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AN IMPROVEMENT OF BODY SURFACE AREA FORMULAS USING THE 3D SCANNING TECHNIQUE

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Abstract
Objectives: Body surface area (BSA) is one of the major parameters used in several medical fields. However, there are concerns raised about its usefulness, mostly due to the ambiguity of its estimation. **Material and Methods:** Authors have conducted a voluntary study to investigate BSA distribution and estimation in a group of 179 adult people of various sex, age, and physique. Here, there is provided an extended analysis of the majority of known BSA formulas. Furthermore, it was supplement with a comparison with the authors' propositions of enhanced formulas coefficients for known formulas models as well as with new power models based on an increased number of anthropometric data. **Results:** Introduction of the enhanced formulas coefficients cause a reduction of at least 30.5% in mean absolute error and 21.1% in maximum error in comparison with their known counterparts. **Conclusions:** In the context of the analysis presented it can be stated that the development of a single universal body surface area formula, based on a small number of state variables, is not possible. Therefore, it is necessary and justified to search for new estimation models that allow for quick and accurate calculation of body surface area for the entire population, regardless of individual body variations. The new formulas presented are such an alternative, which achieves better results than the previously known methods. Int J Occup Med Environ Health 2024;37(2)

Key words:
cancer therapy, diagnosis, 3D body scanning, body surface area formulae, BSA calculations, drugs dosage

INTRODUCTION

People involved in the implementation and evaluation of treatment with given preparations use various parameters describing the physical parameters of patients, on the basis of which appropriate doses of drugs or treatment agents are selected. One of them is a body surface area (BSA), which can be defined as a measured or calculated surface area of the human body [1]. The BSA factor is considered a better indicator of metabolic mass, mortality and other medical indicators than body weight or BMI because, unlike them, it is not dependent on selected physiological factors [2–5]. For this reason, BSA is a benchmark for treatment in fields such as oncology or transplantology for example chemotherapy drugs dosage [6–9], treat-

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ment of chronic hepatitis B [10], treatment of burns [11] or for establishing a dosing regimen for antimicrobials [12], and treatment of rare diseases. The BSA is also employed to calculate an energy expenditure, which is a widely used parameter in the medicine [13,14]. The exponentially growing number of scientific publications on BSA can serve as an indicator of the popularity of this parameter in medicine publications. Despite the rapid development of 3D scanning techniques in recent years, their use in the case of bedridden patients or in time-sensitive medical procedures (e.g., intensive care of accident patients) is difficult, if not impossible. For this reason, in medical practice, simplified formulas based on easy-to-determine parameters such as weight, height, age, sex of the patient, etc., are most often used. However, there are a lot of formulas for BSA calculations described in the literature, that lead to significantly different results. One of the first works in this area was an article by K. Meeh from 1879 [15] and by the end of the 20th century there were already over 40 formulas adapted to various groups of patients. Despite significant progress in the determination of BSA, there are still doubts as to the correctness of determining drug doses using this parameter or using it to index hemodynamic parameters [16–18]. The basic complaint against BSA is its doubtful direct proportionality to metabolic processes, although there is also a problem with the inaccuracy of the used formulas (especially for people with unusual body shapes) [19,20]. The second problem is particularly visible in the case of a total body surface area (TBSA), which is used, e.g., for assessing skin damage, because the total measurement error is then multiplicative. According to the literature data [21], the existing TBSA models are burdened with an error exceeding 60% of the relative skin area, which may result in up to 3 times overestimation of drug doses [22]. A similar situation occurs in the case of cancer patients, who in 30% of cases receive inadequate doses of chemotherapy due to incorrectly estimated BSA value [23]. The above issue is a challenge that can be met by modern advanced techniques of precise assessment of anthropometric parameters, e.g., a body scanning method [24–27].

This article described a detailed analysis of the most popular formulas for calculating BSA, together with a proposal for their modification, which significantly improves the reliability of the obtained results. In addition, the authors presented a new method of calculating the BSA, which uses a larger number of anthropometric parameters, resulting in a better representation of differences within the population. The obtained formulas were verified by means of experimental investigations on a group of patients using a cross-analysis method. Moreover, an easy to use software was prepared to calculate BSA employing the improved formulas, which can be a support for medics.

MATERIAL AND METHODS

The overall objective of the presented investigations was the development of method for an accurate BSA calculations, which uses a large number of easy to measure anthropometrical parameters exhibiting the best correlations with the BSA itself. The secondary task was to show that by appropriate selection of coefficients present in the BSA formulas known so far, their effectiveness can be improved and the dispersion between the calculated and real values can be reduced. For this purpose, a body surface scanning procedure was performed on a group of volunteers, diverse in terms of age, sex and physique (179 adults). The collected data was supplemented with a number of information on the anatomical structure of the patients, such as: height, weight, head circumference, neck circumference, chest circumference, waist circumference, hips circumference, height from the ground to the hip, arm circumference, forearm circumference, wrist circumference, distance between the elbow and the tip of the middle finger, arm

Table 1. Characteristics of the volunteers in body surface area (BSA) measurements performed in September 2015 – November 2016 at Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland

Variable	Participants (N = 179)				
	total	BMI		waist circumference	
		≥18.5 and <25 (N = 82)	<18.5 or ≥25 (N = 97)	<100 cm (N = 129)	≥100 cm (N = 50)
Age [years] (M±SD)	31.77±13.84	24.70±7.42	37.75±15.15	25.98±8.62	46.72±13.61
Age <40 years [n (%)]	131 (73.2)	78 (95.1)	53 (54.6)	117 (90.7)	14 (28.0)
Male sex [n (%)]	123 (68.7)	67 (81.7)	56 (57.7)	102 (79.1)	21 (42.0)
Body measurements (M±SD)					
body surface area [m^2]	2.007±0.245	1.873±0.155	2.121±0.249	1.918±0.198	2.238±0.201
weight [kg]	85.73±24.13	69.63±9.00	99.34±24.54	74.26±14.24	115.33±18.55
height [cm]	175.16±9.04	177.10±7.86	173.53±9.67	177.22±8.24	169.86±8.92
head circumference [cm]	56.81±2.05	56.48±1.91	57.08±2.12	56.71±1.96	57.06±2.25
eyes distance [cm]	10.50±1.27	10.40±0.92	10.59±1.51	10.32±0.97	10.97±1.77
neck circumference [cm]	38.10±4.46	35.66±2.39	40.16±4.76	36.35±3.12	42.60±4.25
chest circumference [cm]	96.99±14.85	87.65±7.57	104.88±14.94	90.27±9.79	114.31±11.21
waist circumference [cm]	91.68±20.97	77.05±5.78	104.05±21.21	80.38±9.04	120.85±13.40
hips circumference [cm]	98.86±19.81	84.33±6.44	111.15±18.96	88.30±9.52	126.12±11.67
hips height [cm]	101.82±8.28	104.74±6.60	99.36±8.76	103.90±7.09	96.47±8.76
arm circumference [cm]	30.44±5.18	27.42±2.46	32.99±5.50	28.47±3.99	35.54±4.36
forearm circumference [cm]	27.52±3.27	25.80±2.07	28.96±3.40	26.48±2.90	30.19±2.58
wrist circumference [cm]	17.29±1.49	16.52±1.07	17.93±1.50	16.78±1.20	18.60±1.37
forearm length [cm]	46.61±3.13	47.09±2.59	46.20±3.48	47.08±2.70	45.39±3.80
arm span [cm]	177.82±10.93	179.71±9.77	176.21±11.62	179.65±10.14	173.09±11.55
thigh circumference [cm]	57.82±7.23	54.38±3.84	60.72±8.12	55.77±6.63	63.09±5.98
calf circumference [cm]	39.96±4.83	37.19±2.40	42.30±5.12	38.06±3.86	44.86±3.44
knee height [cm]	47.12±3.56	48.11±3.12	46.29±3.71	47.77±3.19	45.46±3.96
shoe size[a]	42.01±2.52	42.15±2.36	41.90±2.66	42.25±2.37	41.41±2.82

The body measurement data in the table have been sorted according to the criterion of significance of the impact on the BSA parameter.
The data are normally distributed and statistically significant ($p < 0.05$).
[a] Standard European shoe size.

span, thigh circumference, calf circumference, height from the ground to the knee, and standard European shoe size. The tested group of people was characterized by a large diversity including both a young college students as well as an older citizens. In addition, the study included both healthy people and those suffering from various diseases, such as anorexia or obesity. The volunteers were grouped into 4 categories depending on their body structure determined on the basis of their BMI and waist circumference as it shown in Table 1.

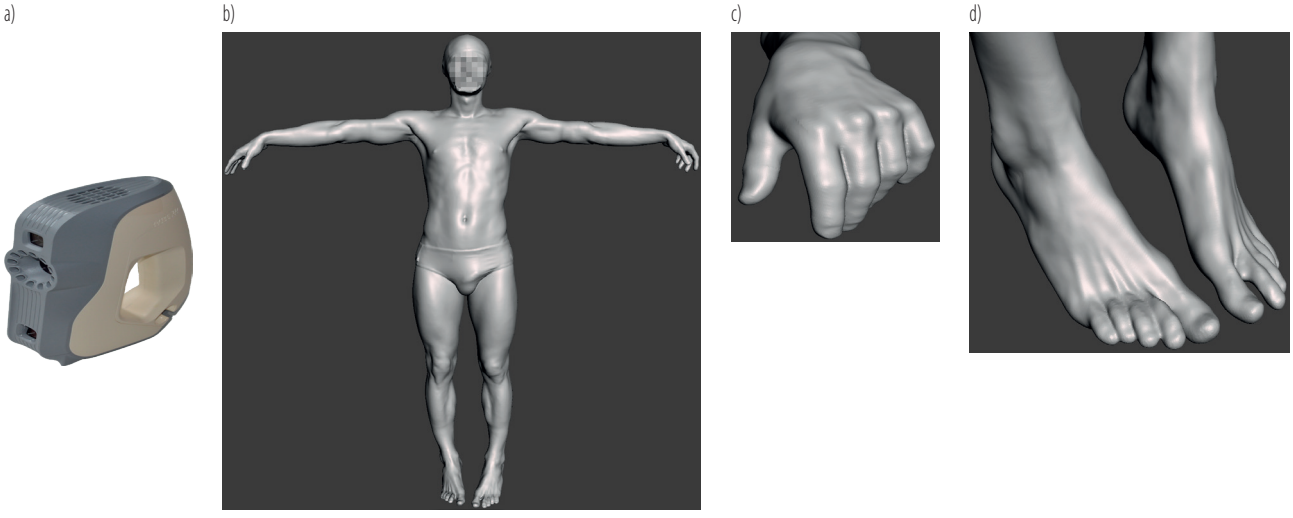


Figure 1. The scanner used in the investigations and examples of obtained results: a) Artec 3D Eva scanner, b) whole-body 3D model of a scanned patient, c) the model's hand, and d) the model's feet; Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland, September 2015 – November 2016

The gathered experimental data was analyzed employing an advanced computational methods in order to find the best formulas to BSA calculations. Data on the age, sex and shoe number of the patients were obtained during the interview qualifying for the experiment.

Data collection process

In order to make the scanning process facilitate and repeatable there were implemented a following procedure:

- placing the patient on a special remotely controlled turntable;
- stabilizing the patient with supports that prevent spontaneous descent of the limbs;
- scanning the patient's body surface while the turntable slowly rotates.

The Artec 3D Eva (Artec 3D, Senningerberg, Luxembourg) handheld scanner (Figure 1a) used in the research works on the basis of irradiation with white light, which is harmless for most people (except epileptics), and video camera triangulation. This high precision device is dedicated, among others, to medical applications and allows to take measurements with a maximum accuracy of 0.1 mm, which results with a high-quality 3D models. The accuracy of the device was verified before measuring the body surface area of the patients and it exceeded 99.27%.

Due to a technical issues each of the limbs and the main body of the studied patient were scanned separately and then joined in the post-processing to the one model. The places of connecting individual elements of the model were previously marked on the patient's body with tape. The final model of the body, which is shown in Figure 1b, was created thanks to a series of graphic processing methods of the collected images. For this purpose, the Artec Studio 11 Professional software (Artec 3D, Senningerberg, Luxembourg) was used, which allowed the following operations to be performed:

- the points cloud obtained from the scan was subjected to a global registration process in order to normalize the points location;
- the normalized point cloud was subjected to a fusion process, which led to a solid representation of the model;
- improvement of the obtained model by a different post processing techniques, i.e., small object filter, hole filling, and smoothing.

The value of BSA was also calculated with the mentioned above software as a surface of the final 3D model. More

information about the human body scanning procedure and related issues can be found in the article [28].

To measure the remaining anthropometric parameters, simple measuring devices were used, such as the Seca 201 tape for measuring circumferences, a stiff measuring tape to measure all lengths, and a MensorWE200P3 M(X) medical weight scale (MENSOR A. J. Lewandowscy, Warsaw, Poland) to measure body height and weight.

Data analysis procedure

The new propositions of BSA formulas were obtained employing an original method of analyzing the collected experimental data, instead of typical solutions based on linear or non-linear regression. This method consists in considering models with a variable number of parameters, with a particular choice of parameters based on the improvement of the predictive power of the model obtained after extraction of the optimal parameters. In addition, the generalization error of the produced models was estimated using a 10-fold cross-validation, which contributed to limiting the degrees of freedom of these models. The mentioned method is based on power models which can be expressed by the following equation:

$$s(x) = a_0 \times \left(x_1^{a_1}\right) \cdots \left(x_k^{a_k}\right) \quad (1)$$

where:

k – the number of anthropometric variables x_i with coefficients a_i.

The reliability of the obtained formulas is determined by the selection of appropriate anthropometric parameters, which in the described case was obtained by interleaving model identification and adding parameters. For this purpose, an iterative procedure was used consisting in adding parameters one by one and extracting the model. The aim of each iteration was to find the parameter that the best improves the predictive power of the previously obtained model. The measure of the degree of model improvement was the statistical analysis of the model error, which was defined as the maximum-to-minimum error span.

For comparison purposes, a model using all available parameters was also developed. Due to the potential risk of model degradation as a consequence of too many degrees of freedom, 10-fold cross-validation was applied during each iteration. It consisted in dividing the available data set into N groups, one of which was used as a testing data, and the rest were used to train the model. Then, the given model was constructed N times, and the estimated error obtained at each step was averaged in order to calculate the generalization error. Determining this indicator was tremendously important from the point of view of assessing the predictive power of the model, with particular emphasis on the ability to predict the system output (in this case, it is the BSA value) for previously unseen sets of input parameters. The adopted solution is a significant improvement compared to methods using simple regression, which only allow to minimize the approximation error. The techniques of deriving BSA formulas used so far work well in the case of the simplest formulas with a significantly limited number of coefficients, but they do not cope with complex equations characterized by many degrees of freedom.

In addition, the models obtained as it is described above were extended by multiplying by a linear function of all available anthropometric variables expressed by the relationship:

$$b_0 + b_1 \times x_1 + \cdots + b_n \times x_n \quad (2)$$

Another supplement to the authors' analysis was taking into account the body build of the examined people, which resulted in the development of formulas dividing patients by BMI and waist circumference.

The data are displayed in terms of means accompanied by standard deviations and maximum values. To assess the normality of the presented measurements and esti-

mates, the D'Agostino's K^2 test was employed. In light of the heteroscedastic nature of the estimated data, the Kruskal-Wallis H-test was used to examine the statistical significance and differences among the groups. A significance level of $p < 0.05$ was considered meaningful. All statistical analyses were carried out using the SciPy 1.0.0 Python package [29].

The comparison of the estimation models is based on their logarithmic accuracy ratio [30]. Specifically, each model's performance was evaluated by applying the method of least squares to its logarithmic accuracy ratio:

$$\sum_{i=1}^{N} (\ln Q_i)^2 \quad (3)$$

where:

N – the population size,

Q_i – the ratio of the estimated BSA value $\hat{y}$ to its true value y_i ($Q_i = \hat{y}_i/y_i$),

$\hat{y}$ – the estimated value and y being the actual value.

Data analysis procedure

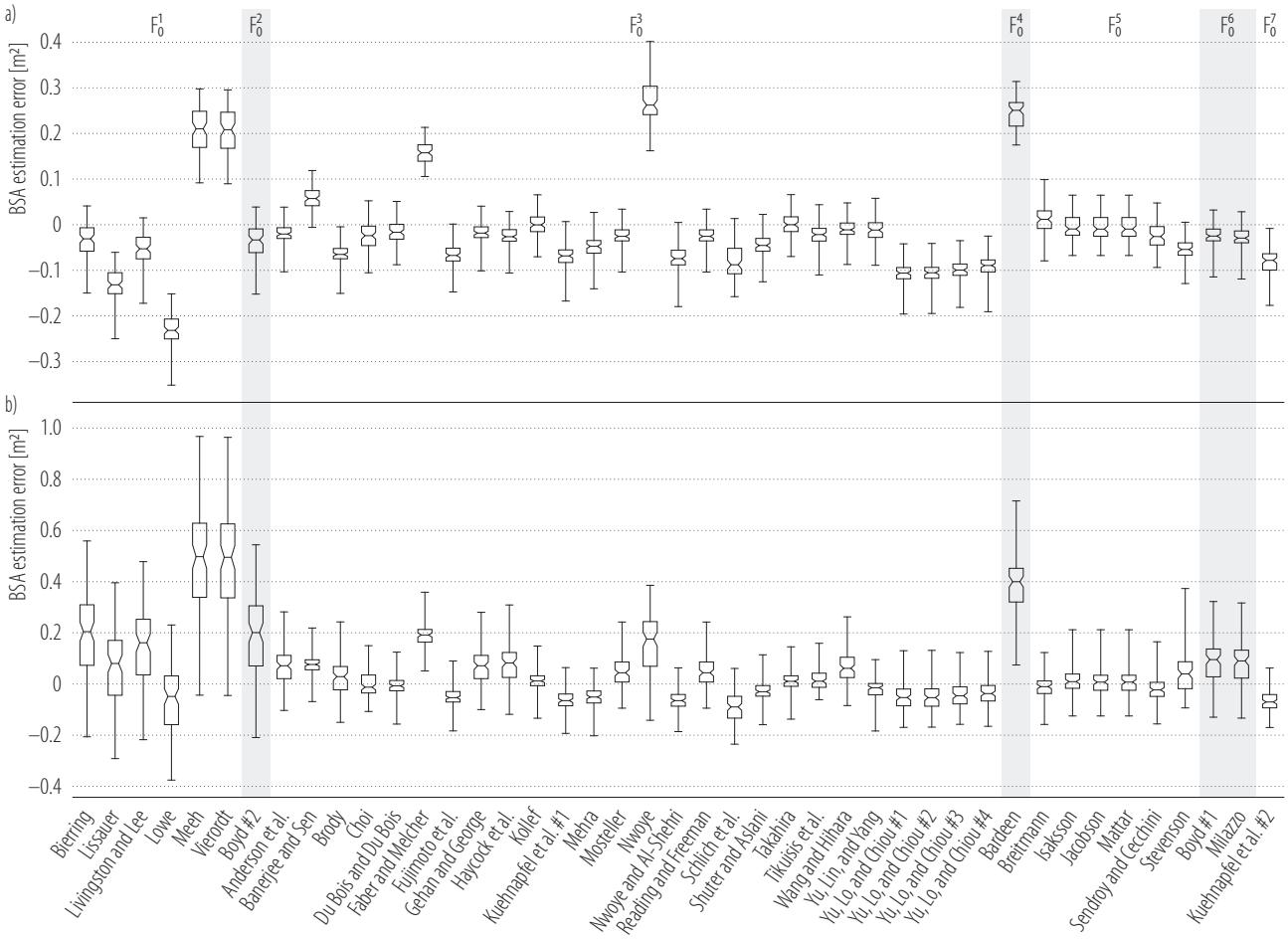
The formulation of research questions and outcome measures did not involve any participants. Similarly, participants were not engaged in devising design plans, recruitment strategies, or study implementation. Their input was not sought for data interpretation or the creation of the manuscript. Furthermore, study results were not shared with the participants. Graphical visualizations were created using the Matplotlib 2.1.0 Python package [29]. The BSA calculator was designed employing Borland C++ Builder software [31].

RESULTS

Currently available BSA formulas

Across a history spanning over a century, the pursuit of accurately estimating BSA has led to the development of >40 mathematical formulas rooted in diverse state variables [12,19,30,32–44]. Researchers have diligently analyzed BSA across various demographic groups from around the world, with the aim of identifying the most optimal formula that minimizes error while relying on easily accessible variables. The existing formulas can be categorized into several groups: those solely reliant on body weight, those incorporating weight and height, those involving weight, height, and sex, those considering weight, height, and age, those encompassing weight, height, sex, and age, and finally, formulas that incorporate additional selective properties and variables.

Throughout the years, several formulas have emerged as particularly popular and widely utilized. These include the Boyd, Du Bois and Du Bois, Gehan and George, Haycock et al., and Mosteller formulas [17]. The formulas exhibit a strong correlation with BSA when applied to a specific sample of individuals, as determined by the characteristics of the subjects included in the study. Nonetheless, when faced with an unfamiliar and previously unexamined group of subjects, the accuracy of these formulas diminishes, as depicted in Figure 2. The outcomes presented in Figure 2a highlight that the majority of established formulas are well-suited for estimating BSA values among individuals with a normal physique ($18.5\ kg/m^2 \leq BMI < 25\ kg/m^2$). However, this effectiveness diminishes when applied to BMI ranges outside of this norm (Figure 2b), leading to a mean absolute error of $0.0309\ m^2$ and a maximum-to-minimum error range of $0.2826\ m^2$ in the most favorable scenario. An intriguing observation emerges from the fact that, despite the BSA data conforming to a normal distribution ($p > 0.5$), certain formulas introduce distortions to the data, causing their estimations to deviate from the expected distribution. Formulas such as Bierring, Lissauer, Livingston and Lee, Meeh, Vierordt, Boyd #2, Isaksson, or Mattar formula exemplify this phenomenon. Given the substantial disparities in relative error and the large number of formulas under consideration, the authors will focus solely on a select few that exhibit the most promising performance for further analysis.



F_0^1	F_0^2	F_0^3	F_0^4	F_0^5	F_0^6	F_0^7
$a_0 \times W^{b_0}$	$a_0 \times W^{b_0+b_1 \times \log_{10}(W)}$	$a_0 \times W^{b_0} \times H^{b_1}$	$a_0 \times W/H + a_1 \times W^{b_0}/H^{b_1}$	$a_0 \times W + a_1 \times H + a_2$	$a_0 \times W^{b_0+b_1 \times \log_{10}(W)} \times H^{b_2}$	$a_0 \times W^{b_0} \times H^{b_1} \times e^{c_0 \times sex_{10}} \times e^{c_1 \times BMI}$

Figure 2. Body surface area (BSA) estimation error for patients with BMI: a) ≥18.5 kg/m² and <25 kg/m²; b) of other ranges – the methods are grouped by the structures of their formulae, which have the general analytical formulation: F_0^1 to F_0^7; measurements performed in September 2015 – November 2016 at Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W. Orłowski in Warsaw, Poland

Improving of the currently available BSA formulas

From the existing known formulas, it becomes evident that these can be categorized into 7 distinct groups based on their overarching analytical formulations (Figure 2). The majority of research in the realm of BSA calculation has been dedicated to determining the optimal parameter values for these models, with the Du Bois and Du Bois model (F_0^3) standing out as the most frequently employed. It is worth noting that the current study demonstrates the feasibility of precisely fitting all previous BSA model types to a specific dataset of anthropometric parameters. Nonetheless, even with this capability, the overall robustness of the model is not assured. The parameter extraction was conducted to tailor standard models to match the gathered data. Table 2 outlines the parameters fine-tuned through the authors' optimization procedure,

Table 2. Characteristics improvement in estimation errors over known formulae for each group given in Figure 3 resulting from newly calculated parameters; measurements performed in September 2015 – November 2016 at Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland

Formulae structure	Formula common name	New parameter	Absolute error [m^2]		$\Sigma(\ln Q)^2$	Improvement [%]		
			M±SD	max		M±SD	max	$\Sigma(\ln Q)^2$
F_0^1	Livingston and Lee	$a_0 = 0.2981$	0.0599±0.0445	0.1895	0.2398	51.8±62.0	60.4	75.8
		$b_0 = 0.4306$						
F_0^2	Boyd #2	$a_0 = 0.0317$	0.0581±0.0457	0.2130	0.2284	57.5±67.4	60.8	81.6
		$b_0 = 1.4598$						
		$b_1 = -0.2713$						
F_0^3	Takahira	$a_0 = 0.0104$	0.0231±0.0221	0.1391	0.0410	7.2±7.1	4.3	11.6
		$b_0 = 0.4157$						
		$b_1 = 0.6627$						
F_0^4	Bardeen	$a_0 = 0.0082$	0.0493±0.0336	0.2081	0.1587	85.0±71.7	70.9	96.2
		$a_1 = 0.0164$						
		$b_0 = 0.5$						
		$b_1 = -0.5$						
F_0^5	Isaksson	BMI[a] <25:	0.0233±0.0220	0.1354	0.0408	24.8±26.4	36.2	42.5
		$a_0 = 0.0127$						
		$a_1 = 0.0065$						
		$a_2 = -0.1665$						
		BMI[a] ≥25:						
		$a_0 = 0.0087$						
		$a_1 = 0.008$						
		$a_2 = -0.1233$						
F_0^6	Milazzo	$a_0 = 0.0088$	0.0237±0.0219	0.1512	0.0419	66.3±66.6	52.2	87.3
		$b_0 = 0.5052$						
		$b_1 = -0.0235$						
		$b_2 = 0.6563$						
F_0^7	Kuehnapfel et al. #2	$a_0 = 0.01$	0.0243±0.0223	0.1528	0.0439	67.6±30.1	13.6	85.6
		$b_0 = 0.4121$						
		$b_1 = 0.6717$						
		$c_0 = -0.0001$						
		$c_1 = 0.0001$						

along with their associated BSA estimation errors and the enhancements over the most effective known formula for each of the mentioned models. The authors findings demonstrate that remarkable enhancements are attainable, with a substantial 85.0% improvement for mean absolute error and a notable 70.9% improvement for max-

Table 3. The authors' propositions of body surface area (BSA) formulae with their estimation errors; Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland, September 2015 – November 2016

Symbol	Formula	Absolute error [m^2]	
		M±SD	max
F_n^1	$0.0104 \times W^{0.4157} \times H^{0.6627}$	0.0231±0.0221	0.1391
F_n^2	$F_n^1 \times (0.778+0.0003 \times A-0.0013 \times W-0.0004 \times H-0.0007 \times HeCC+0.0009 \times ED-0.0016 \times NCC-0.0008 \times ChCC-0.0001 \times WaCC+0.0002 \times HH+0.0013 \times ACC+0.0008 \times FCC+0.0042 \times WrCC+0.002 \times FL+0.0006 \times AS-0.0006 \times TCC+0.0008 \times CaCC+0.0006 \times KH+0.0019 \times SS+0.0041 \times BMI)$	0.0178±0.0178	0.0986
F_n^3	$0.0101 \times W^{0.3766} \times H^{0.4664} \times ACC^{0.0339} \times WrCC^{0.0743} \times AS^{0.1713}$	0.0199±0.0192	0.1199
F_n^4	$F_n^3 \times (0.7846+0.0003 \times A-0.001 \times W+0.0009 \times H-0.0008 \times HeCC+0.0009 \times ED-0.0015 \times NCC-0.0008 \times ChCC-0.0001 \times WaCC+0.0002 \times HH+0.0002 \times ACC+0.0008 \times FCC-0.0004 \times WrCC+0.002 \times FL-0.0004 \times AS-0.0004 \times TCC+0.0008 \times CaCC+0.0006 \times KH+0.002 \times SS+0.0045 \times BMI)$	0.0173±0.0163	0.1146
F_n^5	WaCC/H <0.5: $0.0108 \times W^{0.4287} \times H^{0.4643} \times ED^{0.0114} \times NCC^{-0.0583} \times HH^{0.0283} \times ACC^{-0.0117} \times WrCC^{0.1045} \times AS^{0.1407}$ WaCC/H ≥0.5: $0.0148 \times W^{0.3733} \times H^{0.2869} \times ED^{0.0211} \times NCC^{-0.0589} \times HH^{0.0323} \times ACC^{0.063} \times WrCC^{0.103} \times AS^{0.2468}$	0.0184±0.0167	0.1174
F_n^6	$0.046 \times A^{0.0129} \times W^{0.5445} \times H^{0.139} \times HeCC^{-0.0464} \times ED^{0.0099} \times NCC^{-0.0826} \times ChCC^{-0.0728} \times WaCC^{-0.0001} \times HiCC^{-0.0095} \times HH^{0.0288} \times ACC^{0.0466} \times FCC^{0.0174} \times WrCC^{0.0701} \times FL^{0.0773} \times AS^{0.1036} \times TCC^{-0.0302} \times CaCC^{0.0182} \times KH^{0.0329} \times SS^{0.0983} \times BMI^{-0.1149})$	0.0176±0.0182	0.1273
F_n^7	BMI <18.5: $0.013 \times W^{0.4755} \times H^{0.363} \times ED^{0.0108} \times NCC^{0.0063} \times HH^{0.042} \times ACC^{-0.0976} \times WrCC^{0.0768} \times AS^{0.1808}$ 18.5 ≤ BMI <25: $0.0132 \times W^{0.4357} \times H^{0.4102} \times ED^{0.0058} \times NCC^{-0.0473} \times HH^{0.034} \times ACC^{-0.0047} \times WrCC^{0.1005} \times AS^{0.138}$ $0.0132 \times W^{0.4357} \times H^{0.4102} \times ED^{0.0058} \times NCC^{-0.0473} \times HH^{0.034} \times ACC^{-0.0047} \times WrCC^{0.1005} \times AS^{0.138}$ BMI ≥25: $0.0125 \times W^{0.3801} \times H^{0.3353} \times ED^{0.0252} \times NCC^{-0.073} \times HH^{0.0364} \times ACC^{0.0532} \times WrCC^{0.0991} \times AS^{0.2389}$	0.0185±0.0173	0.1244

A – age (years); ACC – arm circumference (cm); AS – arm span (cm); BMI – body mass index (kg/m^2); CaCC – calf circumference (cm); ChCC – chest circumference (cm); ED – distance between the outer ends of eyes (cm); FCC – forearm circumference (cm); FL – distance between the elbow and the tip of the middle finger (cm); H – height (cm); HeCC – head circumference (cm); NCC – neck circumference (cm); HiCC – hips circumference (cm); HH – height from the ground to the hip (cm); KH – height from the ground to the knee (cm); SS – standard European shoe size; TCC – thigh circumference (cm); W – weight (kg); WaCC – waist circumference (cm); WrCC – wrist circumference (cm). The data are normally distributed and statistically significant ($p < 0.05$).

imum error achieved (F_0^4). In the least favorable scenario (F_0^3) vs. the best-performing standard formula), a 7.2% improvement for mean absolute error and a 4.3% improvement for maximum error are still notable outcomes.

Novel BSA predictors and their outcomes

As demonstrated, it is feasible to derive new coefficients for the standard formulas models, leading to an enhancement in BSA estimation. However, these models still exhibit a lack of robustness, with their accuracy undergoing significant fluctuations when confronted with new testing data. To address this issue, the authors propose an alternative approach for the development of BSA models. Following the outlined methodology (as detailed in the Data analysis section), novel BSA estimation models is introduced, as displayed in Table 3, along with the corresponding error distributions depicted in Figure 3. By incorporating a broader range of anthropometric variables in conjunction with a power model formula, the authors achieve a noteworthy reduction in mean absolute error, down to 0.0173 m^2, as

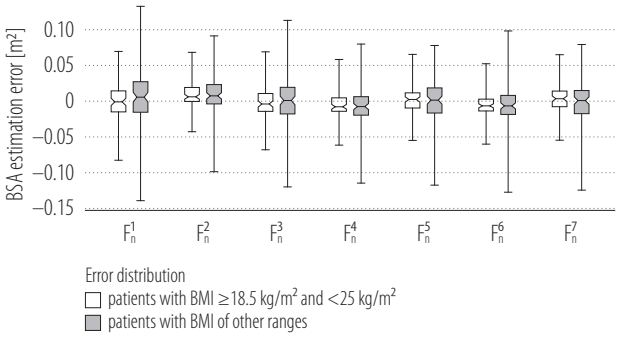


Figure 3. Body surface area (BSA) estimation errors; measurements performed in September 2015 – November 2016 at Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland

compared to the mean error of the best-performing previously known formula at 0.0249 m². Furthermore, this enhancement results in a substantial 21.1% improvement in maximum error.

To provide a comprehensive overview of the advancements offered by the authors' proposal, a synthesis of the most favorable outcomes obtained is presented (Table 4). Within the array of the above-presented formulas, the authors have selected the two most promising candidates from each category: the standard models, the modified standard models, and the newly introduced models. These models are systematically compared across

Table 4. Comparison of absolute estimation errors of the best known and the proposed body surface area formulae (Tables 2 and 3) for groups of participants divided by body mass index (BMI) and waist circumference; measurements performed in September 2015 – November 2016 at Gdańsk University of Technology, University Clinical Center of the Medical University of Gdańsk and Independent Public Clinical Hospital named after prof. W Orłowski in Warsaw, Poland

Variable	Absolute error [m²]					
	F_n^4	F_n^5	F_n^3 mod.[a]	F_n^5 mod.[a]	Kollef	Takahira
BMI						
≥18.5 and <25						
M±SD	0.0134±0.0110	0.0139±0.0111	0.0170±0.0140	0.0174±0.0130	0.0176±0.0131	0.0177±0.0131
max	0.0614	0.0655	0.0826	0.0752	0.0702	0.0697
$\Sigma(\ln Q)^2$	0.0071	0.0077	0.0113	0.0111	0.0112	0.0113
<18.5 or ≥25						
M±SD	0.0206±0.0190	0.0222±0.0194	0.0283±0.0260	0.0282±0.0263	0.0311±0.0290	0.0309±0.0287
max	0.1146	0.1174	0.1391	0.1354	0.1484	0.1453
$\Sigma(\ln Q)^2$	0.0155	0.0167	0.0298	0.0297	0.0355	0.0350
Waist circumference						
<100 cm						
M±SD	0.0142±0.0110	0.0149±0.0113	0.0179±0.0137	0.0185±0.0132	0.0191±0.0137	0.0191±0.0137
max	0.0614	0.0655	0.0826	0.0752	0.0702	0.0697
$\Sigma(\ln Q)^2$	0.0113	0.0123	0.0180	0.0180	0.0193	0.0194
≥100 cm						
M±SD	0.0253±0.0234	0.0275±0.0236	0.0366±0.0318	0.0356±0.0327	0.0401±0.0356	0.0396±0.0353
max	0.1146	0.1174	0.1391	0.1354	0.1484	0.1453
$\Sigma(\ln Q)^2$	0.0113	0.0121	0.0230	0.0228	0.0274	0.0270

$p < 0.5$.

[a] Known formulae structure with new parameters (based on Table 2).

distinct groups based on BMI and waist circumference, thereby accentuating their efficacy in relation to specific body characteristics. The selection criteria for these formulas were based on their $\Sigma(\ln Q_i)^2$ score. Significantly, all the proposed formulas outperform the previously known formulas. Notably, the F_n^4 formula attains a mean error that surpasses the Takahira formula's performance by 25.7% in the lower waist circumference range, and by 36.1% in the other range. Furthermore, the F_n^4 formula achieves a remarkable 33.3% reduction in mean error when compared to the Takahira formula for subjects characterized by abnormal BMI.

DISCUSSION

The existing BSA formulas rely on a limited set of state variables, which are often rearranged in various configurations. These variables are deliberately chosen to be easily accessible for each patient, which rules out alternatives like adopting contemporary 3D scanners for precise BSA measurements. While a 3D scanner could offer exact BSA measurements, its implementation might pose challenges in time-critical medical procedures or for patients who cannot undergo the scanning process due to various reasons. A marginal enhancement can be attained by fine-tuning the coefficients of standard models to align with the specific dataset. Table 2 displays the novel coefficients for established BSA models and their consequent effect on enhancing estimation accuracy compared to their well-known counterparts. However, it is the authors' assertion that this approach, in the end, is inherently limited, as the accuracy of the formulas will inevitably fluctuate with the introduction of new, unfamiliar data. The only viable path to achieving universally accurate estimations would involve the calibration of coefficients using an extensive dataset of anthropometric information. Moreover, considering the current scope of mathematical understanding and the diverse array of individual human attributes, it can be concluded that crafting a singular universal BSA formula, reliant on a limited number of state variables, is unattainable. Consequently, the search for novel estimation models that facilitate swift and precise BSA calculation for the entire population, irrespective of individual anatomical differences, is both necessary and justified.

The newly introduced formulas (as outlined in Table 3) have been developed employing an alternative methodology. Through the utilization of sophisticated optimization techniques coupled with a 10-fold cross-validation approach, enhanced robustness has been achieved. It is important to note that this method comes with a trade-off: the need for a higher number of parameters. For instance, the most effective formula F_n^4 necessitates 19 parameters. Despite this drawback, even the formula with the fewest required parameters (F_n^1 with just 2 parameters) manages to yield slightly superior outcomes in comparison to the standard models. As depicted in Table 4, a comprehensive comparison is provided among the top-performing formulas presented in this paper. The categorization into groups based on BMI and waist circumference offers precise insights into the specific domains where each formula excels. Of significant importance is the observation that across all scenarios, the novel formulas consistently outperform their counterparts. This effect is particularly pronounced within groups exhibiting abnormal physique characteristics, thereby highlighting the heightened effectiveness of the new formulas in such scenarios. The findings showcased not only reveal the potential to curtail extreme BSA errors by 33.3%, but also signify a substantially more favorable distribution of errors around the mean. Across the entire study cohort, a noteworthy decrease of at least 30.5% in mean absolute error and 21.1% in maximum error is achieved. Particularly notable is the superior performance of the F_n^4 formula, which emerges as the overall best-performing formula across various scenarios.

A concise case study involving dose calculation can be undertaken to illustrate the impact of errors on drug

dosage. Taking Irinotecan, a well-known cancer treatment drug often administered in tandem with cisplatin, as an example, it is usually infused continuously >90 min at doses ranging 175–350 mg/m² [45]. Let us assume the dosage level is 262.5 mg/m². For a case involving an overweight adult male with average height (weight 131.9 kg, height 173.3 cm, age 52 years), the ideal irinotecan dose (based on their scanned BSA) amounts to 597.87 mg. If the BSA were calculated using the best of the old formulas – the Takahira formula – the dose would be 636.01 mg. On the other hand, employing the new F_n^4 formula, this value would be adjusted to 618.84 mg. Comparing the Takahira formula to the F_n^4 formula, the former generates a dosage error almost twice as large (overestimation: 38.14 mg vs. 20.97 mg). Considering a severely underweight individual (weight 35 kg, height 165 cm, age 44 years), the accurate dose would be 357.26 mg. Calculated with the Takahira formula, the dose estimation would be 349.25 mg, while utilizing the F_n^4 formula would yield a dose estimation of 355.19 mg. This leads to nearly quadrupled error for the Takahira formula compared to the F_n^4 formula (underestimation: 8.01 mg vs. 2.07 mg). In the context of TBSA, even a tripling of overestimation in medication dosing can be observed [22]. This case study effectively demonstrates the substantial impact that BSA estimation errors can have on drug dosing accuracy.

As evident from the discussion above, the clinical relevance of employing BSA formulas becomes strikingly apparent, especially when dealing with individuals at the extreme ends of the human physique spectrum. Drug dosage calculations hinging on an estimated BSA value often result in either overdosage or underdosage, both of which carry critical implications for patient health. Presently used formulas can lead to substantial dosage miscalculations, reaching up to 38.14 mg (as illustrated in the earlier example), potentially precipitating severe health consequences. Even more concerning is the underestimation of dosage by 8.01 mg for severely underweight patients, potentially causing treatment delays or even cessation. The adoption of the formulas proposed in this study holds the promise of reducing these risks by 2–4 times, significantly enhancing the precision and safety of drug dosing protocols. However, it is important to acknowledge that the research participants constitute a biased group, primarily consisting of younger individuals, with over 70% being <40 years old. Given this demographic skew, the authors must exercise caution in asserting that the outcomes presented can be universally applied to the entire population. This highlights the necessity of expanding the scope of this research to encompass a more diverse set of participants, particularly those aged >40 years old, in order to more accurately validate and generalize the authors' methodology.

In order to make their investigations more useful for medical purpose, the authors designed a simple BSA calculator. This software, which can be used free of charge, is accessible as a supplementary to the following article. Unlike other free BSA calculators, this program allows users to choose the most appropriate formulas for his purposes. The program is based on formulas developed by us, which guarantees greater credibility of the obtained results, thus translating into improved effectiveness of medical therapies.

CONCLUSIONS

Recent research highlights the limited suitability of only a handful of BSA formulas for individuals with a normal physique, leaving gaps in accuracy for those with different conditions such as anorexia or obesity. This study effectively demonstrates that through the application of appropriate mathematical techniques and a refined selection of anthropometric variables, the authors can craft improved and resilient BSA estimation models. These models exhibit a remarkable insensitivity to the wide array of variations in human physique.

The newly introduced formulas result in a noteworthy reduction of errors, often reaching several dozen percent, when compared to the most effective formulas presently in use. Although the inclusion of a greater number of anthropometric parameters lengthens the time required for BSA determination, it significantly enhances their precision. It is reasonable to anticipate that this drawback could eventually be mitigated through the application of contactless measurement systems and rapid computational algorithms, thus balancing precision and efficiency.

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