\text{PI} = \text{mass (kg)} / \text{height (m)}^3 \quad (5)$$

The PI is almost a dimensionless index as necessary for similitude theory. For a cube, it would correspond to density. Its application range is somewhat larger than that of the BMI, because it is valid for very small as well as very tall bodies. A PI between 11 and 14 denotes normal weight. Recommended values are valid for adults. For children, different threshold values are valid in both, PI and BMI. Figure 3 depicts the weight in dependence of height for the range of normal weight according to PI (11–14) and BMI (18–25). It can be seen that the BMI penalizes tall people, respectively, favors small individuals, the PI does *vice versa*.

The third value that can be seen in Fig. 3 is that of the Broca Index (BI), which is defined as:

$$\text{Broca Index} = \text{weight (kg)} / \text{Broca-Weight (kg)} \quad (6a)$$

The Broca-Weight means normal weight and was defined by Pierre Paul Broca in 1871 (22) is written as:

$$\text{Broca-Weight (kg)} = \text{height (cm)} - 100 \quad (6b)$$

A BI of <0.85 denotes underweight, of 0.85–1.0 normal weight and of >1.0 overweight. The Broca-Weight (BI = 1) runs close to the weight for a PI value of 14 up to a height of 175 cm and close to the weight for a BMI of 25 for taller people. With that, it corresponds to the minimum limit to overweight from both measures.

The PI is less often used than the BMI, therefore, much less data are available than for the BMI. However, if height and BMI are known (as in the case of the NCD-RisC data base) the PI can be calculated.

$$\text{PI} = \text{BMI (kg/m}^2\text{)} / \text{height (m)} \quad (7)$$

Figure 4 depicts the worldwide distribution of the PI. PI values were calculated using BMI and height from NCD-RisC (19) data. The color scale is comparable to that of the BMI in Fig. 2. With

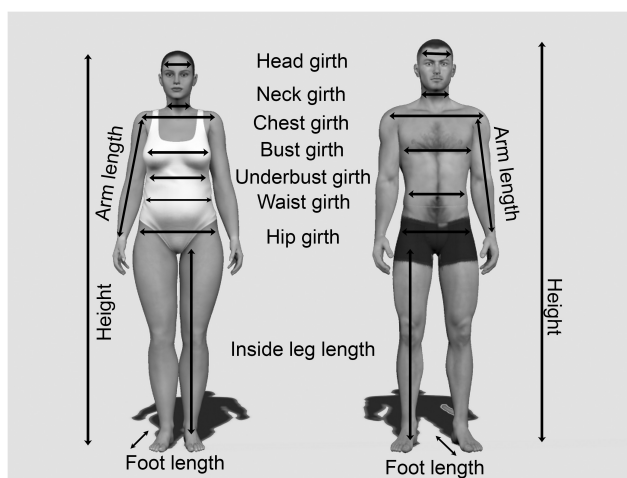
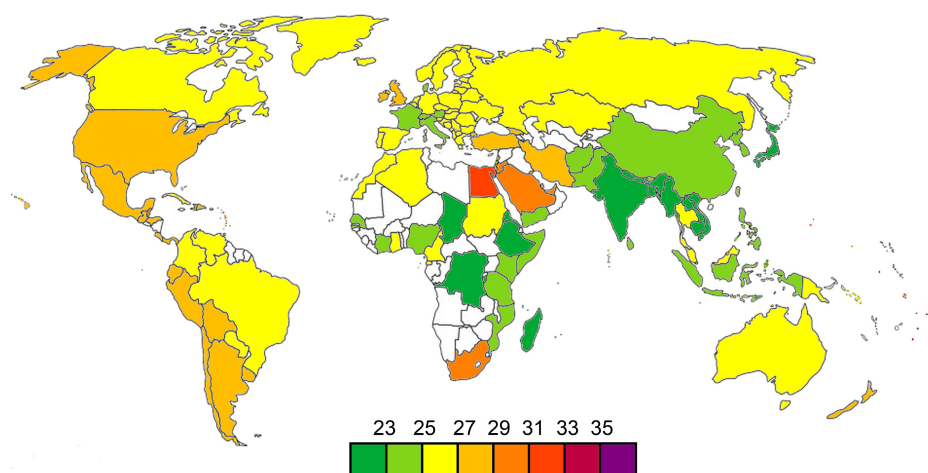


Figure 1. Measures to describe the body shape of a person according to EN13402-1 (2001) (13).

a) BMI - Females



b) BMI - Males

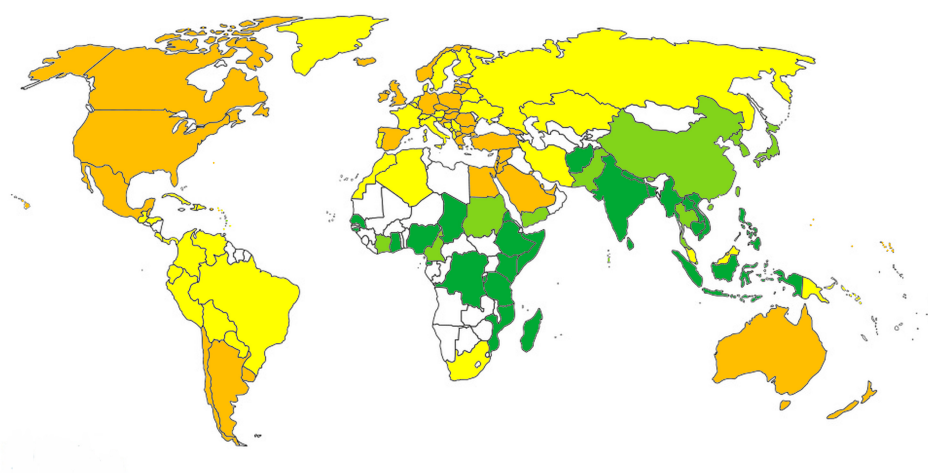


Figure 2. Body mass index (BMI) according to NCD-RisC data (19) a) for females and b) for men. White color denotes that there is no data available. Values up to 25 are rated as “normal weight,” up to 30 as “overweight,” up to 35 as “1st degree obesity” and higher than 35 as “2nd degree” obesity.

that, both figures can be compared. In comparison with the BMI, the PI is reduced in taller bodies (*e.g.* men and taller ethnicities) and enhanced in smaller ones (*e.g.* women and smaller ethnicities). One can see that the global distribution of the PI somewhat differs from that of the BMI, because the BMI penalizes taller people and favors shorter people. With that, the relative weight according to the PI decreases (compared to BMI) in Europe and increases in East and South-East Asia. Differences in gender are obvious. Similar to the BMI, the highest PI values can be found in the populations of the south pacific islands with values up to 19.3 in males (Nauru) and 21.1 in females (American Samoa).

Anthropogenic measures

The Waist-to-Hip-Ratio ignores height and weight of people is originally an aesthetic measure and seems to be important in human perception of the body shape or silhouette (23). In medicine, it is used to estimate health risk from overweight. Contrary to BMI, PI and BI, it focuses on the distribution of fat on the

lower trunk and considers gender. A Waist-to-Hip Ratio of <0.80 denotes normal weight in women and of <0.90 in men. Adiposity starts at >0.84 respectively >0.99 (24).

The Waist-Height Ratio is another measure of appearance (25). The health-related optimum changes with age: <40 year: ≤ 0.5 , 40–50 year: $\leq 0.5–0.6$ and >50 year: ≤ 0.6 . Indirectly, this measure depicts the change of the body shape during life.

A variety of such anthropometric measures has been developed during the past. These measures describe the shape, respectively, the relative weight, for estimations of health risk mainly due to obesity. For a recent overview, see Jayawardena *et al.* (26).

A different approach to describe the body shape was undertaken by William Shaldon (for nowadays obsolete scientific purpose), who divided body shapes into ectomorph (leptosom), mesomorph (metromorph) and endomorph (pyknomorph) (see Fig. 5). Later on, the Heath-Carter formula was developed to quantify these so-called somatotypes. For this, a variety of measures like different skin fold thicknesses, bone breadths and

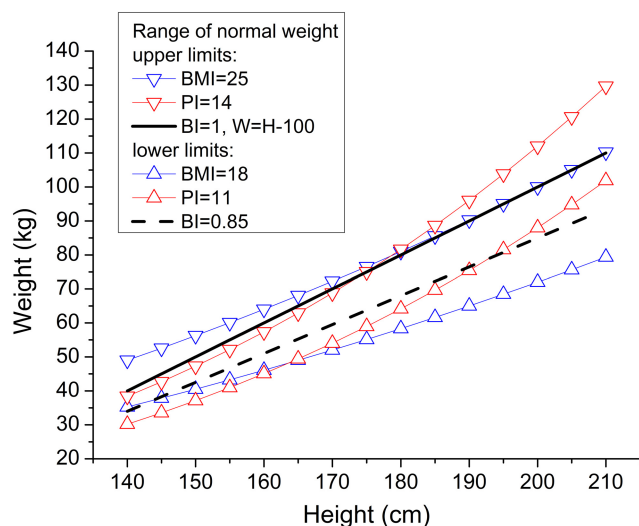


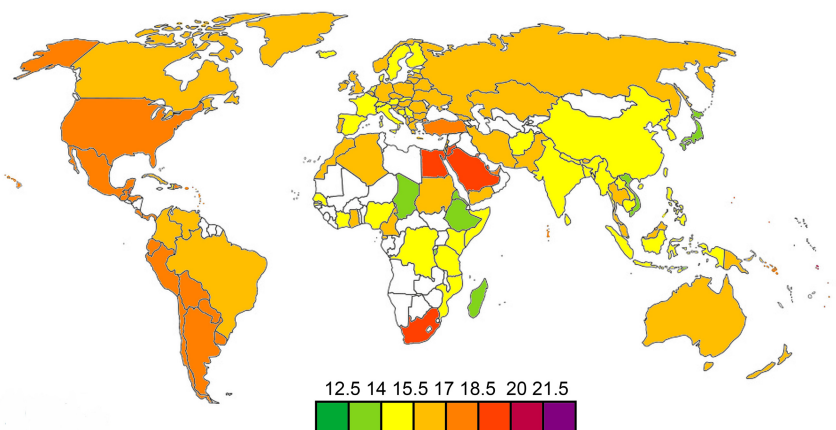
Figure 3. Range of normal weight according to a Ponderal Index (PI) of 11 and 14 (red symbols and lines), according to a body mass index (BMI) of 18 and 25 (blue symbols and lines) and according to a Broca Index (black lines) of 0.85 and of 1.0 (weight = height–100) in dependence of height.

muscle girths are necessary (27) as input parameters. One of its main applications is in athletes, as it indicates the ability or disposition of building muscles and fat.

Body shape in fashion

Today's research in body shape is mostly related to female apparel and the fashion industry. In this context, a variety of body shape categorizations is in use. Some of these refer to fruits (e.g. pear figure, apple, ...), others to letters (e.g. A, V, X, H, O) (28,29). In general, categorization is based on body circumferences like bust, waist and hip. In a few cases, the relative length of the legs is considered. The chest girth is often neglected. A quantitative scheme was introduced by Lee *et al.* (30) and recently adapted by Sokolowski and Bettencourt (31), dividing female body shapes into "Hourglass," "Rectangle," "Triangle" and "Inverted Triangle," "Oval" and "Diamond." The type "Hourglass" is subdivided into "Ideal Hourglass," "Top Hourglass" and "Bottom Hourglass." The body shape "Bottom hourglass" progresses into "Spoon" (see Fig. 6). The division in this scheme bases on differences in girth of bust, waist, high hip and hip. Basing on this categorization, several studies have been

a) PI - Females



b) PI - Males

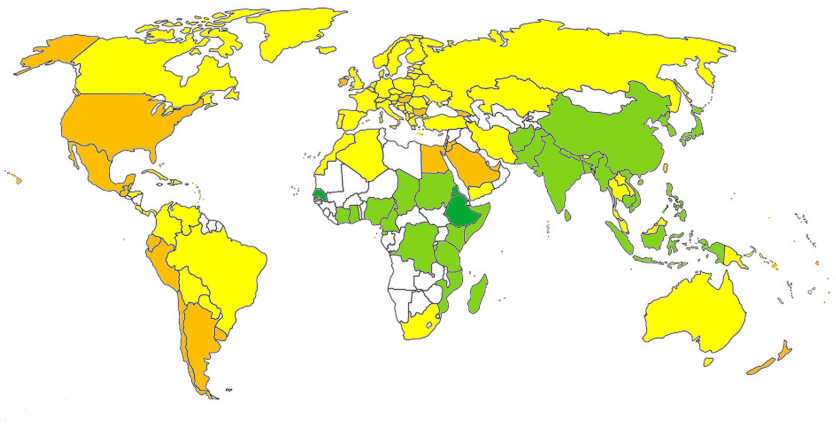


Figure 4. Ponderal Index (PI) or Rohrer Index calculated from NCD-RisC data (19) a) for females and b) for males. White color indicates that there is no data available. A RI between 11 and 14 denotes normal weight.



Figure 5. Somatotypes ectomorph (left), mesomorph (middle) and endomorph (right).

undertaken, which investigated the percentage of shapes in woman in several countries. It could be shown that the body shape of women varies between ethnicities and geographic locations. Additionally, it was shown that body shape changes with age (30,32,33). For male body shapes, such a quantitative categorization is missing. Figure 6 depicts a qualitative division for males following that for females. In men, the chest girth is preferred against the bust girth as the measure of relevance.

Body shape and UV exposure

A variety of studies are available which investigated UV radiation-related topics like Vitamin D level (34–36) or the risk of skin cancer (37–39) in relation to body shape measures like BMI, Waist-to-Hip Ratio and others. Results of the studies are partly contrary. The reason for this is the complex interaction between relative weight (*e.g.* BMI, PI) and behavior, like sun exposure habits (including clothing), which is additionally influenced by gender and age (38,40). Careful analysis is necessary in order to divide the body shape, BSA, behavior and sun exposure. For skin color measurements, an increase in the red component (blood flow) with increasing BMI should be considered (41).

BODY SURFACE AREA

In the case of humans, the received radiant energy Q_{eff} depends on the size of the exposed (uncovered or unprotected) BSA, which bases on the size of the total BSA. The BSA is an essential parameter in thermoregulation and its size has developed

during evolution to adapt to climatic conditions and living conditions. Measuring the BSA of a person is a costly procedure. The BSA of an individual can be estimated by methods like coating, substituting the body by geometric shapes, photographic and photometric methods, and nowadays by 3D Scans. Each of these methods has its advantages and disadvantages (42).

Formulas to calculate the BSA

To substitute direct measurements of the BSA, several empirical formulas have been derived for more than a century, initiated by the pioneering work of Meeh (43) in 1879 on thermoregulation and metabolism. Table 1 lists more than 50 formulas (43–93) found by literature search in chronological order, together with a short description of the study population. It should be noted that we have neglected approaches, focusing on a simplification of existing formulas for a quick use like in emergency medicine. Further we would like to recommend Edith Boyd's (54) monograph (available as reprint) which provides very valuable background information as well as a complete overview of activities, formulas and data in this field (until 1935) and traces back to the early developments, like to Leeuwenhook (94) and Abernathy (95).

On a first order, BSA depends on mass or weight W (volume) and height H of a person. Most of the formulas express the BSA allometrically as:

$$\text{BSA} = a * H^b * W^c \quad (8)$$

The coefficients a , b and c are derived to fit the individual BSA measurements of a study population best. Thereby, a is a

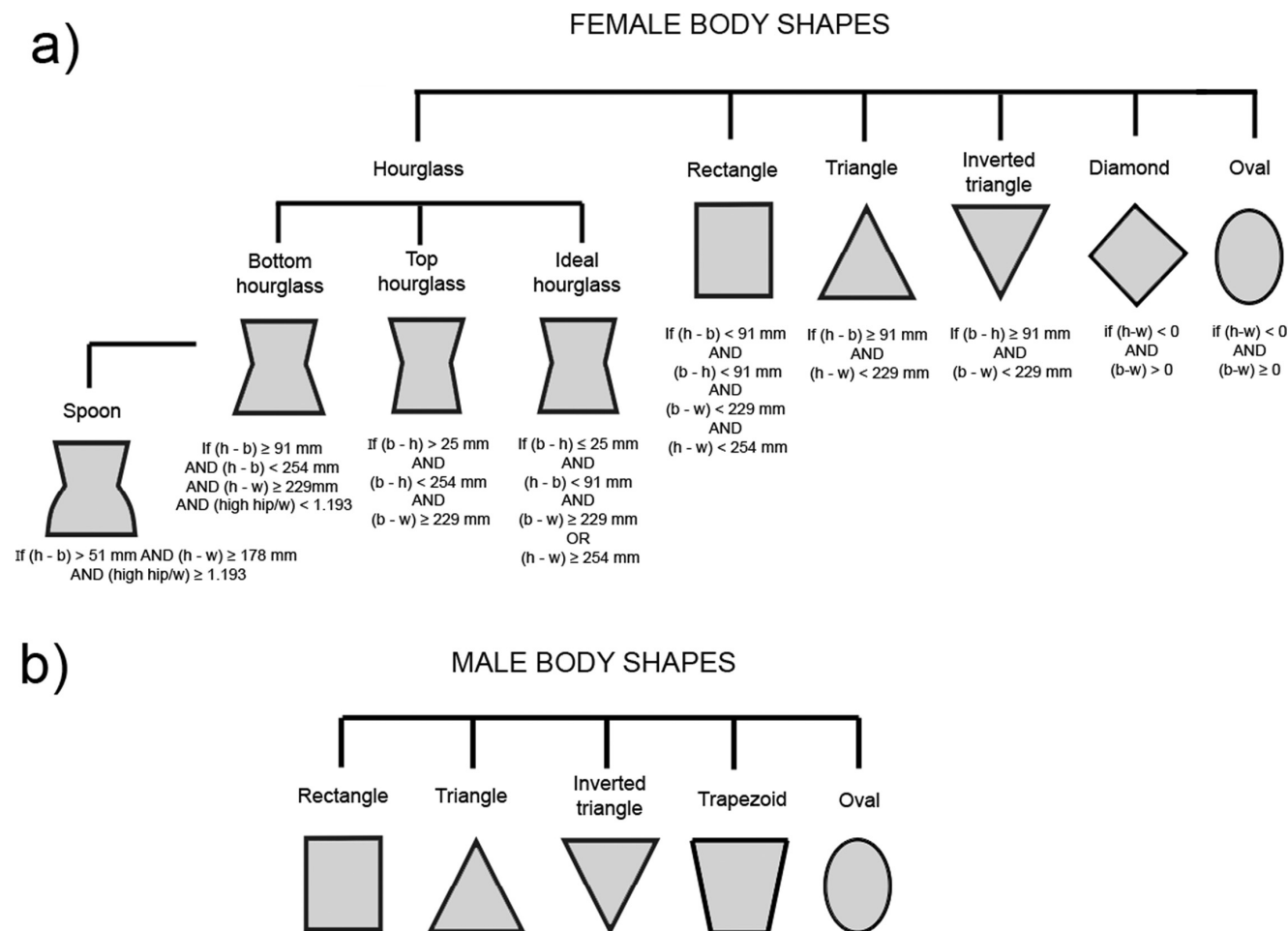


Figure 6. Body shape classification a) for woman body shape classification according to Sokolowski and Bettencourt (31) basing on Lee *et al.* (30) (girths: b = bust, w = waist, h = hip) and b) for men.

conversion factor for the units of H^b and W^c into m^2 , while b quantifies the influence of height on BSA and c that of weight.

Factors affecting BSA

During physical development from birth to adulthood, the proportion of body parts to each other changes significantly. Therefore, different approaches to calculate the BSA of neonates, young children and adolescents have been made. In the very early stages of life, the nutrition status causes obvious differences in proportions, so that different formulas should be used (45,46). In neonates and infants, the weight is preferred as the only measure to determine the BSA, because height may be tricky to measure. Nowadays, the European Medicine Agency (96) divides children into neonates (0–28 days), infants (>28 days–2 years), children (>2 to 12 years) and adolescents (>12 to 18 years), but above studies may have differentiated in a different way.

In respect to gender, there are only slight differences in BSA between women and men (76,80,88). On average, at the same height and weight, the BSA of females is by 1–2% (at Broca-Weight) larger than that of males. This difference increases with increasing BMI or PI, respectively tend to decrease with decreasing BMI or PI. At a height of 170 cm and a weight of 70 kg

(Broca-Weight, BMI = 24, PI = 14), the BSA of females is around 1.83 and 1.81 m^2 for males (according to Tikusis *et al.* [80]).

In a comparison between ethnicities (see Fig. 7), it can be found that for the same height and weight (Broca-Weight), Africans might have a BSA that is around 8% larger, that of Indians might be by 2% larger and that of East Asians (*e.g.* Chinese, Japanese,...) might be by 1% larger than that of Caucasians. This would generally agree with the fact that populations in colder regions should have a smaller surface at the same weight. At the same time, all other populations require a higher share in body fat at the same weight and height. However, the variety of formulas and underlying data do not allow a reliable quantitative interpretation. Further research should be carried out, to quantify differences in respect to ethnicity.

It should be mentioned that the formulas available for a certain ethnicity, like Caucasians, deliver noticeably different results, so that the calculated BSAs differ by around 5% (at the Broca-Weight) (see green dashed lines in Fig. 7). Furthermore, it may seem surprising that so many formulas have been derived. The improvement in accuracy due to newly derived formulas or coefficients was generally small and was rather an adaption to the subpopulation under study, than an improvement in the

Table 1. Collection of formulas to calculate the total body surface area (BSA) together with the description of the underlying sample.

	Author(s)	Formula BSA (m ²)	Sample
01	Meeh (1879) (41)	$0.1053 \cdot W^{2/3}$	
02	Miwa and Stöltzer (1898) (42)	$0.0045335 \cdot \text{ChestCirc.}^{2/3} \cdot H^{1/3} \cdot W^{1/3}$	German adults
03	Rubner and Heubner (1899) (43)	$0.119 \cdot W^{2/3}$	German well-nourished infants
04	Lissauer (1903) (44)	$0.103 \cdot W^{2/3}$	German poorly nourished infants
05	Howland and Dana (1913) (45)	$(0.483 \cdot W \cdot 1000 + 730) / 10\,000$	US children
06	Du Bois (1916) (46)	$0.007184 \cdot W^{0.425} \cdot H^{0.725}$	US children and adults
07	Bardeen (1920) (47)	$0.000143 \cdot (2 \cdot 1000 / H \cdot W + 4 \cdot H \cdot (1000 / H \cdot W)^{0.5})$	US children
08	Faber and Melcher (1921) (48)	$0.00785 \cdot W^{0.425} \cdot H^{0.725}$	German new born infants
09	Takahira (1925) (49)	$0.007246 \cdot W^{0.425} \cdot H^{0.725}$	Japanese adults
10	Niya (1931) (50)	$5.4 / 10\,000 \cdot (W / 1000 \cdot H)^{0.5}$	Japanese adults
		$0.63 / 10\,000 \cdot H^2$	
11	Breitmann (1932) (51)	$0.0087 \cdot (W + H) - 0.26$	German adults
12	Boyd (1935) (52)	$0.0003207 \cdot (W \cdot 1000)^{(0.7285 - 0.0188 \cdot \log_{10}(W \cdot 1000))} \cdot H^{0.3}$	US children 0–18 years
		$4.688 \cdot W^{(0.8168 - 0.0154 \cdot \log W)}$	
13	Stevenson (1937) (53)	$0.0128 \cdot W + 0.0061 \cdot H - 0.1529$	Chinese adults
14	Brody (1945) (54)	$0.02411 \cdot W^{0.53} \cdot H^{0.4}$	USA
15	Sendroy and Cecchini (1954) (55)	$0.0097 \cdot (W + H) - 0.545$	USA
16	Banerjee and Sen (1955) (56)	$0.007466 \cdot W^{0.425} \cdot H^{0.725}$	Indian adults
17	Choi (1956) (57)	Male: $0.005902 \cdot W^{0.407} \cdot H^{0.776}$ Female: $0.008692 \cdot W^{0.442} \cdot H^{0.678}$	Korean adults
18	Mehra (1958) (58)	$0.01131 \cdot W^{0.4092} \cdot H^{0.6468}$	Indian adults
19	Isaksson (1958) (59)	$1 + (W + (H - 160)) / 100$	Swedish adults
20	Murata (1959) (60)	$0.0005142 \cdot W^{0.5} \cdot H^{0.5}$	Japanese adults
		$0.007049 \cdot W^{0.425} \cdot H^{0.725}$	
21	Banerjee and Bhattacharya (1961) (61)	$0.0070 \cdot W^{0.425} \cdot H^{0.725}$	Indian children
22	Costeff (1966) (62)	$(4 \cdot W + 7) / (90 + W)$	US children
23	Fujimoto <i>et al.</i> (1968) (63)	Under 1 year: $0.009568 \cdot W^{0.473} \cdot H^{0.655}$ 1–5 years: $0.038189 \cdot W^{0.423} \cdot H^{0.362}$ 6 years to adulthood: $0.008883 \cdot W^{0.444} \cdot H^{0.663}$	Japanese children 0–18 years
24	Fujimoto and Watanabe (1969) (64)	$0.008883 \cdot W^{0.444} \cdot H^{0.663}$	Japanese adults
25	Van Graan (1969) (65)	$0.007654 \cdot W^{0.425} \cdot H^{0.725}$	South Africans adults: Caucasians, Bantu, Bushmen
26	Gehan and George (1970) (66)	$0.0235 \cdot W^{0.51456} \cdot H^{0.42246}$	USA
27	Haycock (1978) (67)	$0.024265 \cdot W^{0.5378} \cdot H^{0.3964}$	US infants, children and adults
28	Anderson (1985) (68)	$0.0239 \cdot W^{0.517} \cdot H^{0.417}$	US adults
29	Jones <i>et al.</i> (1985) (69)	Female: $0.327 + 0.0071 \cdot W + 0.0292 \cdot \text{UpperCalfCircum.}$	UK female adults without correlation between <i>H</i> and <i>W</i>
30	Takai and Shimaguchi (1986) (70)	$-0.2142 + 0.0617 \cdot W^{2/3} + 0.2453 \cdot 10^{-4} \cdot H^2 + 0.6825 \cdot 10^{-4} \cdot \text{Head Circum. (cm)}^2$	Japanese adult males
31	Mosteller (1987) (71)	$0.016667 \cdot W^{0.5} \cdot H^{0.5}$	Very popular simplification of formula 27
32	Mattar (1989) (72)	$(H + W - 60) / 100$	Adults
33	Nwoye (1989) (73)	$0.001315 \cdot W^{0.262} \cdot H^{1.2139}$	Nigerian adult males
34	Kurazumi <i>et al.</i> (1994) (74)	Both: $0.010315 \cdot W^{0.693} \cdot H^{0.383}$ Male: $0.005318 \cdot W^{0.362} \cdot H^{0.833}$ Female: $0.0110529 \cdot W^{0.445} \cdot H^{0.627}$	Japanese adults
35	Hu <i>et al.</i> (1999) (75)	Both: $0.0124 \cdot W + 0.0061 \cdot H - 0.0099$ Male: $0.0121 \cdot W + 0.0057 \cdot H + 0.0882$ Female: $0.0127 \cdot W + 0.0073 \cdot H - 0.2106$	Chinese adults
36	Shuter and Aslani (2000) (76)	$0.00949 \cdot W^{0.441} \cdot H^{0.655}$	DuBois sample reanalyzed
37	Livingston and Lee (2001) (77)	<10 kg: $0.1037 \cdot W^{0.6724}$ 10–250 kg: $0.1173 \cdot W^{0.6466}$	US new borns to obese adults
38	Tikuisis <i>et al.</i> (2001) (78)	Female: $0.01474 \cdot W^{0.47} \cdot H^{0.55}$ Male: $0.01281 \cdot W^{0.44} \cdot H^{0.6}$	Canadian adults
39	Nwoye and Al-Sheri (2003) (79)	$0.02036 \cdot W^{0.427} \cdot H^{0.516}$	Saudi adult males
40	Yu, Lo and Chiou (2003) (80)	$0.015925 \cdot W^{0.5} \cdot H^{0.5}$	Chinese adults
41	Wang and Hihara (2004) (81)	$0.0168 \cdot W^{0.5} \cdot H^{0.5}$	Theoretical approach
42	Reading and Freeman (2005) (82)	$1/60 \cdot W^{0.5} \cdot H^{0.5}$	Australian adults
43	Lee <i>et al.</i> (2008) (83)	$0.007331 \cdot W^{0.425} \cdot H^{0.725}$	Korean adults
44	Furqan and Haque (2009) (84)	$(4 \cdot W + 7) / (90 + W)$	Pakistani children 0–18 years
45	Schlich <i>et al.</i> (2010) (85)	Female: $0.000975482 \cdot W^{0.46} \cdot H^{1.08}$ Male: $0.000579479 \cdot W^{0.38} \cdot H^{1.24}$	German, adults
46	Yu <i>et al.</i> (2010) (86)	Female: $0.00844673 \cdot W^{0.4176} \cdot H^{0.6997}$ Male: $0.00798106 \cdot W^{0.3980} \cdot H^{0.7271}$ Both: $0.00713989 \cdot W^{0.4040} \cdot H^{0.7437}$	Taiwanese adults with wide range of BMIs
47	Chhapola <i>et al.</i> (2013) (87)	$0.0164551 \cdot W^{0.5} \cdot H^{0.5}$	Indian, malnourished children
48	Kuehnepfel <i>et al.</i> (2017) (88)	Female: $0.0051 \cdot W^{0.3262} \cdot H^{0.8516} \cdot e^{0.0036 \cdot \text{BMI}}$ Male: $0.0051 \cdot W^{0.3262} \cdot H^{0.8516} \cdot e^{0.0036 \cdot \text{BMI}} \cdot e^{-0.0120}$	German adults
49	Lipscombe (2020) (89)	$0.00878108 \cdot W^{0.434972} \cdot H^{0.67844}$	Mean of 16 formulas

(continues)

Table 1. (continued)

	Author(s)	Formula BSA (m ²)	Sample
50	Looney <i>et al.</i> (2020) (90)	Female: $0.013546 \cdot W^{0.4470} \cdot H^{0.5832}$ Male: $0.010977 \cdot W^{0.4348} \cdot H^{0.6335}$ Female: $0.013546 \cdot W^{0.4414} \cdot H^{0.3291} \cdot \text{Armspan}^{0.2578}$ Male: $0.010245 \cdot W^{0.4284} \cdot H^{0.3548} \cdot \text{Armspan}^{0.2956}$	US-Army soldiers
51	Akkawi El Edelbi <i>et al.</i> (2021) (91)	>3 kg: $0.07758 + 0.04165 \cdot W - 0.0003307 \cdot W^2 + 1.25 \cdot 10^{-6} \cdot W^3$ 1–80 kg: $0.09395 \cdot W^{0.7032}$ 1–80 kg: $0.08319 \cdot W^{(0.7955 - 0.03625 \cdot \log W)}$	Swedish children 0–18 years

W = weight in kilograms; H = height in centimeters.

accuracy of calculated BSA in general. Individual deviations from calculated BSA are still obvious. Root mean square errors are in the order of 3% and maximum deviations were found to reach 10%.

To sum up, weight and height, as the only predictors, are sufficient to estimate the individual BSA. However, for high precision calculations, additional measures are necessary. This was recognized early (11), but attempts including circumferences are still rare (44,71,72,92).

Posture has a certain influence on BSA. In upright standing (for which the formulas on BSA are valid), putting arms on the body and legs against each other reduces the BSA by around 5%. Most reduced is BSA in fetal curl (−40%) (van Graan [67]).

Summary and recommendations

For children (of normal nutrition status) the (logarithmic) formulas of Boyd (54) and of El Eldebi (93) deliver reliable results from birth until adulthood. The DuBois formula (DuBois and DuBois [48]) would also be a good choice for body heights of more than 100 cm (older than 4 years). For adults, the DuBois formula delivers results, which are close to the general mean for Caucasians as well as to that for Asians (97). The derived formulas for Africans deliver noticeably higher BSAs by 3–13% (67,75). Taking a reduction in 1% for males and an addition of

1% for females would meet the systematic differences between genders:

BMI ≤ 25:

$$\text{BSA females} = 0.007256 \cdot W^{0.425} \cdot H^{0.725} \quad (9a)$$

$$\text{BSA males} = 0.007112 \cdot W^{0.425} \cdot H^{0.725} \quad (9b)$$

The DuBois formula is appropriate for pregnant women (Wang *et al.* [98]), too. Several comparisons have shown that calculations by this formula agree quite well with recent measurements and maximum deviations seem to be smaller compared to other formulas (99). However, in obese persons (BMI > 35), the DuBois formula tends toward underestimation (3% in males, 5% in women) (100). Taking an addition of 0.3% per 1 BMI for BMIs higher than 25, we suggest rewriting the gender adapted DuBois formula as:

BMI ≥ 25:

$$\text{BSA females} = 0.007256 \cdot W^{0.425} \cdot H^{0.725} \cdot (1 + (\text{BMI} - 25) \cdot 0.003) \quad (10a)$$

$$\text{BSA males} = 0.007112 \cdot W^{0.425} \cdot H^{0.725} \cdot (1 + (\text{BMI} - 25) \cdot 0.003) \quad (10b)$$

As a note for future considerations in respect to the increasing BMI and PI of the populations in many regions of the world, Jones *et al.* (71) undertook a noticeable study. They measured the BSA in a sample of 15 young women (mostly university students, 1.55–1.74 m, 47–81 kg). They could not find a correlation between weight and height ($r = -0.01$) in this sample. However, BSA correlates with weight ($r = 0.92$) and with several circumferences, like that of the calf, gluteal furrow, wrist, ankle, deltoid and upper arm ($r = 0.92$ – 0.75). They recommended the use of weight and the upper calf circumference to calculate the BSA. The reduced importance of height for BSA was confirmed by Livingston and Lee (79) for nowadays' western adults by a sample population which weighted up to 250 kg, was smaller than 190 cm and had a BMI up to 73, respectively, a PI up to 40. BSA was up to 4 m². At a BMI ≥ 30 (PI ≥ 18), body parts start to contribute significantly and differently to BSA than in persons of normal weight.

BSA around the world

Populations around the world differ in average weight and average height (101) and with that, BSA does. According to data from NCD-RisC (19), people are tallest in The Netherlands (median males: 184 cm, 87.9 kg, BMI = 26.1, PI = 14.1, females: 170 cm, 73.2 kg, BMI = 25.3, PI = 14.9) and smallest in

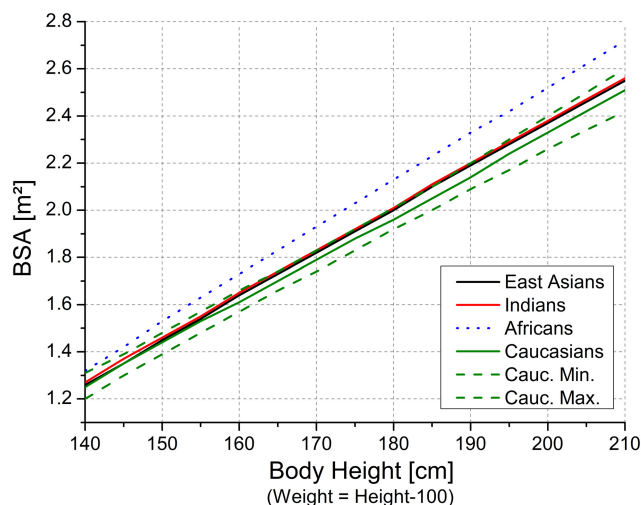
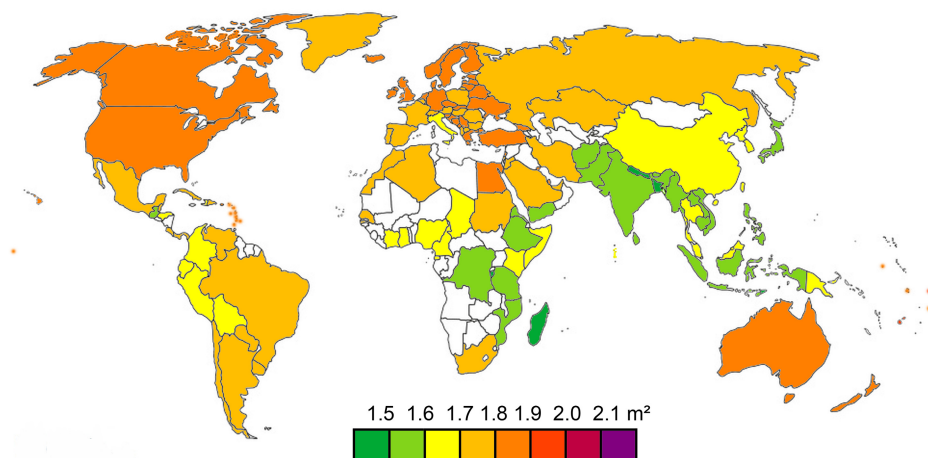


Figure 7. Mean total body surface area (BSA) of different ethnicities such as Africans, East Asians, Indians and Caucasians calculated from the formulas in Table 1 for Broca Weight.

a) BSA - Females



b) BSA - Males

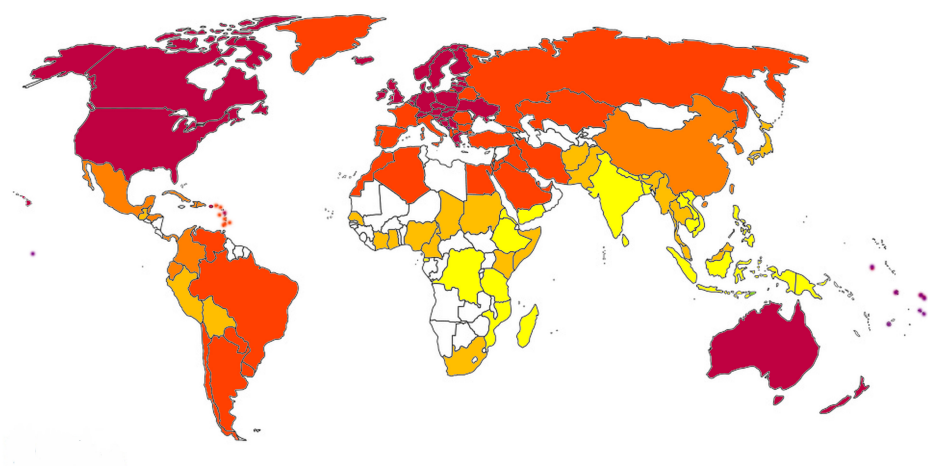


Figure 8. Body surface area (BSA) calculated using the DuBois formula (48) from NCD-RisC data (19) a) for females and b) for males. White color denotes that there is no data available.

Timor-Leste (median males: 159 cm, 53.9 kg, BMI = 21.2, PI = 13.0, females: 152 cm, 49.0 kg, BMI = 21.2, PI = 13.7). With that, the median BSA differs. Using the DuBois formula, the BSA is 2.09, 1.86, 1.53 and 1.45 m², respectively. Therefore, BSA of Dutch people is around 30% larger than that of people on Timor-Leste. Differences in median height of people appear on short distances. In the neighboring country Belgium, women on average are 6 cm and men are 5 cm smaller than in The Netherlands. With that, differences in BSA are around 5%. Both countries have a size of only around 250 × 150 km, similar socio-economic situation and the same life expectancy.

To calculate the median BSA for most countries in the world (see Fig. 8), we used the available median height and BMI data from NCD-RisC (19) (data for weight was not available). For many regions in the world, no specific formulas or coefficients are available and we therefore used the DuBois formula for calculating BSA and adding +1% for females and −1% for males (Eqs. 9a and 9b). The highest values were gained for inhabitants of the south pacific islands (Cook Islands, American Samoa,...)

with around 2.19 m² in males and 2.08 m² in females, the lowest for Timor-Leste (1.53 and 1.45 m²). Timor-Leste and the south pacific islands have similar latitude, so that the difference in received radiant energy is approximately 40% (under the same conditions).

Changes of BSA over time and during lifetime

Body height does not only differ between ethnicities and genders. It changes over time (*e.g.* NCD-RisC [19,102]). Within one century (1914–2014), people from the Netherlands have become around 13.5 cm (males: 13.1 cm, females: 13.9 cm) taller. At the Broca-Weight, this denotes an increase in BSA of approximately 15%. The highest grow was found for South Korea by approximately 17 cm. This continuous grow of populations can be considered as a positive development when looking on the height in dependence of age within a country. Figure 9a depicts the median body height of females and males in dependence of age in Austria, where the increase is much lower than in the upper

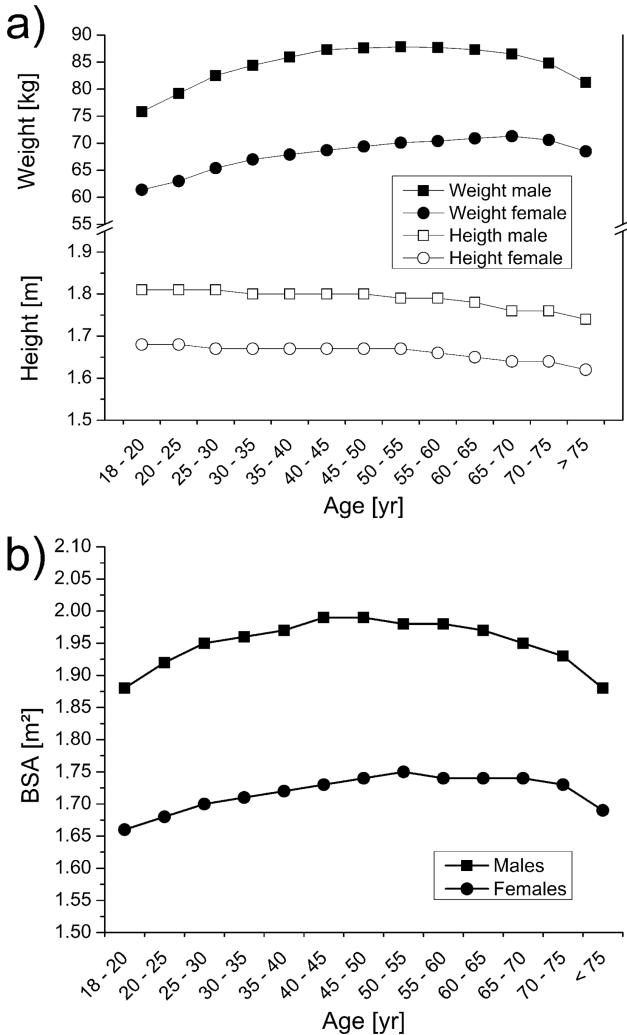


Figure 9. Age dependence of a) height and weight of the Austrian population (103) and b) calculated total body surface area (BSA).

examples, but still obvious in the past 75 years, with an increase in 6 cm in females and by 7 cm in males.

The increase in weight, on the other hand, is significantly bigger. Overweight and obesity has become a matter of concern in many countries (17). Additionally, weight changes noticeable throughout an individual's lifetime due to life style and changes in metabolisms. Figure 9a depicts the average weight of Austrians in dependence of age (103). In females, weight increases until the age of 70 and decreases afterward. In males, weight is highest in the age group of 50–55 years. Consequently, the BSA is largest in females aged 50–55 years (1.75 m²) and in males aged 40–50 years (1.99 m²) as it can be seen in Fig. 9b.

SIZE OF BODY PARTS RELEASED BY CLOTHES

Clothes cover certain parts of the body, and the sun-exposed body surface becomes smaller than the BSA. Choice of clothing in respect to body coverage depends, aside from precipitation, mainly on temperature (104) and wind speed (105,106). To estimate the (sun) exposed body surface area (EBSA), it is necessary

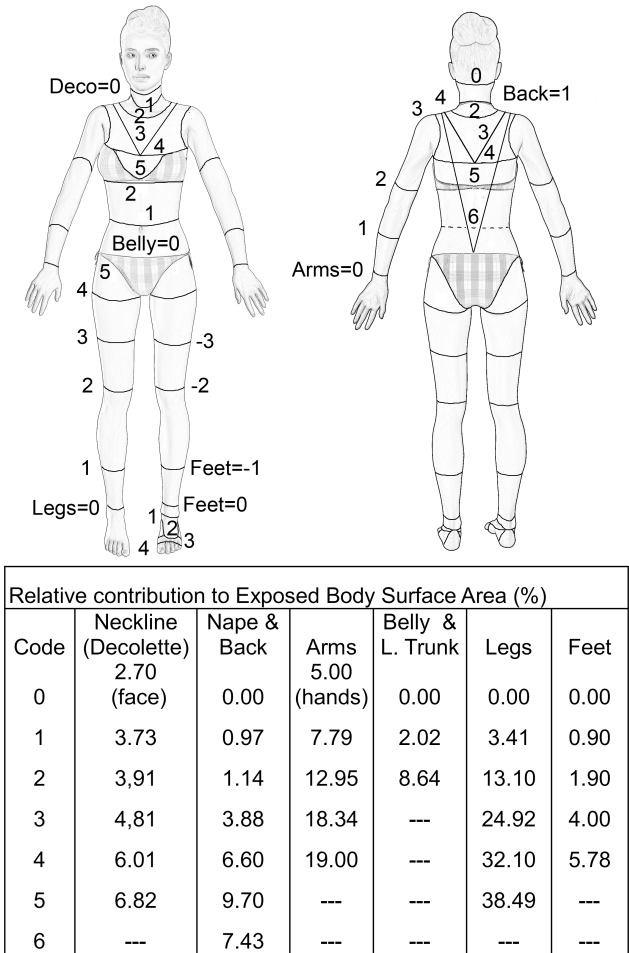


Figure 10. Clothing chart according to Schmalwieser *et al.* (104) and relative contribution to exposed body surface area calculated according to Lee and Choi (110).

to know the size of the area of uncovered body parts. The different body parts contribute individually to the BSA and the size of body parts was investigated already in the first studies on BSA (43).

Rough estimates

A frequently used estimate for the contribution of body parts is the so-called “rule of nines”. This rule was devised by Pulaski and Tennison in 1947 and published by Wallace in 1951 (107), especially for the use in emergency medicine to determine the severity of a burn. It is a very simple rule that divides the human body in 11 parts which make up for 9% of the BSA each (head, right arm, left arm, chest, abdomen, upper back, lower back, right thigh, left thigh, right leg (below the knee), left leg (below the knee) and 1% for the genital region. Later on, the rule of nines was adapted for Children (1–14 years) and infants (<1 year) by taking into account the different growth of body parts. For example, at the age below 1 year, the head takes a share in BSA of 21%, but takes a share of 9% in adults.

Another method is the Palmer Method (palm size method), which was also established to get a rough burn size estimate. A person's palmer surface (hand, fingers positioned together) is 1%

of total BSA. It might be worth mentioning that the person's individual hand size must be used, not that of the observer. However, this is rather a rough estimate, because the % size of the hand depends somewhat on age, gender and BMI (108).

The Lund and Browder chart (109) subdivides the body in 34 sections (17 per body site) and takes into account the change in proportions during the first 15 years of life, too.

These methods assume a person of average size and weight. However, overweight changes the proportion of body parts. Livingston and Lee (110) measured the area of seven body parts in persons up to a BMI of 74 and showed that the relative size of hands decreases from 4% to 2.5%.

Detailed charts and application on clothing

The approaches discussed above, deliver rather rough estimates of EBSA. A much more detailed and more precise approach was undertaken by Lee and Choi (111). They developed a scheme dividing the human body into 142 sections, which enables one to match these sections and real garments. Gage *et al.* (112) undertook a valuable approach in respect to this and delivered an electronic scheme to calculate EBSA for selected garments according to the Lee and Choi scheme.

Schmalwieser *et al.* (104) developed a clothing chart for observational studies to estimate body coverage for sun exposure. The chart describes the body coverage by 6 numbers, which—in combination—allow to distinguish hundreds of different outfits. The application of the Lee and Choi scheme to this chart is depicted in Fig. 10.

This chart was used in an observational study of clothing (such observational studies are generally very rare) of young women during daily errands in Vienna, Austria in dependence of temperature (104). Observations were taken between 10 and 36°C. Taking the gained median coding from this study and converting these by the numbers from Fig. 10 one gets the relative EBSA expressed in % in dependence of temperature.

Figure 11a depicts these EBSA values (left scale). From this it can be seen that the EBSA is almost constant over the range from 10 to 18°C (64°F) and increases afterwards from around 8% (face and hands) up to 60% at 36°C (97°F). It can also be seen that the median EBSA shows stepwise increases. These steps result, for instance, from the change in sleeve length of most (median) people (*e.g.* from $\frac{3}{4}$ length to short sleeves). The right scale indicates the EBSA in units of m^2 assuming a young woman of 1.65 m at Broca-Weight (65 kg). The DuBois formula delivers a BSA of 1.72 m^2 . In total, the EBSA at 36°C is more

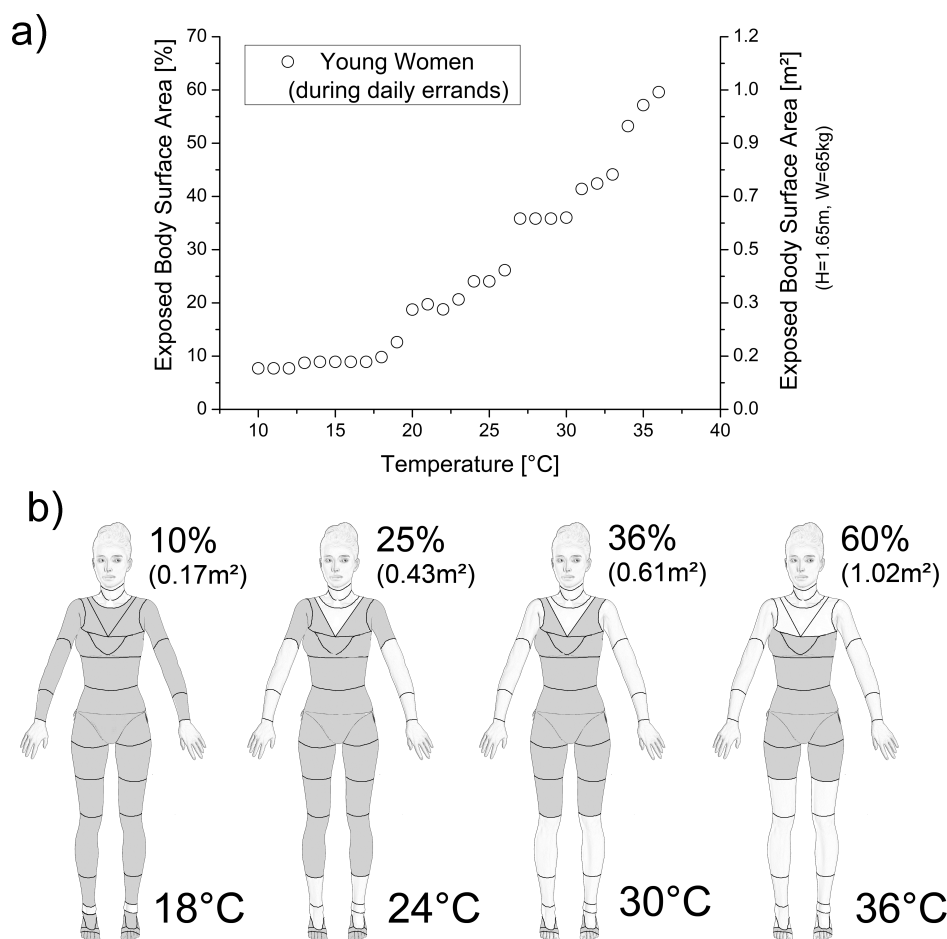


Figure 11. Exposed body surface area (median) of young women during daily errands in Vienna, Austria a) in dependence of temperature in [%] (left scale) and in [m^2] (right scale) assuming a woman of 165 cm in height and 65 kg in weight (BSA = 1.72 m^2 according to ref. [48]) and b) visualized by median outfits at 4 selected temperatures.

than six times larger than at 18°C, leading to an increase from 0.15 m² to around 1 m². Figure 11b visualizes typical (median) outfit of young women at four different temperatures, as well as it indicates the relative EBSA.

CONCLUSION

In the past, UV exposure of people and related health risk was mainly estimated by measured or modeled UV radiant exposure. However, for several effects like DNA damage, the risk of developing skin cancer or the photosynthesis of Vitamin D, the EBSA is of importance and with that the UV radiant energy. For Vitamin D, an effective radiant energy of 10 J_{vitD} is assumed to deliver an equivalent of 400 IU of Vitamin D (113). Larger or smaller EBSA would shorten or prolong the necessary exposure time. For many effects, the influence of the size of EBSA has not yet been investigated.

The EBSA depends on the body coverage by clothes and on the total BSA. The BSA of humans depends on the body shape, which differs systematically by gender and ethnicity and most significantly between each individual and it changes clearly from birth to adulthood, but also during further life. The body shape can be determined by measurements of lengths (body length, arm length,...) and circumferences (chest, hip,...) which is rather costly, so that simple measures considering height and weight of a person have been developed, such as the Body Mass Index (see Eq. 4), the Ponderal Index (see Eq. 5) and the BI (see Eq. 6a). Other simple measures consider ratios of anthropogenic measures (Waist-to-Hip Ratio, ...).

The measurement of the BSA is very laborious. Therefore, formulas have been derived which enable the calculation by using weight and height of a person and partly different circumferences (e.g. chest circumference) or lengths (e.g. arm-span) or the BMI. For the young children (up to a height of 100 cm) the formula of Boyd (54) or El Edelbi *et al.* (93) can be suggested. Both can be applied if only weight is available.

Our comparison of more than 50 formulas has shown that the DuBois formula (Du Bois and Du Bois [48]) is a good choice for humans taller than 100 cm. Individual deviations (root mean square error) are in the order of 2–3%. Additionally, this formula has been used quite often in the past, so that results are comparable with other studies. For males, a correction of –1% should be considered and one of +1% for females in order to correspond to the differences by gender. However, for very heavy persons (BMI > 35) the formula tends to underestimate the BSA by 3% in males and 5% in females. In these populations, the body length loses importance in favor of weight. For rather slim ethnicities like many populations in Africa, the formulas from Nwoye (75) and van Graan (67) could be considered.

Finally, we considered the EBSA due to clothing. Exemplarily, a clothing chart was presented together with observed data of clothing of young women (doing daily errands) in dependence of temperature, which is the most important meteorological quantity for clothing beside precipitation. We carved out that EBSA is rather constant in the order of 10% up to a temperature of 18°C but increases steeply from this point upward. At 36°C, the EBSA is around 60%. With that, days of high temperature contribute 6 times more to received UV radiant energy than days of medium temperature.

For future estimations of UV-related health risk, the influence of size of the irradiated area (EBSA) on photobiological effects and endpoints should be investigated in more detail. Estimates for total BSA could be improved by including a few anthropogenic measures to receive a formula that corresponds to differences in body shape more accurately. Further studies on clothing of people are needed in order to get estimates of EBSA in dependence of gender, age and activity.

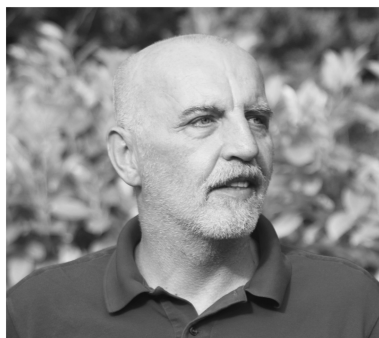
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