

RESEARCH ARTICLE

# Novel Anthropometry-Based Calculation of the Body Heat Capacity in the Korean Population

Duong Duc Pham, Jeong Hoon Lee, Young Boum Lee, Eun Seok Park, Ka Yul Kim, Ji Yeon Song, Ji Eun Kim, Chae Hun Leem\*

Department of Physiology, University of Ulsan College of Medicine, 88 OlympicRo 43-gil Songpa-gu, Seoul, Republic of Korea

\* [leemch@amc.seoul.kr](mailto:leemch@amc.seoul.kr)



**OPEN ACCESS**

**Citation:** Pham DD, Lee JH, Lee YB, Park ES, Kim KY, Song JY, et al. (2015) Novel Anthropometry-Based Calculation of the Body Heat Capacity in the Korean Population. PLoS ONE 10(11): e0141498. doi:10.1371/journal.pone.0141498

**Editor:** David B. Allison, University of Alabama at Birmingham, UNITED STATES

**Received:** July 22, 2015

**Accepted:** October 8, 2015

**Published:** November 3, 2015

**Copyright:** © 2015 Pham et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**Data Availability Statement:** All relevant data are within the paper and its Supporting Information files.

**Funding:** This work was supported by the Bio & Medical Technology Development Program of the National Research Foundation (NRF) funded by the Ministry of Science, ICT & Future Planning (Fund receiver Chae Hun Leem, No. 2012-0009829, No. 2015M3A9B6028310 and No. 2014M3A9D7034366).

**Competing Interests:** The authors have declared that no competing interests exist.

## Abstract

Heat capacity (HC) has an important role in the temperature regulation process, particularly in dealing with the heat load. The actual measurement of the body HC is complicated and is generally estimated by body-composition-specific data. This study compared the previously known HC estimating equations and sought how to define HC using simple anthropometric indices such as weight and body surface area (BSA) in the Korean population. Six hundred participants were randomly selected from a pool of 902 healthy volunteers aged 20 to 70 years for the training set. The remaining 302 participants were used for the test set. Body composition analysis using multi-frequency bioelectrical impedance analysis was used to access body components including body fat, water, protein, and mineral mass. Four different HCs were calculated and compared using a weight-based HC (HC\_Eq1), two HCs estimated from fat and fat-free mass (HC\_Eq2 and HC\_Eq3), and an HC calculated from fat, protein, water, and mineral mass (HC\_Eq4). HC\_Eq1 generally produced a larger HC than the other HC equations and had a poorer correlation with the other HC equations. HC equations using body composition data were well-correlated to each other. If HC estimated with HC\_Eq4 was regarded as a standard, interestingly, the BSA and weight independently contributed to the variation of HC. The model composed of weight, BSA, and gender was able to predict more than a 99% variation of HC\_Eq4. Validation analysis on the test set showed a very high satisfactory level of the predictive model. In conclusion, our results suggest that gender, BSA, and weight are the independent factors for calculating HC. For the first time, a predictive equation based on anthropometry data was developed and this equation could be useful for estimating HC in the general Korean population without body-composition measurement.

## Introduction

Energy transfer, temperature regulation, and human response to cold and heat exposure have been intensively investigated. It had been questioned why the human body needs new food daily as a source of energy input and how the energy is manipulated. Energy input would be transformed into two components, i.e. the storage and the loss. The energy that is released from the body includes the heat loss ( $H_{\text{loss}}$ ) and the work performed by the body [1]. The body consumes energy for maintaining its homeostasis. In the resting state, more than 75% of the energy expenditure is transformed into heat and is the so-called heat production ( $H_{\text{prod}}$ ). Heat released by the metabolic process warms up the body tissue and increases the core and the skin temperature. At rest, almost all  $H_{\text{prod}}$  is released via dry  $H_{\text{loss}}$  in which radiative heat loss, convective and conductive heat loss, respiratory heat loss, and evaporative heat loss account for 54–60%, 25%, 14%, and 7% of total  $H_{\text{prod}}$ , respectively [2]. During exercise, when the body temperature (BT) increases up to a particular threshold, it alerts the preoptic/anterior hypothalamus to initiate heat dissipation by stimulating cutaneous vasodilation and sweating. At a given  $H_{\text{prod}}$ , individual responses of the skin blood flow and the evaporation differ at BT threshold [3]. In particular, the heat stress circumstance occurs when  $H_{\text{prod}}$  is not completely released, and the heat-storage content (heat load,  $H_{\text{load}}$ ):

$$H_{\text{load}} = H_{\text{prod}} - H_{\text{loss}} \quad (\text{Eq1})$$

produces an increase in body core temperature. In terms of BT, heat capacity (HC) is an important factor that determines the magnitude of temperature change in the body at a given  $H_{\text{load}}$ . The investigation of HC dates back to the eighteenth century with experiments on the HC of animals performed by Crawford (cited by Kakitsuba) [4]. The most commonly used value of the average specific HC ( $S_{\text{p}}\text{HC}$ ), the HC per mass, of the human body was proposed as  $0.83 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  by Senter in the nineteenth century (cited by Kakitsuba) [4]. The value of  $0.83 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  has been widely used until the present despite the criticisms that the value overestimates the actual HC in estimating the heat-storage content [2, 5]. It has been revealed that  $S_{\text{p}}\text{HC}$  of body components are not identical and the HC equation using  $S_{\text{p}}\text{HC}$  for particular body components was more precise [4–9]. Based on  $S_{\text{p}}\text{HC}$  ( $1.88 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  for fat and  $3.72 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  for fat-free mass), as cited by Minard [6], Webb developed an equation and reported a  $S_{\text{p}}\text{HC}$  as  $0.837$  and  $0.669 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  for those who have a fat proportion of 12 and 50% of fat, respectively [7]. Using the same approach, Blaxter provided slightly different values for the same calculation as  $0.765$  and  $0.652 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  [8]. Using a two-compartment model (fat and fat-free mass), Havenith created an equation for HC in which the  $S_{\text{p}}\text{HC}$  for fat tissue was  $2.51 \text{ kJ}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  ( $0.60 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$ ) and the  $S_{\text{p}}\text{HC}$  for fat-free mass was  $3.65 \text{ kJ}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$  ( $0.872 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$ ) [10, 11], whereas a four-element model proposed  $S_{\text{p}}\text{HC}$  for water, fat, protein, and mineral tissues as 1, 0.507, 0.299, and  $0.201 \text{ kcal}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$ , respectively [2]. Although the HC equation based on body-composition-specific HC can predict the heat storage more precisely than an average  $S_{\text{p}}\text{HC}$  for the whole body, body composition analysis is not available for general population.  $H_{\text{load}}$  and  $H_{\text{loss}}$  should be equal so as to maintain the constant BT.  $H_{\text{loss}}$  depends on the body surface area (BSA) and the temperature gradient from the body to the environment [12, 13].  $H_{\text{load}}$  increases the BT depending on the HC of the body. Therefore, BSA and HC may be correlated to each other. Our study attempted to compare the previously known HC estimating equations in order to investigate the relationship between HC and the anthropometric variables, including weight and BSA, to derive a predictive equation for HC with anthropometry data for the first time.

## Materials and Methods

### Study Participants

The study participants were apparently healthy volunteers aged from 20 to 70 years and who attended the project intending to develop the Korean Constitution Multicenter Bank, that was described elsewhere [14, 15]. Six hundred participants were randomly selected by random sampling using the replacement method from the pool of 902 participants that has been collected at Asan Medical Center from 2010 to 2015 for the training set. The remaining 302 participants were used as the test set for validation analysis. The study and the written consent procedure were approved by the Institutional Review Board of the Asan Medical Center and all participants provided the written consents for this study.

### Measurements

Standing height and weight were assessed using a digital scale. BSA was calculated using the DuBois and DuBois EF formula [16]. Body components including body-fat mass, protein mass, mineral mass, and total body water were measured by multi-frequency bioelectrical impedance analysis (BIA) using the InBody 720 body composition analyzer (Inbody, Seoul, Korea).

HC was estimated using four equations including HC\_Eq1 which was based on the widely used average  $S_pHC$  ( $0.83 \text{ kcal} \cdot \text{kg}^{-1} \cdot \text{C}^{-1}$ ) and body weight (BW) [2], HC\_Eq2 which was based on Webb's equation [7], HC\_Eq3 which was based on Havenith's equation [10, 11], and HC\_Eq4 which was based on a four-component model [2].

$$HC (\text{kcal} \cdot \text{C}^{-1}) = 0.83 \times \text{Weight} \quad (\text{HC}_{Eq1})$$

$$HC (\text{kcal} \cdot \text{C}^{-1}) = [(\text{Fat mass}) \times 0.449 + (\text{Lean mass}) \times 0.889] \quad (\text{HC}_{Eq2})$$

$$HC (\text{kcal} \cdot \text{C}^{-1}) = [(\text{Fat mass}) \times 0.600 + (\text{Lean mass}) \times 0.872] \quad (\text{HC}_{Eq3})$$

$$HC (\text{kcal} \cdot \text{C}^{-1}) = \left[ \begin{array}{l} (\text{Fat mass}) \times 0.507 + (\text{Protein}) \times 0.299 + \\ (\text{Water}) \times 1 + (\text{Mineral}) \times 0.201 \end{array} \right] \quad (\text{HC}_{Eq4})$$

### Statistical analysis

Pearson correlation coefficient and difference were calculated to determine the agreement between HCs estimated from the four equations. HC\_Eq4 which was based on a four-component model was selected to perform regression analysis with weight, BSA, and other confounding factors. A predictive model for HC-based anthropometry data was developed. The validation analysis for the predictive model and the HC estimated by the selected equation was performed using Bland-Altman analysis. Data were analyzed using the R program version 3.2.1. Statistical significant level was set as a p value <0.05.

## Results

The training set included 282 men and 318 women, whereas the test set was composed of 138 men and 164 women. There was no difference in the demographic data, body composition characteristics or HC among the training and test sets (Table 1). Fig 1 shows the correlations between each HC equation. In general, the HC equations were well-correlated to each other.

**Table 1. Demographic, body composition, and heat capacity by gender in the training and test sets.**

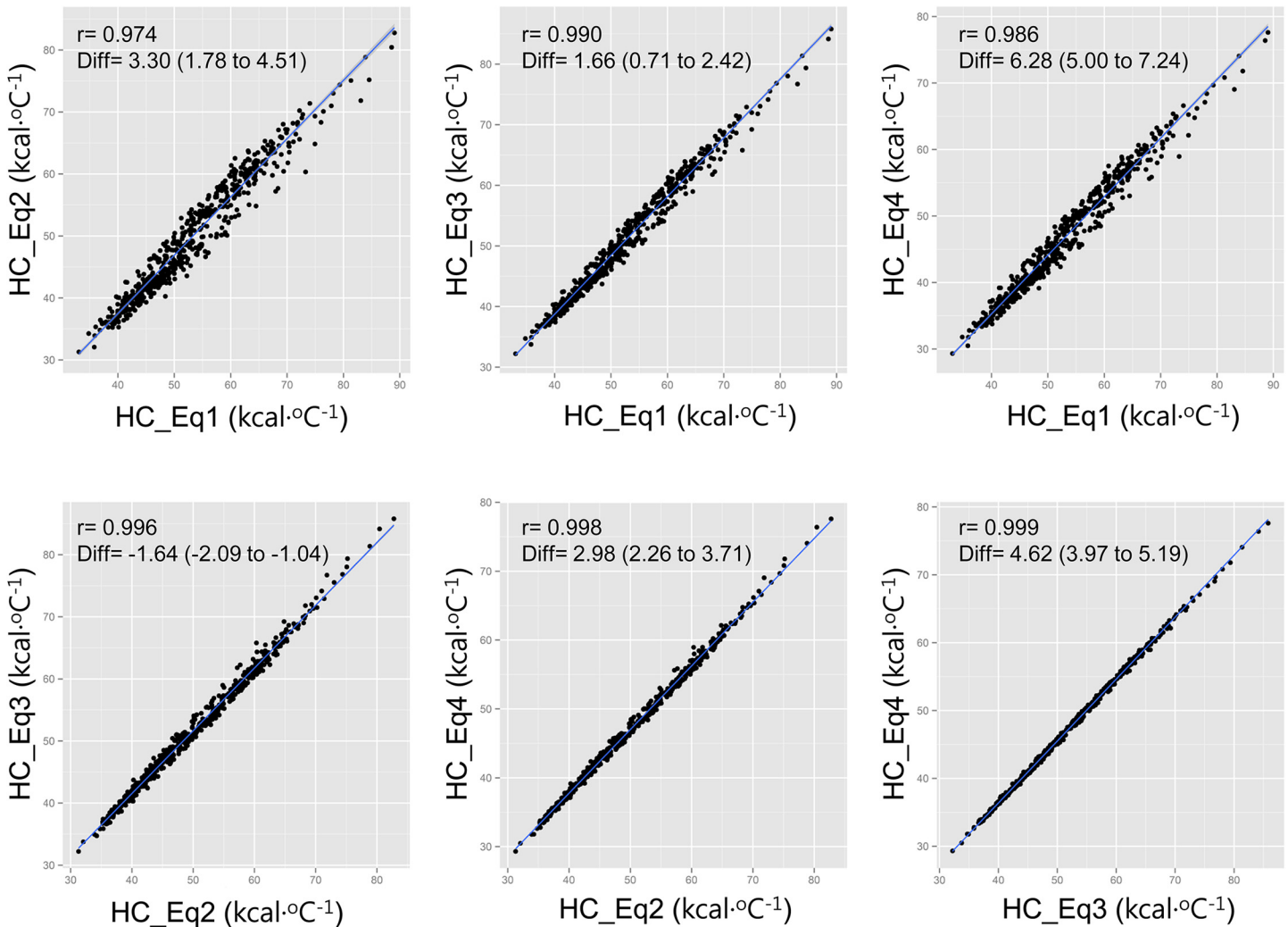
	Training set (n = 600)		Test set (n = 302)	
	Men (n = 282)	Women (n = 318)	Men (n = 138)	Women (n = 164)
Age (yrs)	34.6 (10.9)	38.6 (11.5)	34.1 (10.6)	39.4 (12.2)
Weight (kg)	72.2 (10.1)	56.8 (7.6)	71.9 (10.0)	57.0 (7.4)
Height (cm)	173.0 (5.7)	159.7 (5.3)	173.2 (5.6)	159.8 (5.6)
BMI (kg·m <sup>-2</sup> )	24.1 (2.9)	22.3 (3.0)	23.9 (3.0)	22.3 (2.9)
BSA (m <sup>2</sup> )	1.9 (0.1)	1.6 (0.1)	1.9 (0.1)	1.6 (0.1)
Total body water (kg)	41.8 (4.6)	29.2 (2.9)	41.7 (4.3)	29.1(3.0)
Body fat mass (kg)	15.3 (5.9)	17.0 (5.3)	15.1 (6.3)	17.3 (5.4)
Protein mass (kg)	11.3 (1.3)	7.8 (0.8)	11.3 (1.2)	7.8 (0.8)
Mineral mass (kg)	3.8 (0.5)	2.8 (0.3)	3.8 (0.4)	2.8 (0.3)
HC_Eq1 (kcal·°C <sup>-1</sup> )	59.8 (8.4)	47.1 (6.3)	59.6 (8.3)	47.3 (6.1)
HC_Eq2 (kcal·°C <sup>-1</sup> )	57.4 (7.1)	43.0 (4.9)	57.2 (6.8)	43.1 (4.8)
HC_Eq3 (kcal·°C <sup>-1</sup> )	58.8 (7.6)	44.9 (5.4)	58.6 (7.3)	45.0 (5.3)
HC_Eq4 (kcal·°C <sup>-1</sup> )	53.7 (6.8)	40.7 (4.8)	53.5 (6.5)	40.8 (4.7)

Data are presented as mean (SD). BMI, body mass index; BSA, body surface area; HC\_Eq1, heat capacity calculated based on the widely used average specific heat capacity (0.83 kcal·kg<sup>-1</sup>·°C<sup>-1</sup>) and BW; HC\_Eq2, heat capacity calculated based on Minard's equation; HC\_Eq3, heat capacity calculated based on Havenith's equation; and HC\_Eq4, heat capacity calculated based on a four-component model.

doi:10.1371/journal.pone.0141498.t001

Equations based on two components (HC\_Eq2 and HC\_Eq3) and four components (HC\_Eq4) were strongly correlated ( $r = 0.996$  to  $0.999$ , mean difference =  $1.64$  to  $4.62$  kcal·°C<sup>-1</sup>), whereas equations using the average  $S_p$ HC for the whole body overestimated HC compared to the other equations ( $r = 0.974$  to  $0.990$ , mean difference =  $1.66$  to  $6.28$  kcal·°C<sup>-1</sup>). The difference among HCs estimated by equations based on body composition data was lowest between HC\_Eq4 and HC\_Eq2. Because HC\_Eq4 originated from more precise body composition analysis, further analysis regarding the relationship between HC and the anthropometric indices was performed using HC\_Eq4.

The relationship between BW versus HC\_Eq4 and BSA versus HC\_Eq4 could be described by a linear regression model (HC\_Eq4 versus BW,  $r = 0.986$ ,  $0.988$ , and  $0.986$  for the total, men, and women, respectively; HC\_Eq4 versus BSA,  $r = 0.985$ ,  $0.974$ , and  $0.955$  for the total, men, and women, respectively). In Fig 2, the correlation coefficients between HC\_Eq4 and weight were high, however, there was a clear gender difference. The gender difference was attenuated between HC\_Eq4 and BSA. This pattern was also found in the same analysis for HC\_Eq2 and HC\_Eq3 (S1 Fig). Table 2 shows the results of the multivariate regression analysis. In the case of model 1 adjusted according to age, gender, and BW, all of the factors were significantly associated. In the case of model 2 adjusted according to age, gender, and BSA, all of the factors were also significantly associated for predicting HC, however, the gender differences were clearly attenuated and the coefficient for female was decreased from  $-2.96$  to  $-0.36$ . In the case of model 3 adjusted with age, gender, BW, and BSA, age was not associated with HC whereas gender, BW, and BSA, were significantly associated. Interestingly, although BSA and BW was strongly correlated ( $r = 0.97$ ), they contributed independently in predicting HC. After adjusting for BW and BSA, women on the average had lower HC than men by  $1.96$  kcal·°C<sup>-1</sup> (95%CI,  $1.76$  to  $2.16$  kcal·°C<sup>-1</sup>). Three factors, including gender, BW, and BSA, explained more than 99% of the variation of HC estimated by HC\_Eq4 among individuals (Table 2). The predictive model for HC with anthropometry data of the 600 study patients was  $HC$  (kcal·°C<sup>-1</sup>) =  $14.29 \times BSA$  (m<sup>2</sup>) +  $0.46 \times BW$  (kg) -  $1.96$  (if women) -  $6.06$ .



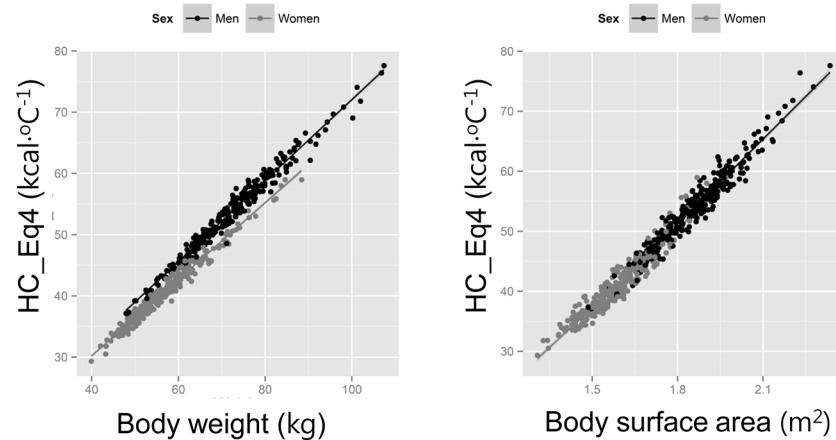
**Fig 1. Correlation between the heat capacity (HC) values estimated by four equations.** HC\_Eq1, heat capacity calculated based on the widely used average specific heat capacity ( $0.83 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$ ) and body weight; HC\_Eq2, heat capacity calculated based on Minard's equation; HC\_Eq3, heat capacity calculated based on Havenith's equation; and HC\_Eq4, heat capacity calculated based on four components model. r, correlation coefficient; Diff, mean and 95% confident interval of difference between the two HC values ( $x-y$ ).

doi:10.1371/journal.pone.0141498.g001

As for the analysis of concordance on the test set, the predictive model for HC with anthropometry data showed extremely highly satisfactory values ( $r = 0.996$ ;  $\text{ICC} = 0.996$ ). The predictive model also had a low standard error of measurement ( $\text{SEM} = 0.77 \text{ kcal}\cdot\text{°C}^{-1}$ ) with the limits of agreement varying approximately  $\pm 1.5 \text{ kcal}\cdot\text{°C}^{-1}$  (Fig 3). The final predictive model for HC with anthropometry data from all of the study patients was  $\text{HC} (\text{kcal}\cdot\text{°C}^{-1}) = 14.482 \times \text{BSA} (\text{m}^2) + 0.456 \times \text{BW} (\text{kg}) - 1.996 (\text{if women}) - 6.064$  ( $r = 0.996$ , S1 Table.)

## Discussion

Although HC plays an important role in the process of heat balancing, very few studies pay attention on investigating an accurate and simple tool for calculating HC. In previous studies, HC has been popularly calculated by multiplying BW to the average  $S_p\text{HC}$ ,  $0.83 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$ . However, it has been revealed that the equation using the average  $S_p\text{HC}$  overestimated the actual human body HC [4–9]. In concordance with that, in the present study the HC equation



**Fig 2. Relationship between heat capacity (HC) estimated using the equation based on the four-component model (HC\_Eq4) and weight (a) and body surface area (b) for men (black dots) and for women (grey dots).**

doi:10.1371/journal.pone.0141498.g002

using the average  $S_pHC$  provided a higher value compared with those using body composition data, particularly with that using the four components model. We also found that gender interacted more strongly in the relationship between HC and weight, but unsteadily in the relationship between HC and BSA. In addition, BSA contributed to HC as an independent factor in addition to weight. The model that includes both BW and BSA appears to be better than that containing each variable alone. The model composed of weight, BSA, and gender appeared to be extremely well fitted for predicting HC without any information regarding body composition. With the 99% variation of HC which could be explained by the model with gender, weight, and BSA, we are able to correctly estimate HC without using complicated body

**Table 2. Multivariate regression analysis for predicting HC\_Eq4.**

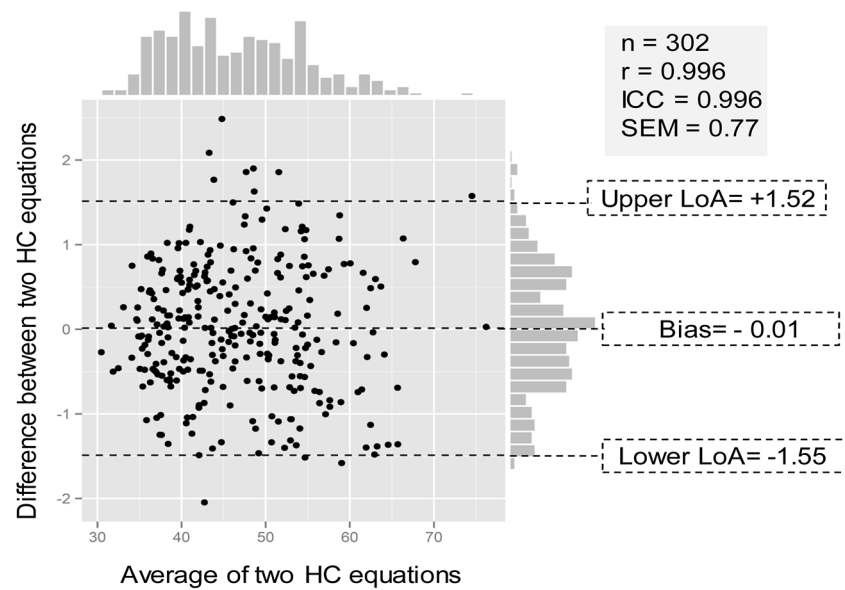
	Regression coefficient (95% CI)	Coefficient of determination ( $R^2$ )
Model 1: Predictors are age, gender, and body weight		
Intercept	7.544 (6.878–8.209) ***	0.988
Age (yrs)	-0.014 (-0.021 to -0.008) ***	
Gender (Female)	-2.962 (-3.159 to -2.765) ***	
Body weight (kg)	0.646 (0.638–0.654) ***	
Model 2: Predictors are age, gender, and body surface area		
Intercept	-33.475 (-35.361 to -31.589) ***	0.972
Age (yrs)	0.031 (0.020 to 0.041) ***	
Gender (Female)	-0.359 (-0.711 to -0.008) *	
BSA (m2)	46.445 (45.478 to 47.413) ***	
Model 3: Predictors are age, gender, body weight, and body surface area		
Intercept	-6.048 (-7.718 to -4.379) ***	0.993
Age (yrs)	0.000 (-0.006 to 0.006)	
Gender (Female)	-1.961 (-2.160 to -1.762) ***	
Body weight (kg)	0.460 (0.438 to 0.483) ***	
BSA (m2)	14.299 (12.640 to 15.958) ***	

\* $p < 0.05$ ,

\*\*\* $p < 0.001$

doi:10.1371/journal.pone.0141498.t002





**Fig 3. Bland Altman plot with marginal histograms for the agreement between the predictive model and HC\_Eq4 in the test set.** Bias, mean of differences between the two HC equations, the predictive model and HC\_Eq4; Upper LoA, upper level of limits of agreement = mean of differences + 1.96 standard deviation; Lower LoA, lower level of limits of agreement = mean of differences - 1.96 standard deviation; r, Pearson correlation coefficients; ICC, Intraclass correlation coefficient; SEM, standard error of measurement.

doi:10.1371/journal.pone.0141498.g003

component measurement. The validation analysis showed that the predictive model was reliable and sufficient to be applied for estimating HC. Anthropometry-based calculation of HC is a very useful feature in many other fields, including sports science, architectural engineering, environment physiology, etc.

Our study is the first to date to attempt to investigate the relationship between BSA and HC. Heat load increases the BT depending on HC. Heat loss depends on the temperature gradient between the BT and the ambient temperature and BSA. Both heat load and heat loss should be the same for the maintenance of BT. Therefore, if the ratio of the change of BT and the temperature gradient is relatively constant, the HC and BSA should be linearly correlated with each other. Our results very strongly demonstrate this possibility. The relationship between weight and HC was highly correlated in our results, however, there were clear gender differences. Interestingly, the gender differences were greatly attenuated in the relationship between BSA and HC. These results suggest the possibility that the human body during its development adaptively matches HC and BSA to each other in order to regulate the BT.

The relationship of BW, BSA, and HC may shed some light on the heat flow in the body. During prolonged physical exercise, BW may be remarkably reduced due to dehydration while the BSA remains constant [17]. That consequently induces the reduction of HC, increases the temperature load, and enhances the heat-related damage. All of our study participants were healthy and without any known disease. The linear relationships between HC and BSA were observed in a healthy population in which all of the participants were considered as normal in their thermoregulation response and in their capacity to balance the heat flow. We assume that the balance between HC and BSA may be skewed in unhealthy status patients and which might be related to a thermoregulation disorder. This could be a potential study hypothesis in future studies.

Our findings should be interpreted in the context of their strength and limitations. The present study enrolled a relatively high number of participants with a wide age range. However,

because validation analysis was performed on the estimated HC values, the predictive model should be confirmed with measured values. Furthermore, because there were fewer patients aged in their 60s and no patient was 70 or older, the findings should be cautiously applied in the elderly population. It has been widely accepted that multi-frequency BIA is valid tool to estimate body composition, particularly in predicting lean mass, fat mass, and total body water [18–22]. Evidence also revealed that multi-frequency BIA is a useful approach for body somatic protein store [23] and body bone mineral content estimation [24]. In addition, because proportion of protein and mineral mass is relatively low in contribution to BW, potential bias of these body components measurement in predicting body HC seems to be not crucial. Since the body fat content strongly affects the HC, the bias from our new equation may be caused by the fat content. We found the fat mass or the % fat mass correlated with the difference in predictive model HC and HC\_Eq4, however, the estimation bias was relatively low and less than  $\pm 1$  kcal $\cdot$ C $^{-1}$  per 10 kg fat mass or per 10% fat mass (S2 Fig). Therefore the new equation can be applied within our data range of fat mass or % fat mass and should be employed with care for those who have extremely low or high fat mass.

In conclusion, our results suggest that gender, BSA, and weight are the independent factors for calculating HC. For the first time, a predictive equation based on anthropometry data was developed and this equation could be useful in estimating HC in the general population without body composition measurements.

## Supporting Information

**S1 Fig. Relationship between heat capacity (HC) estimated by the equation HC\_Eq1, HC\_Eq2, and HC\_Eq3 versus weight and body surface area for men (black dots).**  
(TIF)

**S2 Fig. Relationship between difference in predictive model HC and HC\_Eq4 versus fat mass and proportion of body fat (using whole data, n = 902).**  
(TIF)

**S1 Table. Multivariate regression analysis for predicting HC\_Eq4 (Data n = 902).**  
(DOCX)

## Acknowledgments

This work was supported by the Bio & Medical Technology Development Program of the National Research Foundation (NRF) funded by the Ministry of Science, ICT & Future Planning (Fund receiver Chae Hun Leem, No. 2012–0009829, No. 2015M3A9B6028310 and No. 2014M3A9D7034366).

## Author Contributions

Conceived and designed the experiments: CHL. Performed the experiments: DDP JHL YBL ESP KYK JYS JEK. Analyzed the data: DDP CHL. Wrote the paper: DDP CHL.

## References

1. Scott CB. Contribution of anaerobic energy expenditure to whole body thermogenesis. *Nutr Metab (London)* 2005; 2:14, doi: [10.1186/1743-7075-2-14](https://doi.org/10.1186/1743-7075-2-14)
2. Herman IP. *Physics of the Human Body*, NewYork: Springer 2007, Chapter 6: Metabolic: Energy, Heat, Work, and Power of the Body. 319–403
3. Charkoudian N. Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. *Mayo Clin Proc.* 2003; 78(5):603–12.



4. Kakitsuba N, Mekjavic IB. Determining the rate of body heat storage by incorporating body composition. *Aviat Space Environ Med.* 1987; 58(4):301–7. PMID: [3579815](#)
5. Burton AC. Human calorimetry II. The average temperature of the tissue of the body. *J. Nutr.* 1935; 9:261–80.
6. Minard D. Body heat content. In: Hardy JD, Gagge AP, Stolwijk JAJ, eds. *Physiological and behavioral temperature regulation.* Springer, IL: Charles C. Thomas, 1970; 345–57
7. Webb P. Heat storage and body temperature during cooling and rewarming. *Eur J Appl Physiol* 1993. (66: ):18–24
8. Blaxter K. *Energy metabolism in animal and man,* Cambridge University Press, Cambridge 1989: 40
9. Aoyagi Y, McLellan TM, Shephard RJ. Determination of body heat storage: how to select the weighting of rectal and skin temperatures for clothed subjects. *Int Arch Occup Environ Health.* 1996; 68(5):325–36. PMID: [8832298](#)
10. Havenith G, Coenen JM, Kistemaker L, Kenney WL. Relevance of individual characteristics for human heat stress response is dependent on exercise intensity and climate type. *Eur J Appl Physiol Occup Physiol.* 1998; 77(3):231–41. PMID: [9535584](#)
11. Havenith G. Individualized model of human thermoregulation for stimulation of heat stress response. *J Appl Physiol* 2001, 90: 1943–1954.
12. Kurazumi Y, Tsuchikawa T, Matsubara N, Horikoshi T. Effect of posture on the heat transfer areas of the human body. *Build Environ.* 2008, 43:1555–1565.
13. de Dear RJ, Arens E, Hui Z, Oguro M. Convective and radiative heat transfer coefficients for individual human body segments. *Int J Biometeorol.* 1997; 40(3):141–56.
14. Jin HJ, Baek YH, Kim HS, Ryu JH, Lee SW. Constitutional multicenter bank linked to Sasang constitutional phenotypic data. *BMC Compl Alt Med* 2015; 15:46 doi: [10.1186/s12906-015-0553-3](#)
15. Pham DD, Lee JH, Park ES, Baek HS, Kim GY, Lee YB, et al. Thermoregulation response to graded exercise differ among Sasang types. *Evid Based Comp Alt Med* 2015, <http://dx.doi.org/10.1155/2015/879272>
16. Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be known. *Nutrition* 1989, 5(5):303–11.
17. Thompson DL, Thompson WR, Prestridge TJ, Bailey JG, Bean MH, Brown SP et al. Effects of hydration and dehydration on body composition analysis: a comparative study of bioelectric impedance analysis and hydrodensitometry. *J Sports Med Phys Fitness,* 1991. 31(4): p. 565–70. PMID: [1806735](#)
18. Kim HJ, Kim CH, Kim DW, Park M, Park HS, Min SS et al. External cross-validation of bioelectrical impedance analysis for the assessment of body composition in Korean adults. *Nutr Res Pract.* 2011; 5(3):246–252 doi: [10.4162/nrp.2011.5.3.246](#) PMID: [21779529](#)
19. Lim JS, Hwang JS, Lee JA, Kim DH, Park KD, Jeong JS et al. Cross-calibration of multi-frequency bioelectrical impedance analysis with eight-point tactile electrodes and dual-energy X-ray absorptiometry for assessment of body composition in healthy children aged 6–18 years. *Pediatr Int.* 2009 Apr; 51(2):263–8. doi: [10.1111/j.1442-200X.2008.02698.x](#) PMID: [19405930](#)
20. Ling CH, de Craen AJ, Slagboom PE, Gunn DA, Stokkel MP, Westendorp RG et al. Accuracy of direct segmental multi-frequency bioimpedance analysis in the assessment of total body and segmental body composition in middle-aged adult population. *Clin Nutr.* 2011; 30(5):610–5 doi: [10.1016/j.clnu.2011.04.001](#) PMID: [21555168](#)
21. Sartorio A, Malavolti M, Agosti F, Marinone PG, Caiti O, Battistini N et al. Body water distribution in severe obesity and its assessment from eight-polar bioelectrical impedance analysis. *Eur J Clin Nutr.* 2005; 59(2):155–60.
22. Bedogni G, Malavolti M, Severi S, Poli M, Mussi C, Fantuzzi AL et al. Accuracy of an eight-point tactile-electrode impedance method in the assessment of total body water. *Eur J Clin Nutr.* 2002; 56(11):1143–8.
23. Nakao T, Kanazawa Y, Nagaoka Y, Iwasawa H, Uchinaga A, Matsumoto H, et al. Body protein index based on bioelectrical impedance analysis is a useful new marker assessing nutritional status: applications to patients with chronic renal failure on maintenance dialysis. *Contrib Nephrol* 2007; 155:18–28
24. Fürstenberg A, Davenport A. Assessment of body composition in peritoneal dialysis (PD) patients using bioelectrical impedance and dual-energy x-ray absorptiometry. *Am J Nephrol.* 2011; 33(2):150–6 doi: [10.1159/000324111](#) PMID: [21293116](#)