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Compilation of basal metabolic and blood perfusion rates in various multi-compartment, whole body thermoregulation models

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Abstract

The assignments of basal metabolic rates (BMR), basal cardiac outputs (BCO) and basal blood perfusion rates (BBPR) were compared in nine multi-compartment, whole body thermoregulation models. The data are presented at three levels of detail: total body, specific body regions and regional body tissue layers. Differences in the assignment of these quantities among the compared models increased with the level of detail, in the above order. The ranges of variability in the total body BMR was 6.5% relative to the lowest value, with a mean of 84.3±2 Watts, and in the BCO it was 8% with a mean of 4.70±0.13 l/min. The least variability among the body regions is seen in the combined torso (shoulders, thorax and abdomen: ±7.8% BMR and ±5.9% BBPR) and in the combined head (head, face, and neck: ±9.9% BMR and ±10.9% BBPR), determined by the ratio of the standard deviation to the mean. Much more variability is apparent in the extremities with the most showing in the BMR of the feet (±117%), followed by the BBPR in the arms (±61.3%). In the tissue layers, most of the bone layers were assigned zero BMR and BBPR, except in the shoulders and in the extremities that were assigned non-zero values in a number of models. The next lowest values were assigned to the fat layers, with occasional zero values. Skin basal values were invariably non-zero but involved very low values in certain models, e.g., BBPR in the feet and the hands. Muscle layers were invariably assigned high values with the highest found in the thorax, abdomen and legs. The brain, lung and viscera layers were assigned the highest of all values of both basal quantities with those of the brain layers showing rather tight ranges of variability in both basal quantities.

Average basal values of the "time-seasoned" models presented in this study could be useful as a first step in future modeling efforts, subject to appropriate adjustment of values to conform to most recently available and reliable data.

Keywords: Modeling; Cardiac output; Body regions; Tissue layers

Introduction

Modeling of the human thermoregulatory system has been carried out, with a steadily increasing level of detail and sophistication, since the first half of the 20th Century (cf. Burton 1934, Eichna et al. 1945; Machle and Hatch 1947). The main purpose of this effort has been to develop experimentally verifiable codes and capabilities to simulate and predict the thermal behavior of the human body under various exposure scenarios to environmental conditions and activity levels. Two complementary applications of such models are the evaluation of potentially life-threatening conditions, on the one hand, and the evaluation of thermally comfortable conditions, on the other. The former case is obviously not amenable to experimental verification while the latter requires extensive testing for a variety of environmental parameters. Reliable and detailed models of the thermoregulatory system can potentially augment and even substitute the required experimentations in either case and provide useful information on thermally life-threatening conditions.

To achieve this goal, multiple anatomical, physiological and thermo-physical data are required, in addition to fast and efficient computational schemes. In the following we present a brief account of the historical milestones in the development of different types of whole body thermoregulation models. Interested readers are referred to a host of detailed reviews on the subject (e.g., Fan et al. 1971; Hardy 1972; Hwang and Konz (1977; Wissler 1988; Yokoyama and Maeda 2007).

Earlier models were rather simple and lacked many essential anatomical, physiological and detailed control elements. The first model was probably developed by Burton (1934) who simulated the human body as a single homogeneous cylinder with uniform metabolic heat generation. Subsequent models were typically of the core-and-shell type (cf. Machle and Hatch 1947). In these models body organs were lumped together into one inner compartment whereas the skin was assumed as an external layer, completely engulfing the core. In a number of these earlier models blood circulation connected the inner and outer compartments with an assumed "heart" supplying the cardiac output (e.g., Morgan 1970).

The USA space program provided the incentive and impetus for developing much more detailed and elaborate models. This effort was driven by the need to simulate the effects of the hostile and life-threatening conditions in space on astronauts enclosed in a whole-body protective gear, including an inner liquid cooled garment for removal of metabolic heat. The earlier simple models cited above proved inadequate to meet this challenge and more detailed, multi-compartment models, simulating all body regions, were required. The first who engaged in this challenge were Wissler (1961) in his pioneering work and Stolwijk (1966). Subsequently, both investigators developed multi-compartment models, separately treating the head, trunk, arms, hands, legs and feet (Stolwijk 1970; Wissler 1964, 1985). Each body region, in addition to being composed of a number of interconnected cylindrical segments, was subdivided outwardly into four adjoining layers representing, respectively, the core, muscle, fat and skin. This assembly represented the “passive,” heat conducting pathways system, simulating the anatomy and physical properties of the various body parts and their interconnections via the circulatory system. Superimposed on the “passive” system was the “active” system, manifesting the body's control mechanisms that activate the regulatory mechanisms in response to changing environmental conditions and activity levels, e.g., blood re-distribution, sweat production, and vasomotor activity.

The modeling principles established by these two pioneers have since been the *golden standard* in whole-body thermal modeling. The more recently developed models utilize advances in fast computing for expanding the number of included body compartments and details and incorporating updated, state-of-the-art physiological data. What differentiates all these models is not only their computational schemes and intended applications, e.g., cold water immersion (Montgomery 1974; Tikuisis et al. 1987 1988 (a)(b)(c), Wissler 1964 1988), therapeutic hyperthermia (Charny 1988; Spiegel 1980), determination of thermal comfort (CBE 2001; Fiala 1998; Fiala et al. 1999 2001, Tanabe et al. 2002), aerobic fitness and dehydration (Kraning and Gonzalez 1997), etc., but also the assumed physiological data used to construct the “passive” parts of each model.

In this article we compile and compare the basal metabolic and basal blood perfusion rates that were assumed in nine of the more detailed multi-compartment, whole body thermoregulation models {Arkin 1982; CBE 2001; Huizenga, et al. 2001 [also referred to as the Berkeley Comfort Model]; Fiala 1998; Gordon 1974; Gordon et al. 1976 1976; Stolwijk 1971; Tanabe et al. 2001; Werner and Webb 1993; Wolf and Garner 1997}. The reader will note the absence of Wissler's (1961 1964) keystone model from this comparison. The reasons for this exclusion are explained in the discussion. The basal physiological variables, when coupled with the anatomical details and control algorithms, form the basic data that are required for simulating the dynamics of the thermoregulatory system. The assumed values, along with their distributions in the body, fundamentally influence the computational outcomes of each of the considered models.

The nine models included in this study were chosen primarily because detailed data for their assumed basal metabolic and blood perfusion rates were readily available. Models not included in this study are not to be construed as less useful than those that were.

The purposes of this study are: (1) Collate and present basal data that are used in a number of detailed thermoregulation models, (2) Identify and define ranges of variability and commonality among the assumed data sets, (3) Provide a common basis of these data for future modelers.

Analysis

(a) Basic data of the compared models

Table 1 summarizes the anthropometric and basic computational details of the compared models. As seen, all models (except Arkin's (1982), for which these data were not available) assume rather narrow ranges of body heights (1.68 to 1.755 m) and weights (72.4 to 74.43 kg). The average height for all compared models, 171±3 cm, compares favorably with Cooney's (1976) value for a "standard man" of 173 cm. The average weight of 73.6±2.3 kg, however, falls noticeably above Cooney's (1976) value of 68 kg which is based on data published earlier, in 1971. The reason for this disparity in weights likely reflects the wide spread "weight gaining" phenomenon of humans in recent decades. Recent data (www 2014) put these anthropometric values at 176.3 cm and 88.3 kg, again reflecting considerable recent gains in average human height and weight.

Table 1: Summary of anthropometric and computational data in the compared models

SOURCE	HEIGHT (cm)	WEIGHT (kg)	SKIN SURFACE AREA (m^2, Dubois)*	BODY FAT (%)	NUMBER OF BODY SEGMENTS
Stolwijk (1971)	174.6	74.1	1.89		6
Wissler (2010)**	172.8	73	1.86		
Gordon (1974 1976)	168	72.4	1.82		12 cylindrical 2 spherical
Arkin (1982)					14
Smith (1991)	168.7	71.9	1.83		15
Werner & Webb (1993)	170	78	1.89		6
Wolf & Garner (1997)	168.7	70	1.80	10	6
Fiala (1998 1999)	171.6	73.5	1.86		14
CBE (2001)	175.5	74.4	1.90	14.05	16
Tanabe (2002)	171*	74.43	1.87		16
Averages ±S.D	171±3	73.6±2.3	1.86±0.04		

* Estimated from Dubois' equation

** Values not included in averages

The relative similarity among heights and weights in the compared models stems from the fact that each subsequently developed model relied on and borrowed from its predecessor(s), with minor adjustments made mostly in accordance with the specifically available anthropometric and experimental data. It is apparent that future models will need to adjust the anthropometric, and thus also the basal data of the modeled human to conform to more current values.

Most models use cylindrical elements to simulate body segments except for Gordon (1974) who used, additionally, 2 spherical elements to simulate sectors of the head and Fiala (1998 1999) who used a semi-spherical shell for the face. The listed models differ, however, in the computational details according to which the body passive system is simulated: from using a minimal number of only 6 body segments to the more detailed 14 to 16 segments models, Table 1. This factor impacts on the potential accuracy of each model and its capability to incorporate the thermal responses of more body elements.

(b) Total body basal metabolic rates and cardiac outputs

Figure 1 shows total body basal metabolic rates as were applied in each of the compared models. The range of variability of these data is from 81.41 (Wolf and Garner 1997) to 86.69 Watt (Werner and Webb 1993), indicating a 6.5% variance relative to the lowest value. Figure 2 indicates a similarly tight range (8%) in the assumed basal cardiac outputs (representing the sum total of all the models' tissue layers blood perfusion rates) in each of the compared models, from 4.48 (Arkin 1982) to 4.84 l/min (Gordon 1974).

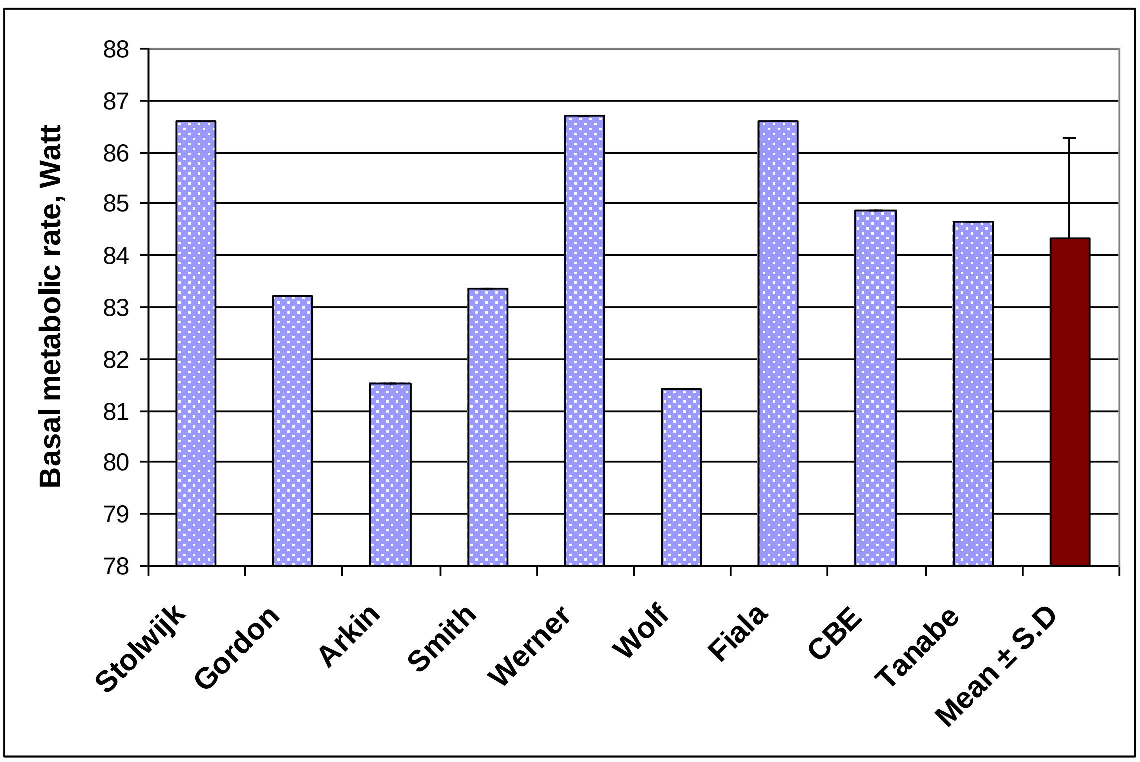

Figure 1: Whole body basal metabolic rates

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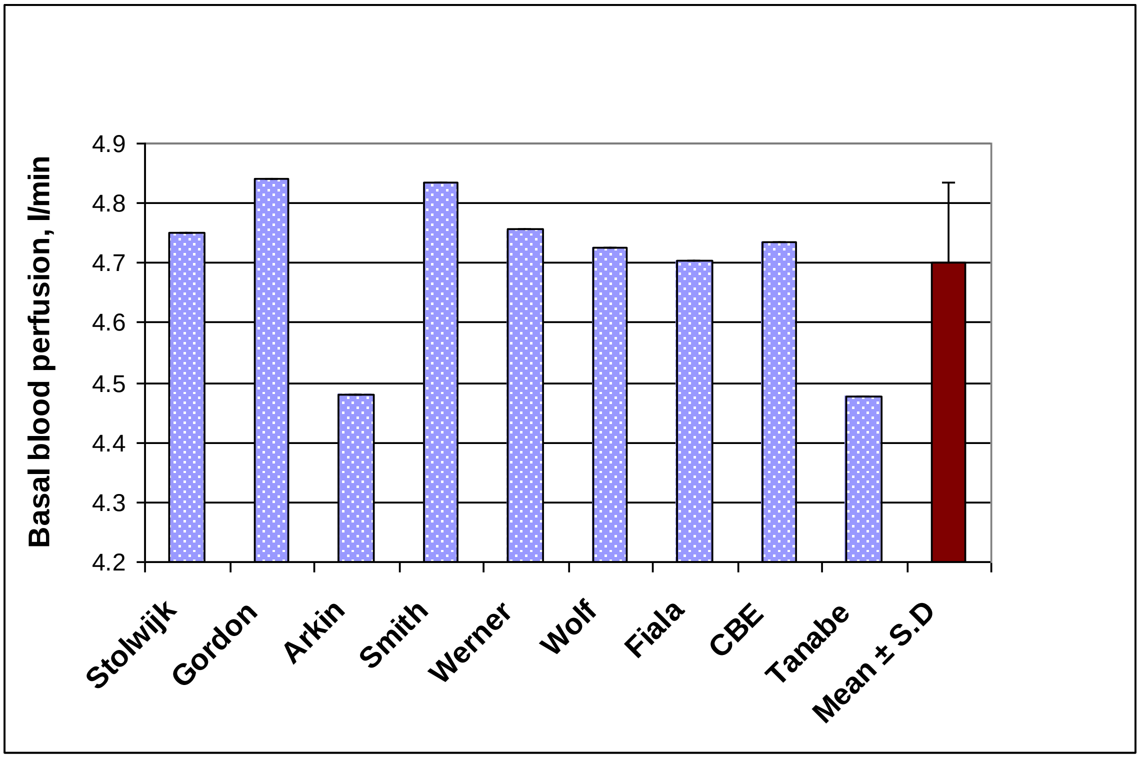

Figure 2: Whole body basal cardiac outputs

<u>(c) Total regional basal metabolic and blood perfusion rates</u>

Differences among the compared models become more accentuated with regard to the number and identity of the body segments included in each model. All the compared models depicted the extremities by 4 separate compartments: arms, hands, legs, and feet. In the models with the largest number of body segments, each of these limbs was depicted in the computational scheme by two separate cylinders, distinguishing between the right and left sides. In the models with the lowest number of segments (Stolwijk 1971; Werner and Webb 1993), the pairs of lateral extremities were lumped together into single cylindrical elements (Table 1). The head and the torso were subdivided variously into: head (All), face (Fiala 1998; Gordon 1974) and neck (Fiala 1998; Gordon 1974; Smith 1991), or shoulders (Fiala 1998; Tanabe et al. 2002), thorax (All) and abdomen (CBE 2001; Fiala 1998; Gordon 1974; Tanabe et al. 2002). Fiala's (1998) is the only model employing all of these listed subdivisions. The layout of each model's body segments is shown in the Appendix.

Regional distributions of basal metabolic and blood perfusion rates among the various models are shown in Figs. 3 and 4, respectively. The upper two plots in each of these figures lump together the combined head and the combined torso for each model. Unlike the data shown in both Figs. 1 and 2, in which the scales are truncated, the scales in these figures show the full ranges of change in the displayed variables, except for the combined torso in Fig. 4.

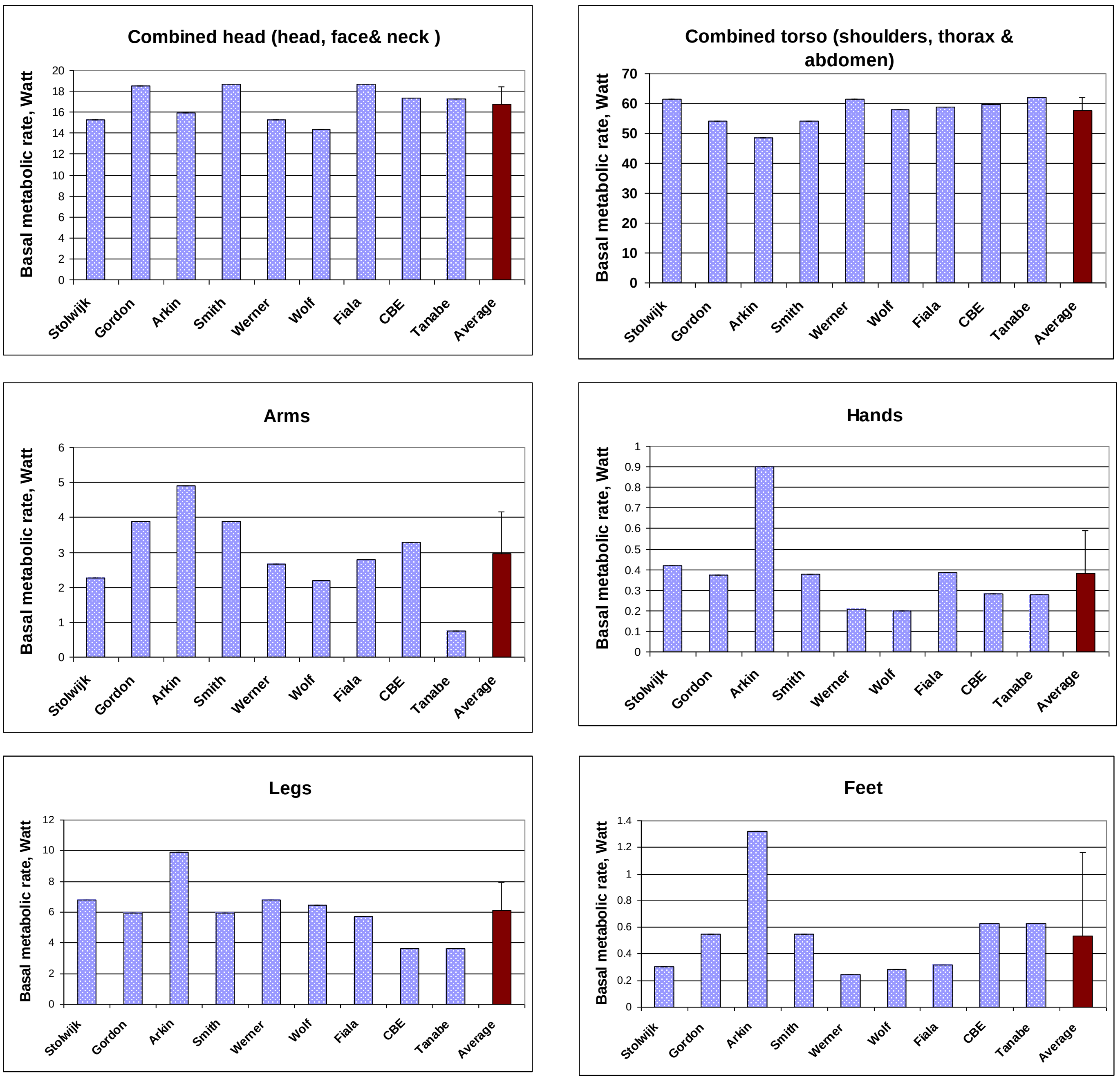

Figure 3: Regional basal metabolic rates

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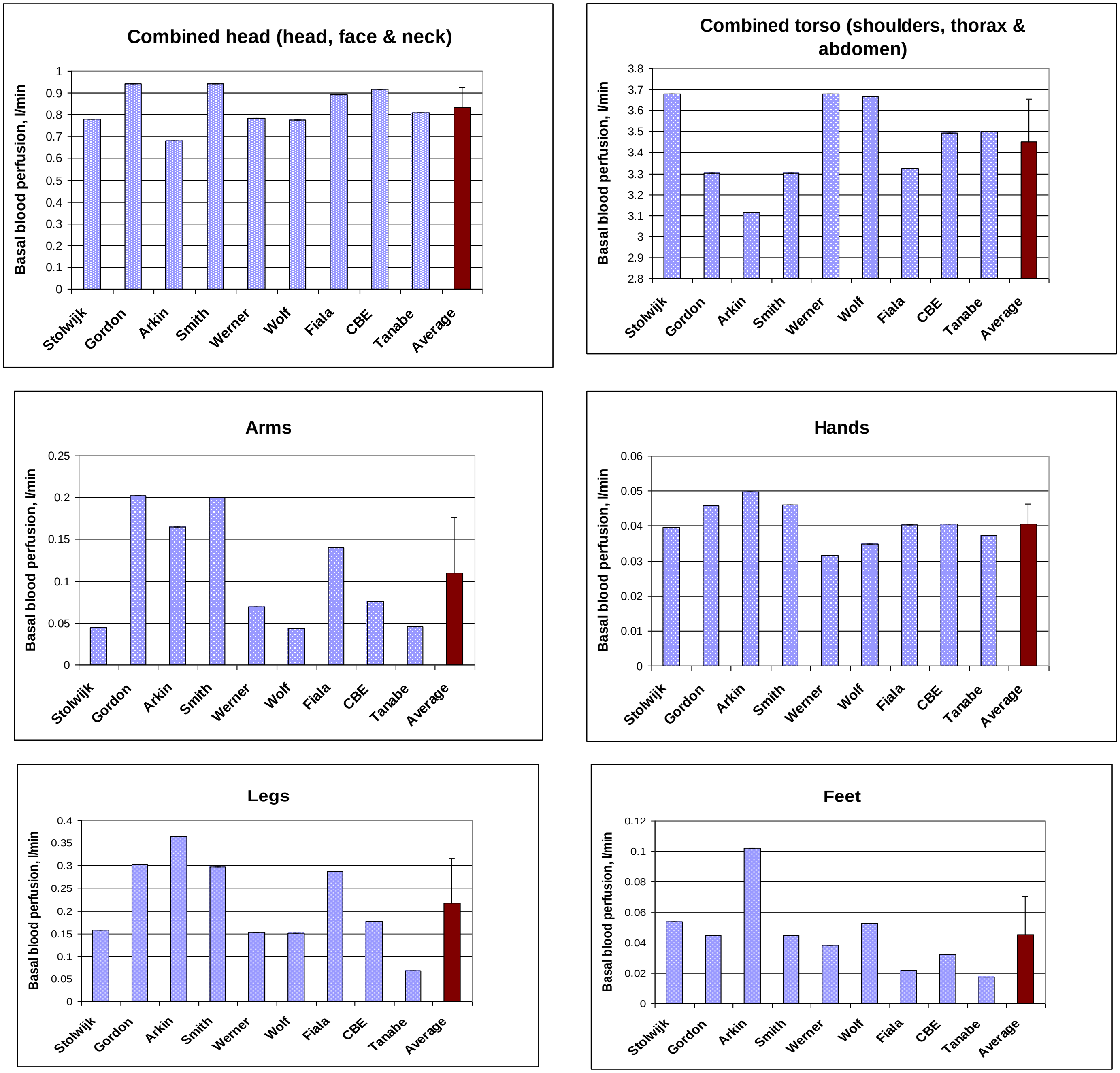

Figure 4: Regional basal blood perfusion rates

Variability among the compared models is quite apparent with the least variability, as indicated by the ratio of the standard deviation to the mean, seen in the combined torso (±7.8% metabolic and ±5.9% blood perfusion) and in the combined head (±9.9% and ±10.9%). Significantly more variability is apparent in the extremities with the most showing in the basal metabolic rate in the feet (±117%, Fig. 3), followed by the basal blood perfusion in the arms (±61.3%, Fig. 4).

(d) Ranges of variability in tissue layers of the various body regions

Yet another level of comparison among these models is obtained by considering the basal values assigned to each of the tissue layers in each of the body regions. The number of elements to be compared are more than 4 times larger than those used in the preceding sections since each body region is further subdivided into four adjoining layers: core, muscle, fat and skin, and beyond (brain in the head, lung in the thorax and viscera in the abdomen). Moreover, these assigned values naturally exhibit a spread of a few orders of magnitude differences among them. Thus, when plotted on the same graph the larger values will completely over shadow the smaller ones. We therefore chose to list, in Tables 2 and 3, only ranges of variability and means ± S.D. of basal metabolic and blood perfusion rates in the tissue layers of the various body regions. Detailed data for all compared models, body regions and tissue layers are listed in the Appendix.

As seen, most of the bone layers were assigned zero metabolic and blood perfusion rates, as is to be expected. The exceptions are the bone layers in the shoulders and in the extremities which were assigned non-zero values in a number of models. The next lowest values are assigned to the fat layers, with occasional zero values, depending on the source model. Skin basal values are invariably non-zero in all models but may involve very low values indeed in certain models (e.g., basal blood perfusion in the feet and the hands, Table 3). Muscle layers are invariably assigned high values with the highest basal metabolic and blood perfusion rates found in the thorax, abdomen and legs (Tables 2 and 3). The brain, lung and viscera layers are assigned the highest of all values of both basal quantities. Brain layers show rather narrow ranges of variability in both basal quantities whereas significant differences exist in the values assigned to both the lung and the viscera (Tables 2 and 3).

Table 2: Ranges of variability and means ±S.D. of basal metabolic rates of various body regions tissue layers, Watt

		Bone	**Muscle**	**Fat**	**Skin**	**Other**
Head	Range	0	0-0.304	0-0.128	0.024-0.233	Brain 14.02-17.85
	Mean ±S.D.	0	0.139±0.12	0.055±0.054	0.123±0.062	16.28±1.44
Face (2)*	Range	0	0.093-0.297	7E-04-0.012	0.01-0.058	
	Mean ±S.D.	0	0.195±0.144	0.006±0.008	0.034±0.034	
Neck (3)*	Range	0	0.39-0.474	3E-04-0.002	0.005-0.035	
	Mean ±S.D.	0	0.42±0.047	(8±8)E-04	0.024±0.016	
Shoulder (2)*	Range	0-0.362	0.105-0.846	0.024-1.22	0.033-0.1	
	Mean ±S.D.	0.181±0.256	0.475±0.524	0.622±0.846	0.066±0.047	
Thorax	Range	0	0-8.048	0-2.477	0.099-2.939	Lung 1.96-58.62
	Mean ±S.D.	0	4.732±2.224	0.841±0.879	0.751±0.877	29.9±23.44
Abdomen (4)*	Range	0	4.067-5.842	0.027-0.806	0.127-0.721	Viscera 8.05-43.81
	Mean ±S.D.	0	4.753±0.834	0.5±0.378	0.339±0.261	33.4±15.3
Arms	Range	0-0.044	0.019-0.155	0-0.008	0.003-0.081	
	Mean ±S.D.	0.014±0.016	0.065±0.059	0.002±0.003	0.028±0.025	
Hands	Range	0-1.612	0-0.338	0-0.047	0.033-0.186	
	Mean ±S.D.	0.231±0.52	0.126±0.115	0.02±0.02	0.102±0.053	
Legs	Range	0-5.908	0-5.436	0-0.521	0.173-0.993	
	Mean ±S.D.	1.861±2.116	3.456±1.798	0.244±0.21	0.527±0.327	
Feet	Range	0-0.209	0-0.291	0-0.112	0.044-0.256	
	Mean ±S.D.	0.232±0.379	0.116±0.119	0.041±0.044	0.146±0.083	

* Number of models containing detailed data on this body region

Table 3: Ranges of variability and means ±S.D of basal blood perfusion rates of tissue layers of various body regions, l/min

		Bone	**Muscle**	**Fat**	**Skin**	**Other**
Head	Range	0	0-0.304	0-0.128	0.024-0.233	Brain 14.02-17.85
	Mean ±S.D	0	0.139±0.12	0.055±0.054	0.123±0.062	16.28±1.44
Face (2)*	Range	0	0.093-0.297	7E-04-0.012	0.01-0.058	
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	Mean ±S.D.	0.232±0.379	0.116±0.119	0.041±0.044	0.146±0.083	

* Number of models containing detailed data on this body region

Discussion

It is apparent from the preceding that, although the compared models share much of the basal data, they also differ in many aspects. The differences become more pronounced as the level of detail progresses from the total body basal values to the regional and finally to the specific tissue layers.

Figures 5 and 6 show the data from Figs. 1 and 2 normalized by the body surface areas of each model, as is customary for presenting physiological data. The results (excluding Arkin's (1982) data due to the unavailability of specific anthropometric details) are shown in Fig. 5, for the specific basal metabolic rates, and in Fig. 6, for the specific basal cardiac outputs. The specific basal metabolic rates are seen to incur a lower range of variability: from 44.7 to 46.6 W/m^2, for a 4.2% variance relative to the lowest value, compared to the previous 6.5% of the non-specific data in Figure 1. Another difference regards the standard deviation of the data that is only ±1.2% indicating a tighter spread for the specific values as compared to ±2.3% for the non-specific basal metabolic rates. Yet another difference is seen in the relative ranking positions of the various models. Whereas Werner and Webb's (1993) model exhibited the maximal basal metabolic rate, and Wolf and Garner's (1997) the minimal (Fig. 1), in the specific values Fiala's (1998) model occupies the maximal value position and CBE's (2001) the minimal (Fig. 5).

The opposite trend is seen with regard to the basal cardiac outputs. First, the range of variability of the specific data is increased somewhat from 2.39 to 2.66 (l/min)/m^2 for an 11.1% variance relative to the lowest value in the specific data, compared to the previous 8% for the non-specific (see above). This trend is also reflected in the relative standard deviation which is ±3.5% for the specific values (Fig. 6) compared to the ±2.9% for the non-specific values (Fig.2). However, the relative ranking positions of the various models do not change for the cardiac outputs: Gordon's (1974) data are the maximal and Tanabe et al.'s (2002) are the minimal, for both the specific and non-specific data.

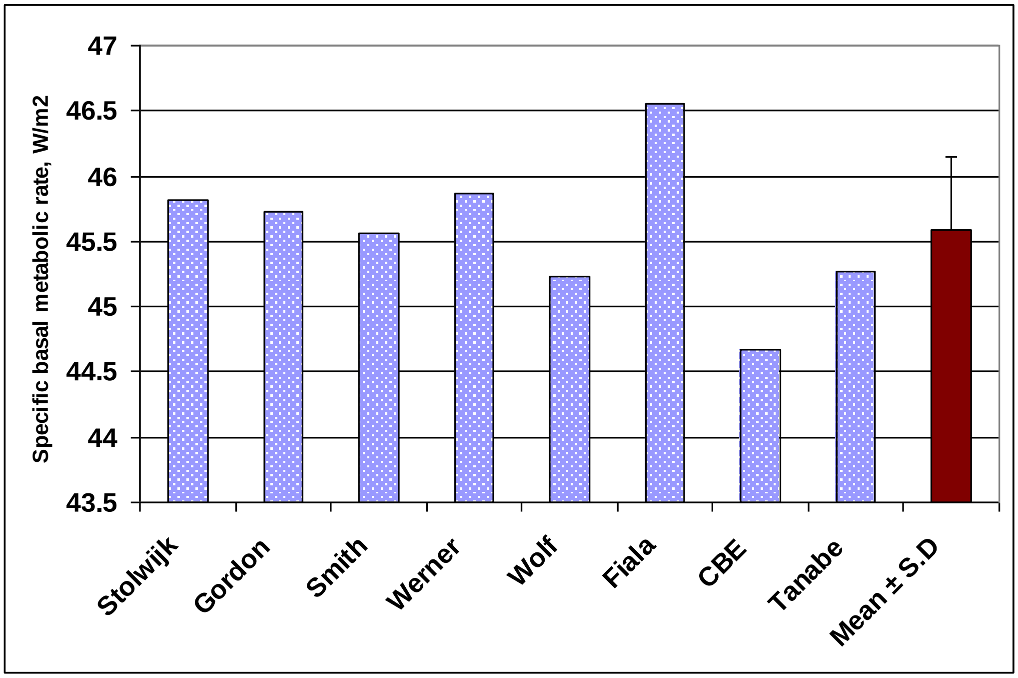

Figure 5: Whole body specific basal metabolic rates, W/m^2 (excluding Arkin (1982))

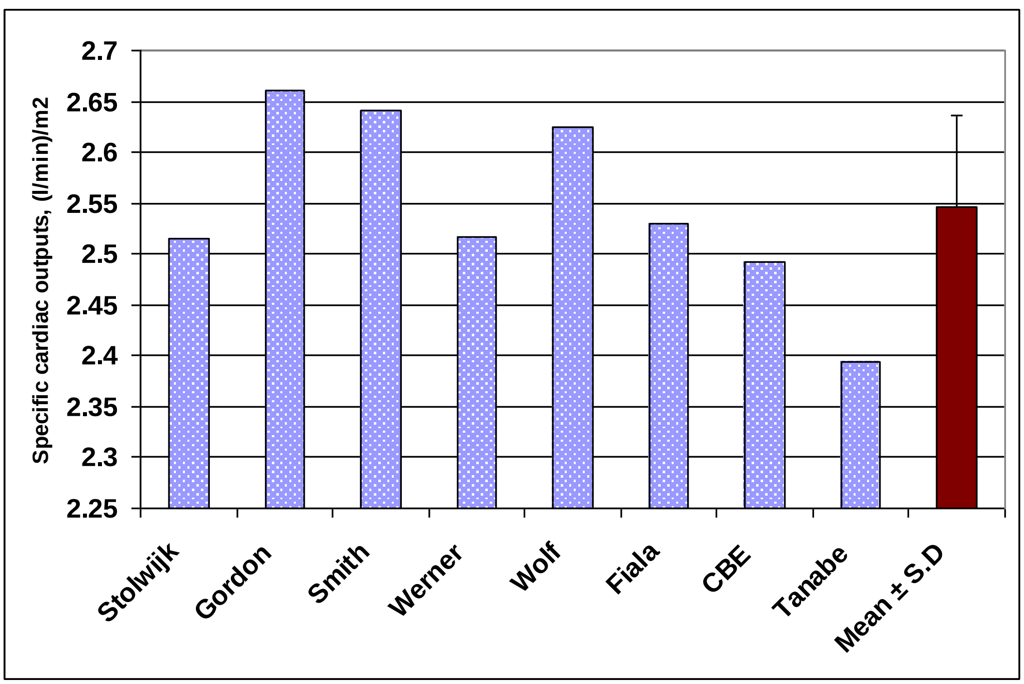

Figure 6: Whole body specific basal cardiac outputs, (l/min)/m^2 (excluding Arkin (1982))

Basal metabolic rates and basal cardiac outputs are normally linked in the body in that the circulating blood basically supplies the oxygen needs of the various tissues and organs. Literature values set the approximate ratio of energy produced per blood flow rate, under normal resting conditions, at about 15.7 W/(l_{blood}/min) (data abridged from Brooks 1966 and Cooney 1976). Figure 7 shows the ratios of total body basal metabolic rates to basal cardiac outputs for all compared models. The ranges of values shown are from 17.2 to 18.9 W/(l/min) with a relative standard deviation of ±3.4%. The minimal listed value is due to Gordon (1974), followed closely by both Smith (1991) and Wolf and Garner (1997), while the maximal is due to Tanabe et al. (2002). All values shown are considerably higher than the literature average quoted above. One possible explanation to this ostensible disparity is due to the difference between *normal resting conditions*, for which literature values are quoted, versus the *basal conditions* assumed in this study. Another possible explanation relates to the differences in physiologic activity among the organs. Accordingly, Cooney (1976) sets this value for the brain at about 21 W/(l_{blood}/min). The value obtained for the averages of brain basal metabolic rate (Table 2) to brain basal blood perfusion (Table 3) in the present study, is about 21.1 W/(l_{blood}/min) which is practically identical to Cooney's (1976) value. Thus, the total body values shown in Fig. 7, which are actually total body average values, should not be construed as fundamentally deviating from the average literature value but rather as the combined results of the metabolic activity of each organ and the specific choices made by the individual developers of each model.

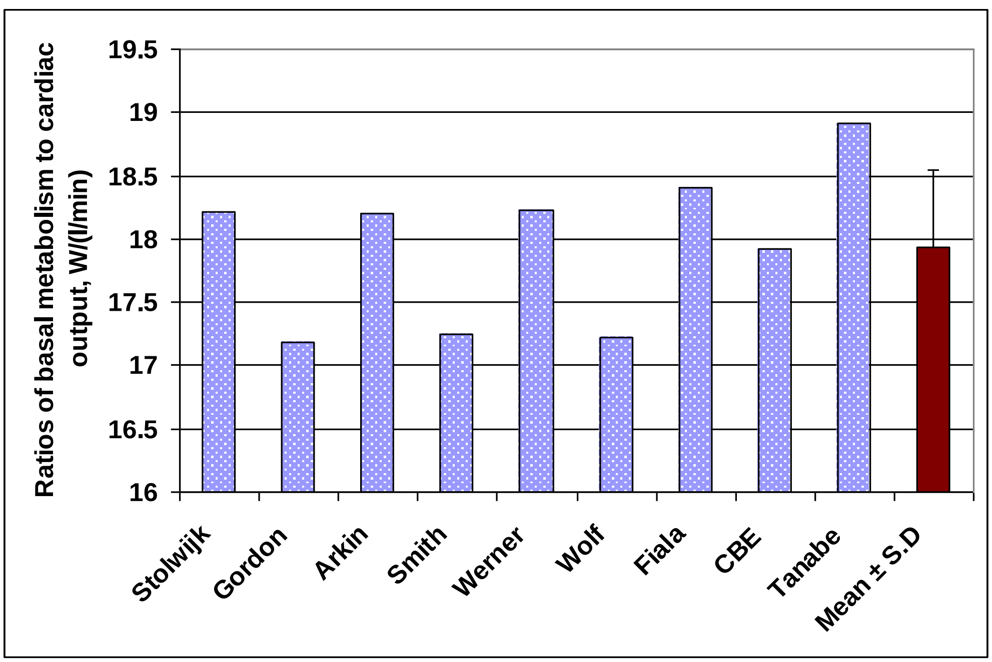

Figure 7: Ratios of total body basal metabolic rates to basal cardiac outputs

Table 4 presents the relative distributions of both of the total basal metabolic and blood perfusion rates assigned to each of the tissue layers in all body regions for all compared models. The listed values, expressed as percentages, were obtained by dividing the actual mean total tissue layers values by the total body averages. It is immediately apparent that the distribution among layers of either quantity is not identical, except, perhaps, in the viscera. The largest difference is seen in the lung wherein about 35% of the metabolic rate is assigned compared to about 45% of the basal cardiac output. A similar trend is seen in the muscle, bone and skin layers. The skin exhibits the reverse trend: more of the relative basal cardiac output, about 6.3%, is assigned compared to only 2.5% of the relative basal metabolic rate. This is, perhaps, a manifestation of the heat dissipation function played by the circulating blood in the skin, over and above of its basic function of supplying oxygen for metabolic processes.

Table 4: Relative mean distributions of all models' basal metabolic and blood perfusion rates assigned in the various tissue layers, %

	Brain	**Lung**	**Viscera**	**Bone**	**Muscle**	**Fat**	**Skin**
Relative basal metabolic rate, %	19.3	35.4	22	3.8	14.9	2.1	2.5
Relative basal blood perfusion rate, %	16.1	45	20.2	1.2	10.4	0.7	6.3

As noted in the Introduction, data from Wissler's keystone model (e.g., 1961 1964) were not included in the comparison. The main reason for this exclusion is because basal data are not listed in any of his multiple publications. Wissler (1985) evaluates metabolic heat production directly by constructing the metabolic balance for the principal reactants and products involved in the metabolic reactions. Equations used in his model are based on a greatly simplified metabolic scheme which, nevertheless, retains its essential features. Energy is assumed to be obtained from the oxidation of digested foods, represented by carbohydrate for further simplicity. The chemical reactions involved in the forming of ATP, which is the energy source in mechanical work, are incorporated in the model through material balances for each chemical species, e.g., O_2, CO_2, glucose, lactate, etc., in the tissue and in the blood.

Under resting conditions in a neutral environment, Wissler (1985) assigns local values of metabolic and perfusion rates which are consistent with available experimental data and provide reasonable values for total metabolic rate and cardiac output. Local perfusion rates in the model are defined in terms of the minimum rate necessary to supply the metabolic demand for oxygen. Wissler (2010) cordially provided the *resting* metabolic and blood perfusion rates for an individual whose anthropometric data are listed in Table 1. His model computed resting values are listed, along with the average *basal* values of the compared models, in Table 5.

Table 5: Average *basal* values of all models compared to Wissler's (2010) *resting* values

Body region	All models' average *basal* metabolic rates, Watt	Wissler's *resting* metabolic rates, Watt	All models' average *basal* blood perfusion rates, l/min	Wissler's resting *blood* perfusion rates, l/min
Head	16.80	15.3	0.835	0.713
Torso	57.56	60.51	3.452	4.13
Arms & hands	3.34	1.77	0.150	0.08
Legs & feet	6.62	12.7	0.263	0.55
Totals	84.32	90.28	4.700	5.473

In spite of the fundamental differences between "basal" and "resting" conditions, certain observations may still be made: (a) Wissler's (1985) computed resting metabolic rate is only about 7% higher than the compared models' average value whereas his cardiac output is appreciably higher (16.5%). (b) As a consequence, Wissler's ratio of total metabolic rate to cardiac output is 16.5 W/(l_{blood}/min), a value that is closer to the normal literature *resting* conditions: 15.7 W/(l_{blood}/min) (data abridged from Brooks 1966 and Cooney 1976), and, (c) In the combined legs & feet Wissler's metabolic and blood perfusion values are significantly higher, while in the combined arms & hands they are significantly lower than the compared models' data. This clearly implies a difference in distribution between these body regions under resting conditions in Wissler's model.

A crucial element in the modeling of the thermoregulatory system is the formulation of the "active" system that manifests the actions of the control functions that are implemented in the model. Under active conditions the assumed control functions respond to conditions other than the "basal" and modify accordingly the metabolic and blood perfusion rates in the various body tissues and organs, among other things. The basal values of both quantities remain unchanged and form the bases for the modified values. Certain models allow the assignment of individual basal data that are adjusted according to the specific anthropometric data of the modeled individual, usually based on organ mass distribution. Discussion of the various control strategies applied in different models is another important and rather involved aspect in comparing the performance of these models. This task is, however, beyond the scope of this study which is designed to consider only basal values and their assignment in body tissues and organs.

Conclusion

This article compares the assignment of basal metabolic rates and basal cardiac outputs (blood perfusion) in nine multi-compartment, whole body thermoregulation models. The analysis is presented at three levels of anatomical details: total body, different body regions and body tissue layers. Differences in the assignments of these quantities among the compared models are noted and can be seen to increase with the level of detail, following the above order. Conceivably these differences reflect the data available to each modeler and may, in certain cases, reflect adjustments made to specific experimental data and a variety of listed and unlisted factors.

This non-uniformity of assignments of these data among the compared models raises the important question for future modeling: which basal data should be used in the formulation of a new model? Our basic recommendation would be to use the *average* basal values of the "time-seasoned" models presented in this study, as a *first step* in the modeling process. These values should next be updated against the recent changes in human height and weight (e.g., www 2014) and critically evaluated and contrasted against the most updated recent and reliable data presented in the literature. Fine-tuning of these implemented data, to adjust the predictions of the newly developed models to experimental results, should be performed as the final stage of the modeling process of the "passive" thermoregulatory system.

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Appendix A: Basal metabolic rates of all models, Watt

Head	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Brain	14.9329	17.7765	15.504	17.7366	15.0027	14.02	17.8503	16.8868	16.843
Bone	0	0	0	0	0	0	0	0	0
Muscle	0.1163	0	0.27	0.30353	0	0.1275	0	0.21748	0.217
Fat	0.12793	0.00048	0.0597	0.00113	0	0.0813	0.0056	0.10932	0.109
Skin	0.09304	0.13607	0.0732	0.18834	0.2326	0.093	0.02429	0.13142	0.131

Face	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Muscle		0.09304					0.08859		
Bone		0					0		
Muscle		0					0.208		
Fat		0.0007					0.01205		
Skin		0.05815					0.01015		

Neck	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone		0		0			0		
Muscle		0.39542		0.39031			0.47406		
Fat		0.00029		0.00028			0.00169		
Skin		0.03489		0.03116			0.00598		

Shoulders	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone							0		0.362
Muscle							0.10452		0.846
Fat							0.0242		1.22
Skin							0.03292		0.1

Thorax	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Lung	52.7769	1.9771	42.335	1.96046	58.6151	49.83	3.44642	18.3056	39.881

Bone	0	0	0	0	0	0	0	0	0
Muscle	5.815	3.05869	4.5931	8.04804	0	6.124	4.79256	5.08696	5.074
Fat	2.47719	0.01	1.3094	0.03605	0	1.547	0.04743	1.07229	1.069
Skin	0.4652	0.51172	0.3662	1.23665	2.93858	0.4682	0.09911	0.33727	0.337

Abdomen	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Viscera		42.6472		42.7202			43.8126	29.7495	8.05
Bone		0					0	0	0
Muscle		5.02416					5.84221	4.07748	4.067
Fat		0.02675					0.36151	0.80596	0.804
Skin		0.72106					0.12743	0.2547	0.254

Arms	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.8141	0	2.8558	0	2.32106	0.6609	0	0.55126	0.188
Muscle	1.10485	3.32618	1.7664	3.30769	0	1.155	2.57987	1.29093	0.44
Fat	0.19771	0.003	0.1308	0.00299	0	0.2118	0.10017	1.28628	0.062
Skin	0.15119	0.55824	0.1538	0.56642	0.3489	0.168	0.10147	0.15119	0.052

Hands	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.09304	0	1.6124	0	0.1163	0.0766	0	0.09071	0.09
Muscle	0.2326	0.18608	0.0784	0.18901	0	0.0258	0.33807	0.04419	0.044
Fat	0.03489	0.0012	0.006	0.00119	0	0.0326	0.01281	0.04652	0.046
Skin	0.05815	0.18608	0.1016	0.18593	0.09304	0.0646	0.03304	0.10002	0.1

Legs	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	2.59349	0	4.4308	0	5.90788	2.038	0	0.89318	0.89
Muscle	3.32618	4.93112	4.854	4.91418	0	3.46	5.436	2.0934	2.088
Fat	0.50009	0.01326	0.2698	0.01314	0	0.521	0.13598	0.37216	0.372
Skin	0.37216	0.98855	0.347	0.99314	0.87184	0.4164	0.17291	0.29075	0.29

Feet	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe

Bone	0.15119	0	1.2094	0	0.1163	0.127	0	0.24423	0.244
Muscle	0.02326	0.29075	0.0394	0.28868	0	0.0258	0.23207	0.06978	0.07
Fat	0.04652	0.00283	0.0084	0.00277	0	0.0489	0.03829	0.11165	0.112
Skin	0.08141	0.25586	0.0666	0.25427	0.12793	0.0827	0.04422	0.20004	0.2

Appendix B: Basal blood perfusion rates of all compared models, l/min

Head	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Brain	0.75	0.80933	0.64623	0.80915	0.75002	0.75	0.8091	0.75	0.75
Bone	0	0	0	0	0	0	0	0	0
Muscle	0.002	0	0.00658	0.01402	0	0.00219	0	0.01276	0.0145
Fat	0.00217	3E-05	0	7.3E-05	0	0.0014	2.1E-05	0.00567	0.00567
Skin	0.024	0.05757	0.0273	0.09542	0.03333	0.02372	0.0217	0.14658	0.03733

Face	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Muscle		0.00417					0.00418		
Bone		0					0		
Muscle		0.01					0.00982		
Fat		4.5E-05					4.5E-05		
Skin		0.03867					0.01849		

Neck	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone		0		0			0		
Muscle		0.01817		0.01802			0.02237		
Fat		1.9E-05		1.8E-05			6.3E-06		
Skin		0.00558		0.00542			0.00663		

Shoulders	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone							0		0.01067
Muscle							0.00493		0.04267
Fat							9E-05		0.00533
Skin							0.00542		0.02867

Thorax	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Lung	3.5	0.07933	2.88596	0.0788	3.60013	3.5	0	2.56983	2.873

Bone	0	0	0	0	0	0	0	0	0
Muscle	0.1	0.14267	0.14158	0.37145	0	0.10532	0.22618	0.20957	0.46
Fat	0.04267	0.00065	0	0.00235	0	0.0266	0.00018	0.04199	0.08067
Skin	0.035	0.03283	0.08947	0.09523	0.07999	0.03488	0.02553	0.04102	0.08717

Abdomen	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Viscera		2.75		2.7549			2.7634	0.30317	
Bone		0		0			0	0	
Muscle		0.2345					0.27571	0.26414	
Fat		0.00172					0.00135	0.036	
Skin		0.06207					0.02992	0.02694	

Arms	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.014	0	0.04393	0	0.04665	0.01137	0	0.016	0.00533
Muscle	0.019	0.155	0.0401	0.15263	0	0.01987	0.12175	0.03083	0.02233
Fat	0.00333	0.0002	0	0.00019	0	0.00364	0.00037	0.00817	0.00283
Skin	0.00833	0.0468	0.0807	0.04727	0.02328	0.00834	0.0182	0.02122	0.015

Hands	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.00167	0	0.011	0	0.00333	0.00132	0	0.00063	0.00303
Muscle	0.004	0.00883	0.00089	0.00873	0	0.00044	0.01595	0.00241	0.0026
Fat	0.00067	7.8E-05	0	7.7E-05	0	0.00056	4.8E-05	0.0014	0.0014
Skin	0.03333	0.03693	0.03779	0.03713	0.02833	0.03242	0.02445	0.03614	0.03033

Legs	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.04483	0	0.09549	0	0.10004	0.03505	0	0.0145	0.0145
Muscle	0.05717	0.2305	0.11205	0.2268	0	0.0595	0.25654	0.08567	0.03083
Fat	0.00867	0.00086	0	0.00085	0	0.00896	0.00051	0.00562	0.00563
Skin	0.0475	0.07005	0.15798	0.07023	0.0531	0.04733	0.0296	0.07234	0.01633

Feet	Stolwijk	Gordon	Arkin	Smith	Werner	Wolf	Fiala	CBE	Tanabe
Bone	0.00267	0	0.03738	0	0.00167	0.00218	0	0.00163	0.00163
Muscle	0.00033	0.0135	0.00089	0.01333	0	0.00044	0.01095	0.00241	0.00033
Fat	0.00083	0.00018	0	0.00018	0	0.00084	0.00014	0.00063	0.00063
Skin	0.05	0.03133	0.06361	0.03113	0.03665	0.04935	0.01081	0.02755	0.015