Potter AW, Looney DP, Hancock JW, Castellani MP, & Santee WR. Review of the Rational and Mathematical Basis of the SCENARIO Thermal Model.
J Sport Human Perf 2022; 10(1):14-29.

DOI: https://doi.org/10.12922/jshp.v10i1.176

JOURNAL OF SPORT AND HUMAN PERFORMANCE

REVIEW ARTICLE OPEN ACCESS

REVIEW OF THE RATIONAL AND MATHEMATICAL BASIS OF THE SCENARIO THERMAL MODEL

Potter AW [1*], Looney DP [1], Hancock JW [1,2], Castellani MP [1,2], and Santee WR [1]

[1] *U.S. Army Research Institute of Environmental Medicine, Natick, Massachusetts 01760, USA*
[2] *Oak Ridge Institute for Science and Education (ORISE), Oak Ridge, TN, 37830, USA*

**Corresponding author:* adam.w.potter.civ@mail.mil

ABSTRACT

Mathematical models of human thermal responses can be used to provide useful information to prevent heat injuries, plan risk mitigation strategies, and evaluate potential responses to stressors. This paper reviews the mathematical principles used to operate the SCENARIO thermal model. SCENARIO is a rational first principles model that consists of seven compartments made up of five concentric cylinders that represent human core, muscle, fat, and vascular and avascular skin, a central blood compartment, and a clothing layer. Modeled interaction of heat exchange through these compartments allows for the prediction of thermal state over time. The model uses inputs of individuals characteristics and health status along within environmental conditions, clothing properties, and activity to generate physiological predictions (metabolism, heart rate, cardiac output, stroke volume, skin and core body temperature) over a given time course. This paper reviews the inputs, outputs, mathematical principles and general history of the SCENARIO model.

Keywords: physiology, biophysics, thermoregulation, clothing, environment, modeling

INTRODUCTION

Quantifying human physiological responses to environmental exposures has a rich history within the scientific community. Notable scientific work can be traced back to observational studies from Sir Charles Blagden is 1775 (1), mathematical representations of heat balance in solids by Fourier in 1822 (2), to conceptual representations of the human as sphere with internal core body heat exchange into the environment by Lefevre 1911 (3). Combining theories, tangible concepts, and mathematics to specifically quantify human responses took shape in 1934 when Burton applied Fourier's law to represent the human mathematically as a single cylinder (4). Possibly most notable with respect to rational modeling is the work by Pennes in 1948 (5) with the development of the bioheat transfer equation, where tissue, blood, and metabolism were specifically considered.

The U.S. military develops and uses human thermal models for understanding and preparing for operational exposures to extreme environments. In response to World War II, the country mobilized scientists to specifically address heat strain/stress that Soldiers were encountering in the hot and dry North African deserts and in the hot and humid Pacific Islands (6). Some of the most notable origins of these efforts can be traced back to scientists at the Harvard Fatigue Lab, University of Minnesota, and J.B. Pierce Foundation Laboratory at Yale University (7-11). In 1961, this work area was transformed into a US Army laboratory specifically dedicated to this field of research, the U.S. Army Research Institute of Environmental Medicine (USARIEM) (12, 13).

USARIEM, have continued to more accurately predict the specific interactions between the human, their clothing, and the environment (14-20). The Institute has focused several years of efforts to develop and refine models, methods, and usable decision aids for predicting thermoregulatory responses based on biophysics, physiology, clothing testing, and testing of human volunteers exposed to selected combinations of clothing, activities, and environmental conditions (21-30).

One of the more comprehensive US Army models is the SCENARIO model (31-34); named for its intended capability of running time-series predictions for a given human, set of activities, and environmental exposure (i.e., scenarios). Although widely used, the last review and update of the SCENARIO model was published in 2004 (34). This paper reviews the history of the SCENARIO model, its basis in the principles of thermal physiology, and the associated decision aids developed by USARIEM researchers for military end users.

History of SCENARIO

The SCENARIO model was originally developed by Kraning and Gonzalez (31-34). The original version of it was used by Kraning as a platform to analyze human study data to test physiology hypotheses, and to help inform study designs for testing new physiological hypotheses. The concept during its creation was to use all of the "best available" algorithms to mathematically represent specific physiological functions. The inspirational primary sources for the model came from Atkins and Wyndham (35, 36), Gordon et al., (37), Stolwijk and Hardy (38-40), Montgomery (41, 42), Werner (43-46), Gagge (47-49), and Wissler (50, 51); while many of the biophysics equations for clothing came from work by Woodcock, Breckenridge, and Goldman (18, 52-66). Work conducted by Tan et al., (67) has provided some recent improvements that have optimized and improved the accuracy of the model.

The concept of SCENARIO was to build a modular system that included both passive and active control systems along with physiological mechanisms relevant to thermoregulation (e.g., cardiorespiratory elements). Modularity of the design allows for continuous update to enabled use of the 'current best science' as per use of the "best available algorithms" to yield the most accurate predictions and create a true thermoregulatory model.

METHODS

SCENARIO Structure

The SCENARIO model structurally represents the human in seven compartments made up of five concentric cylinders (core, muscle, fat, and vascular and avascular skin), a central blood compartment, and a clothing layer (Figure 1). Heat exchange between the cylinders occurs via conductance between each of the layers and by convection via blood circulation. Thermal states of each of the model layers are described using an energy balance equation; these equations comprise the passive heat exchange system. Heat exchange between the individual and surrounding environment occurs primarily at outer surface and is defined by radiant, convective, and evaporative heat exchanges. In addition to passive heat transfer between nodes, algorithms describe the active modes of thermoregulation via blood flow, sweating and to a minor extent shivering.

Passive System

The main rational function describing this balance represented in a total body heat content (Q_n) at a given time point (t) by each n^{th} compartment is shown below as:

$$\begin{aligned}\frac{d}{dt}Q_{n\,(t)} = H_n(t) &+ \left(K_{n-1,n}[T_{n-1}(t) - T_n(t)]\right) \\ &- \left(K_{n,n+1}[T_n(t) - T_{n+1}(t)]\right) \\ &- (BF_n(t) \cdot \rho_{bl} \\ &\cdot c_{bl}[T_n(t) - T_{bl}(t)])\end{aligned}$$

where $H_n(t)$ is rate of heat production, K_n is heat conductance between layers, T_n is temperature, T_{n-1} and T_{n+1} are temperatures of compartments adjacent to n, $BF_n(t)$ is rate of blood flow through compartment n, and ρ_{bl}, c_{bl}, and T_{bl} represent density, heat capacity, and temperature of the blood compartment. The rational balance of the heat content of the blood compartment (Q_{bl}) is described as:

$$\begin{aligned}\frac{d}{dt}Q_{bl} = \rho_{bl} \cdot c_{bl}([(T_c - T_{bl})BF_{cr}] &+ [(T_{mu} - T_{bl})BF_{mu}] \\ &+ \left[\left(T_{fat} - T_{bl}\right)BF_{fat}\right] \\ &+ [(T_{vsk} - T_{bl})BF_{vsk}]) \\ &- (C_{res} + E_{res})\end{aligned}$$

where c, bl, mu, fat, and vsk represent core, blood, muscle, fat, and vascular skin layers, C_{res} and E_{res} are convective and evaporative heat transfer by respiration.

Active System

The active system for blood flow (BF) is broken down into segments for skin, core, and muscle. Skin blood flow (BF_{sk}) is moderated by skin temperature (T_{sk}), posture, work intensity, state transitions, and dehydration. It is described linearly as a function of blood temperature (T_{bl}), compensated for by the influence of T_{sk} and volume of oxygen uptake (VO_2) by adjusting the maximum skin blood flow ($MaxBF_{sk}$) using a proportional control equation with conditional variables factored by percentage of this ($PctMaxBF_{sk}$). This equation is show as:

$$BF_{sk} = (MaxBF_{sk}) \cdot \frac{PctMaxBF_{sk}}{100}$$

Maximum blood flow ($MaxBF_{sk}$) is adjusted based on the work rate, where $MaxBF_{sk}$ can range from 7.0 to 5.0 $l \cdot min^{-1}$ and set based on three conditions of VO_2 (≤ 0.5, between 0.5 and 2.0, and >2.0 $l \cdot min^{-1}$. If $VO_2 \leq 0.5$, $MaxBF_{sk} = 7.0$ $l \cdot min^{-1}$. If $VO_2 > 0.5$ and < 2.0, $MaxBF_{sk} = 7.0 - 1.33(VO_2 - 0.5)$ $l \cdot min^{-1}$. If $VO_2 \geq 2.0$, $MaxBF_{sk} = 5.0$ $l \cdot min^{-1}$. Additionally, there is a factor for adjusting $MaxBF_{sk}$ to compensate for gradual dehydration (weighting the change by 0.1%). Percentage of maximum blood flow ($PctMaxBF_{sk}$) is a conditional equation that is calculated using a blood-skin threshold temperature ($Th_{bl-BFsk}$) that is adjusted by work intensity and skin temperature and dehydration. This threshold allows for increases in blood flow for lower VO_2 and decreases based on higher VO_2, seen as:

$$PctMaxBF_{sk} = \alpha_{\mathrm{BFsk}}(T_{bl} - Th_{bl-BFsk})$$

where $\alpha_{\mathrm{BFsk}} = 70.3$ [$\% \cdot C^{-1}$] signifies a proportionality coefficient that can be adjusted for dehydration based on a percentage of body weight loss ($\%\downarrow$W), as $\alpha_{BFsk} = 70.3$ [$1 - 0.13 \cdot (\%\downarrow W)$].

Sweat rate

Sweat rate (SR) response is calculated functionally into a total sweating rate ($\dot{m}_{sw}$) based on the relationship of blood and skin temperatures and the given thresholds (e.g., Th_{bl}, Th_{sk}) and an associated metabolic rate (i.e., oxygen uptake, VO_2). This is functionally described based on a calculated total surface area (A_D) (68, 69), a multiplying factor (λ_{sr}), and conditional gain coefficients, seen as:

$$\dot{m}_{sw} = A_D \cdot \lambda_{SR}(\alpha_{SR}[T_{bl} - Th_{bl-SR}] + \beta_{SR}[\bar{T}_{SR} - Th_{sk-SR}])^{\left(\frac{T_{sk} - Th_{sk-SR}}{10}\right)}$$

where $\lambda_{sr} = \frac{\left(160 \cdot \frac{\mathrm{VO2max}}{\mathrm{W}}\right) - 3.2}{3.84}$ represents normal rates for sedentary health males (70), α_{sr} is a coefficient to describe the relative augmented effect or "gain" of the deviation in internal hypothalamic signal driving responses (71) where additional adjustments can be made for dehydration based on a factor of $\%\downarrow$W (72), and β_{SR} is gain for deviations from normal or basal skin temperature.

Cardiorespiratory Systems

Key functions related to central circulation include stroke volume (SV), cardiac output (CO), and the related heart rate (HR) and T_{sk}. The function for SV is based on the Fick equation, where $SV = CO/HR$. The original calculations assumed all started simulations began at rest. For these steps in the model, there is an assumed resting value of CO and HR (CO_{rst} and HR_{rst}), making the initial SV (SV_i), $SV_i = CO_{rst}/HR_{rst}$. The steps of calculating HR beyond rest require a moving calculation of CO required (CO_{req}) represented as a sum of required blood flow to the core, muscles, fat, and vascular skin (BF_{cr}, BF_{mu}, BF_{fat}, and BF_{vsk}). This calculated CO_{req} value is then used to balance the ongoing calculations of HR from CO_{req}/SV.

RESULTS

SCENARIO Inputs and Outputs

SCENARIO requires initialization variables related to the individual, their metabolic rate and activity, environmental conditions, and clothing properties. Though inputs over time have varied a bit, the general structure of inputs can be seen in Table 1. One of the unique aspects of some variants of the model is the flexibility to account for user-defined state change conditions (e.g., changes in environmental conditions, work rates).

The format of the SCENARIO model iterates human status calculations of each of the dependent variables based on elapsed time to provide outputs that are time linked (Table 2). The main parameter outputs typically used are those related to the physiological state changes over a given simulated time period. An example output plot of core body temperature (T_c), T_{sk}, and HR over time during work and rest is shown in Figure 2; while a comparison of T_c change to rate of heat loss (dQ/dt) is shown in Figure 3 and sweat rate (SR) and fluid loss is shown in Figure 4, both for the same simulation.

Table 1. General Inputs Required for SCENARIO

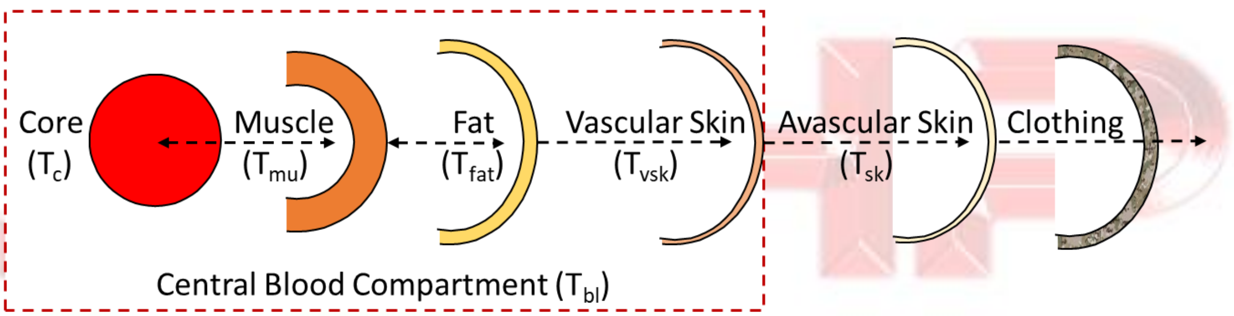
Variable Group	*Number of Variables*	*Variables*
Individual	8*	• body mass (Wt; kg) • height (Ht, m), • percent body fat (%Fat), • age (age, years) • acclimation level (Accl; 0=none, 1=partial, and 2=fully) • hydration status (set levels or by % dehydrated) • initial core body temperature (Tc, °C) • maximal rate of oxygen uptake (VO_2max; mL·kg·min)
Metabolic Rate	6*	• Body movement relative to still air (Vmove, m/s) • Metabolic rate (VO_2) • Total metabolic rate (Mtot, W) • Resting metabolic rate (Mrst, W) • External work rate (Mwork, W) • Activity Type (WorkMode, f=free walking, t=treadmill, r=rest, e=ergometer)
Environmental Conditions	9*	• Ambient or dry bulb temperature (Tdb, °C) • Mean radiant temperature (Tmr, °C) • Black globe temperature (Tg, °C) • Air movement (Vair, m/s) • Ambient Vapor Pressure (Pvap) • Relative Humidity (RH, %) • Wet bulb temperature (Twb, °C) • Dew point temperature (Tdp, °C) • Natural wet bulb temperature (Tnwb, °C)
Clothing Properties	2	• clothing insulation (Icl, clo) • permeability factor (i_m, N.D.)

*Not all variables are required, as some can override others

Table 2. Time-dependent outputs from SCENARIO

Variable Group	*Variable Name*	*Variable Descriptions* **Each at a given time point*
Human	*Mtot*	The collective sum of metabolic rate (can be input)
	Mext	Total metabolic cost from external work (can be input)
	HR	Heart Rate
	SV	Stroke Volume
	CO	Cardiac Output
	Tc	Core body temperature
	Tra	Right arterial blood temperature
	Tsk	Skin temperature (avascular)
	SR	Sweat rate
	BFvsk	Vascular skin blood flow
	dQ/dt	Rate of heat loss for the given time period

Figure 1. Graphical representation of SCENARIO model and compartment dimensions



Compartment	Volume % of total	Translated dimensions: Male, 70 kg, 1.8m^2 surface area	
		Mass (kg)	Thickness (cm)
Central Blood (T_{bl})	3%	2.2 kg	-
Core (T_c)	30%	21.1 kg	4.3 cm
Muscle (T_{mu})	46%	32.3 kg	2.4 cm
Fat (T_{fat})	14%	9.9 kg	0.7 cm
Vascular Skin (T_{vsk})	1%	0.8 kg	0.04 cm
Avascular Skin (T_{sk})	5%	3.6 kg	0.2 cm
Clothing	Varied	Varied	Varied

Figure 2. Example output plot of core body temperature (T_c), skin temperature (T_{sk}), and heart rate (HR) during a series of work and rest overtime.

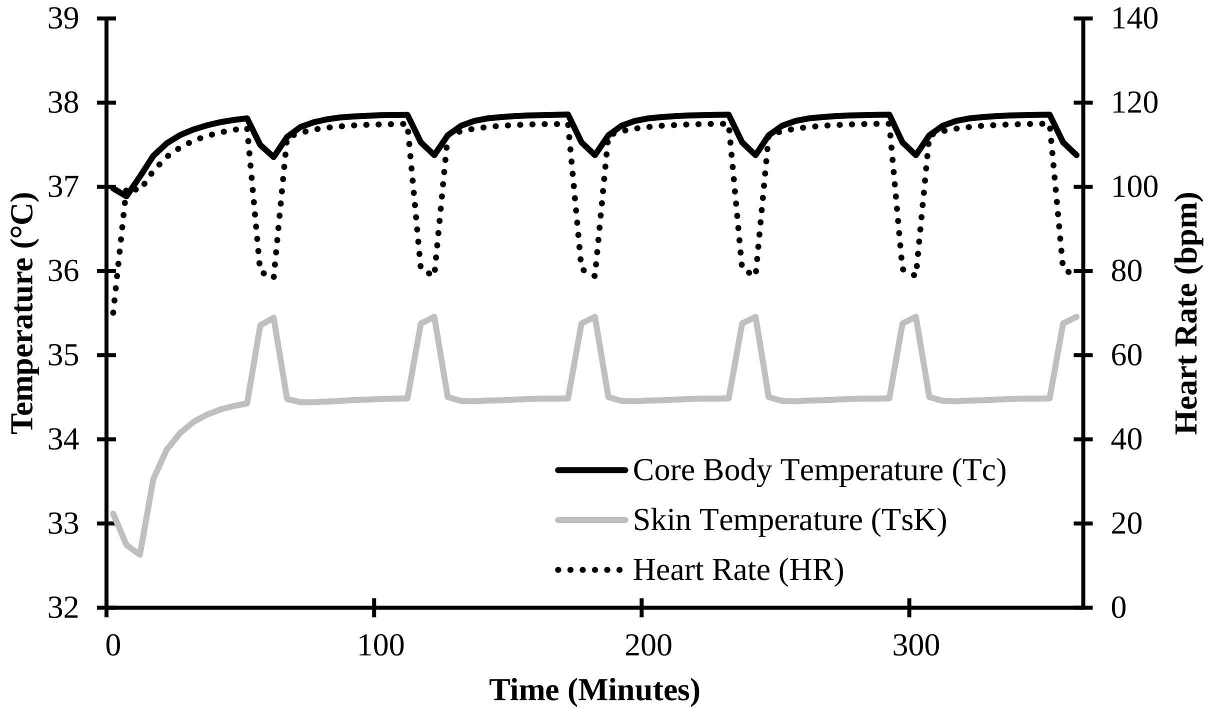


Figure 3. Example output plot of total metabolic rate (*Mtot*), rate of heat loss (dQ/dt), and associated core body temperature (T_c) during a series of work and rest overtime

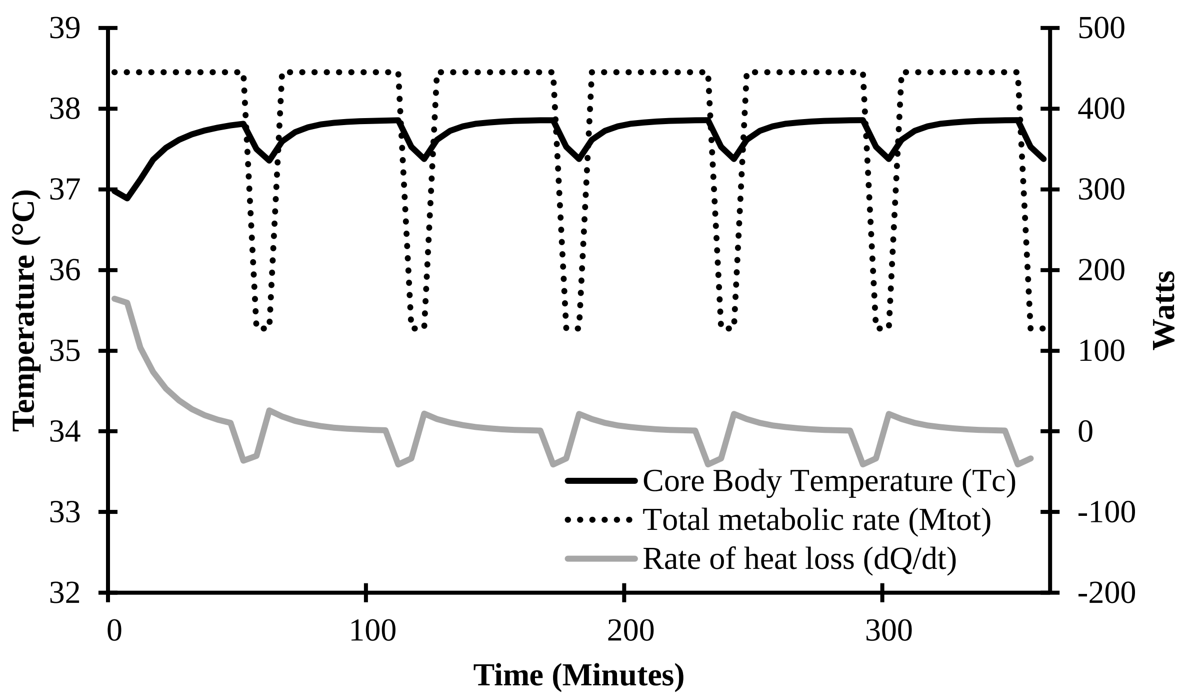
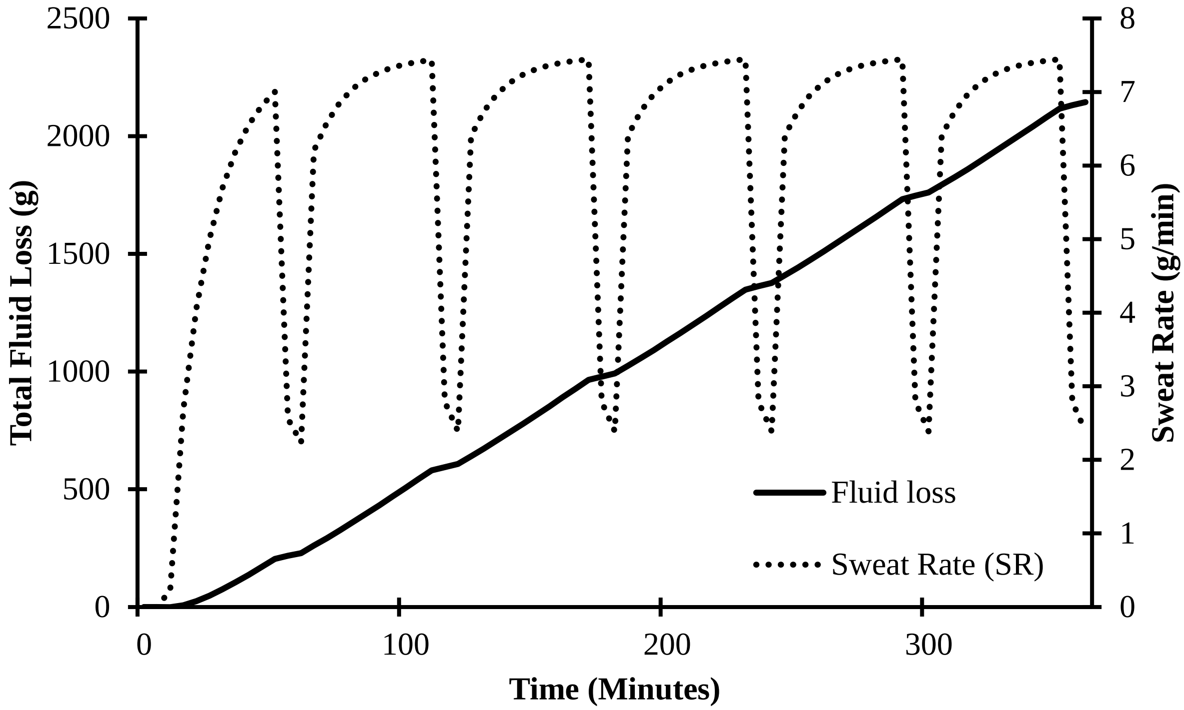


Figure 3. Example output plot of fluid loss and sweat rate (SR) during a series of work and rest overtime



DISCUSSION

SCENARIO as a Decision Aid

SCENARIO has taken shape in several forms as a computer-based decision aid and has been used as the underpinning for several other development efforts. Program developers have created several versions of the SCENARIO model as command line MS-DOS program, Quick Basic (QBasic), a C-code variant, and a Java version. As the creators, Kraning and Gonzalez were also the first program developers for the SCENARIO model. However, over time with changes in programming languages and computers systems, there have been several other notable contributors that have worked on the model, to include Furlong (73), Doherty (74, 75) Matthew (76, 77), extensive work by Berglund and Yokota (78-80), and various applied use cases (81-84).

Early versions provided meaningful platforms to test hypotheses and run modeling and simulations of anticipated events. However, one of the more important improvements came with the transition to object oriented programming, which allowed for a framework for development and further expansion. Versions of these collective works include the transition of the original SCENARIO model into the java version (SCENARIO-J) (78), and into the foundational basis for the Individual Capability Decision Aid (ICDA) (29, 30), a Disabled-Submarine thermal model (21), and the framework for a canine thermal model (CTM) (85-88).

Some notable improvements have been made recently related to one of the main input elements, metabolic rate. From a resting and baseline perspective, most often thermoregulatory models use inputs of individual height and mass to determine a body surface area (BSA). This BSA is then used to interpreted resting metabolic rate (typically calculated as BSA * 58.2 or 58.2 W/m^2). Until recently, a 1916 equation had been used that was based on a small sample of white males (68); however, recent methods have been developed to more accurately make predictions of BSA based on sex and other inputs (69). Additionally, the accuracy of these models during more dynamic activity conditions can be directly linked to shifts in metabolic demands (i.e., metabolic heat production) and therefore accurate predictions of metabolic costs are critical that have been tested to more realistic complex conditions (89-95). This principle was directly demonstrated by Tan et al., (67), where mathematical penalties were applied to metabolic rate predictions.

Why SCENARIO?

While the originally designed SCENARIO model had several limitations for use as it was designed from data of young and healthy males; improvements have been made to account for individual and sex differences in physiological responses (34) as well as specific handling of circadian rhythm (75). Additionally, the modular design allows for testing and further improvement of the underlying equations to account for specific populations. Newer studies provide some promise for both testing and making these adjustments specific to age (96, 97), sex (98, 99), and various fitness levels (100, 101).

There are essentially three mathematical modeling methods for predicting human thermal responses, empirical, rational, or hybrid models. Empirical (functional) models use mathematical or statistically-based representations of observed relationships found in experimental data. Rational (mechanistic) models use mathematically representations of explicit phenomena based on first principles understanding of physics and physiology (biology, chemistry, physics). Independently, both empirical and rational methods are scientifically valid approaches. However, perhaps the most effective approach is a hybrid or mixed model method that uses a combination of the two. Hybrid models often use a framework of rational relationships/equation, but the equations may be adjusted or supplemented with data based metrics/values. The hybrid approach is most useful when the basic principles or rationale is known, but specific input/variable values need to be adjusted for a given population or set of conditions. The SCENARIO model is well-suited to be a physiologically-based platform for a true hybrid or even the foundation of a combined or multi-model approach (102). In a multi-model approach, a series of models are assembled, then based on the specific criteria for a given case or scenario, either a specific model is selected from the ensemble, or several models may be run simultaneously, then compared. Ideally multiple models will converge on a single solution, but in some cased feedback from initial observations may favor one model. The later approach is similar to current practice in meteorology for severe storm forecasting, where the results/storm tracks and other predictions/predicted parameters from multiple models are compared, and the results from best performing models are selected or emphasized. The result from multiple models may also be combined to generate a range of probable outcomes.

The Heat Strain Decision Aid (HSDA) (22, 26, 103-105) is the most widely recognized USARIEM example of an empirically-based thermal model; while SCENARIO is perhaps the most well-known rationally-based model (32-34). However, while both of their origins began within their respective classification, they are each both technically hybrid methods as they both rely on first principle methods for calculated the physics of heat exchange, but also use data based content in the equations input. The main difference between them is the construction of their main output functions (e.g., method to predict core body temperature). The HSDA method uses an empirically-derived equation for projecting a core body temperature trajectory based on an equilibrium state within a given set of thermal conditions (106). SCENARIO combines physiologically based variables and calculations (e.g., blood flow, heart rate, cardiac output) to predict body core temperature. Both methods include approximations of underlying values such as effects of wind or wettedness on clothing properties (107, 108).

Across the open literature, several notable models exist that are designed specifically to predict thermal statuses in varied environments (39, 41, 46, 51, 109-117). Each of these models have provided key improvements to the field; however, each have had shortcomings when applied to broader environments or can pose challenges implementing. Several of these models were designed with specific application focuses, e.g., in hot, cold, or immersed environments. However, it remains a critical task to validate these models for specific use cases and conditions, and specialized clothing (118-120) and when possible to up- or down-select methods base on needs and their respective performance demands (121, 122). Additionally, the ideal model or combination of models can be used to provide predictive abilities across a dynamic set of conditions (e.g., a person traveling on land in the heat, then immersed, then back on land in cooler or cold conditions).

Acknowledgements

The authors acknowledge the invaluable contributions of the human test volunteers and the talented scientists whose work has made this model possible. The authors would also like to thank Drs. Richard Gonzalez and Larry Berglund for their helpful reviews of this manuscript.

Declarations

Ethics Approval and Consent to Participate

This study received approval by the U.S. Army Research Institute of Environmental Medicine (USARIEM) (Natick, MA).

Funding

This study and analysis was funded by the U.S. Army Military Operational Medicine Research Program (MOMRP), and U.S. Army Research Institute of Environmental Medicine (USARIEM).

Disclaimer

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

REFERENCES

1. Blagden C. XII. Experiments and observations in an heated room. *Philosophical Transactions of the Royal Society of London*. 1775(65):111-23.
2. baron Fourier JBJ. Théorie analytique de la chaleur: F. Didot; 1822.
3. Lefevre J. Chaleur animale et bioénergétique: Masson et cie; 1911.
4. Burton AC. The application of the theory of heat flow to the study of energy metabolism: Five figures. *The Journal of Nutrition*. 1934;7(5):497-533.
5. Pennes HH. Analysis of tissue and arterial blood temperatures in the resting human

forearm. *Journal of Applied Physiology*. 1948;1(2):93-122.
6. Goldman RF. Introduction to heat-related problems in military operations. Medical Aspects of Harsh Environments. 2001;1:3-49.
7. Adolph EF. Physiology of Man in the Desert. Physiology of Man in the Desert. 1947.
8. Bean WB, Eichna LW, editors. Performance in relation to environmental temperature. Reactions of normal young men to simulated desert environment. *Federation Proceedings Federation of American Societies for Experimental Biology*; 1943: Baltimore.
9. Eichna LW, Ashe W, Bean W, Shelley W. The Upper Limits of Environmental Heat and Humidity Tolerated by Acclimatized Men Working in Hot Environments. *Journal of Industrial Hygiene and Toxicology*. 1945;27(3):59-84.
10. Nelson N, Eichna LW, Horvath SM, Shelley WB, Hatch T. Thermal exchanges of man at high temperatures. *American Journal of Physiology-Legacy Content*. 1947;151(2):626-52.
11. Nelson NA, Shelley WB, Horvath SM, Eichna LW, Hatch TF. The influence of clothing, work, and air movement on the thermal exchanges of acclimatized men in various hot environments. *The Journal of Clinical Investigation*. 1948;27(2):209-16.
12. Francesconi R, Byrom R, Mager M. United States Army Research Institute of Environmental Medicine: First Quarter Century. *The Physiologist*. 1986;29:58-62.
13. Pandolf KB, Francesconi R, Sawka MN, Cymerman A, Hoyt RW, Young AJ, et al. United States Army Research Institute of Environmental Medicine: Warfighter research focusing on the past 25 years. *Advances in Physiology Education*. 2011;35(4):353-60.
14. Goldman RF. Tolerance time for work in the heat when wearing CBR protective clothing. *Military Medicine*. 1963;128:776-86.
15. Goldman RF, Joy RJT. Prevention of heat casualties in men wearing chemical biological protective clothing. Natick, MA; 1967 7/1967 July. Report No.: EPT-1.
16. Givoni B, Sohar E. Rectal temperature in the prediction of permissible work rates in hot environments. *International Journal of Biometeorology*. 1968;12(1):41-50.
17. Breckenridge JR, Levell CA. Heat stress in the cockpit of the AH-IG Hueycobra Helicopter. *Aerospace Medicine*. 1970;41(6):621-6.
18. Breckenridge JR, Goldman RF. Solar heat load in man. *Journal of Applied Physiology*. 1971;31:659-63.
19. Goldman RF. Prediction of human heat tolerance. In: Folinsbee LJ, Wagner JA, Borgia JF, Drinkwater BL, Gliner JA, Bedi JF, editors. Environmental Stress. New York: Academic Press; 1978. p. 53-69.
20. Berglund LG, Levine L, Cadarette BS, Kolka MA. Human responses to intermittent work while wearing encapsulating chemical-biological protective clothing with personal HVAC. *ASHRAE Transactions*. 2005.
21. Berglund LG, Yokota M, Potter AW. Thermo-physiological responses of sailors in a disabled submarine with interior cabin temperature and humidity slowly rising as predicted by computer simulation techniques. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T13-6; 2013.
22. Gonzalez R, McLellan T, Withey W, Chang SK, Pandolf K. Heat strain models applicable for protective clothing systems: comparison of core temperature response. *Journal of Applied Physiology*. 1997;83(3):1017-32.
23. Gonzalez RR, editor Predictive modeling: its use in forecasting human responses to the environment. Canberra, Australia2000.
24. Gonzalez RR, McLellan TM, Tenaglia SA. Heat strain in women: comparison of model and experimental results with NBC protective clothing systems.; 1997 TTCP-HUM-TP-6/SGU/97/KCA6.
25. Gonzalez RR, McLellan TM, Withey WR. Physiological evaluation of two heat strain models effective in protective clothing systems. Natick, MA; 1995 1995 May. Report No.: T95-14.
26. Potter AW, Blanchard LA, Friedl KE, Cadarette BS, Hoyt RW. Mathematical prediction of core body temperature from environment, activity, and clothing: The heat strain decision aid (HSDA). *Journal of Thermal Biology*. 2017;64:78-85.
27. Potter AW, Looney DP, Santee WR, Gonzalez JA, Welles AP, Srinivasan S, et al. Validation of new method for predicting human skin

temperatures during cold exposure: The Cold Weather Ensemble Decision Aid (CoWEDA). *Informatics in Medicine Unlocked*. 2020:100301.

28. Yokota M, Berglund LG, Santee WR, Buller MJ, Hoyt RW. Modeling physiological responses to military scenarios: initial core temperature and downhill work. *Aviation, Space, and Environmental Medicine*, 2005; *76*(5), 475-480.
29. Yokota M, Berglund LG. Initial capability decision aid (ICDA) thermal prediction model and its validation. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T06-03; 2006.
30. Yokota M, Berglund LG, Cheuvront SN, Santee WR, Latzka WA, Montain SJ, et al. Thermoregulatory model to predict physiological status from ambient environment and heart rate. *Computers in Biology and Medicine*. 2008;38:1187-93.
31. Kraning KK. A computer simulation for predicting the time course of thermal and cardiovascular responses to various combinations of heat stress, clothing and exercise. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T13-91; 1991.
32. Kraning KK, Gonzalez RR. Scenario: A military/industrial heat strain model modified to account for effects of aerobic fitness and progressive dehydration. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Note, TN97-1; 1997.
33. Kraning KK, Gonzalez RR. A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. *Journal of Thermal Biology*. 1997;22:331-42.
34. Gonzalez RR. SCENARIO revisited: comparisons of operational and rational models in predicting human responses to the environment. *Journal of Thermal Biology*. 2004;29(7-8):515-27.
35. Atkins A, Wyndham C. A study of temperature regulation in the human body with the aid of an analogue computer. *Pflügers Archiv*. 1969;307(2):104-19.
36. Wyndham C, Atkins A. A physiological scheme and mathematical model of temperature regulation in man. *Pflügers Archiv*. 1968;303(1):14-30.
37. Gordon RG, Roemer RB, Horvath SM. A mathematical model of the human temperature regulatory system-- transient cold exposure response. *IEEE Transactions on Biomedical Engineering*. 1976;23(6):434-44.
38. Stolwijk J, Hardy J. Temperature regulation in man—a theoretical study. *Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere*. 1966;291(2):129-62.
39. Stolwijk JA. A mathematical model of physiological temperature regulation in man. No. NASA-CR-1855. NASA, 1971.
40. Stolwijk JA. Mathematical models of thermal regulation. *Annals of the New York Academy of Sciences*. 1980;335(1):98-106.
41. Montgomery LD. A model of heat transfer in immersed man. *Annals of Biomedical Engineering*. 1974;2(1):19-46.
42. Montgomery LD, Williams BA. Effect of ambient temperature on the thermal profile of the human forearm, hand, and fingers. *Annals of Biomedical Engineering*. 1976;4(3):209-19.
43. Werner J. Thermoregulatory models. Recent research, current applications and future development. *Scandinavian Journal of Work, Environment & Health*. 1989;15 Suppl 1:34-46.
44. Werner J, Buse M, Foegen A. Lumped versus distributed thermoregulatory control: results from a three-dimensional dynamic model. *Biological cybernetics*. 1989;62(1):63-73.
45. Werner J, Webb P. A six-cylinder model of for general use on human thermoregulation personal computers. *The Annals of Physiological Anthropology*. 1993;12(3):123-34.
46. Xu X, Werner J. A dynamic model of the human/clothing/environment-system. *Applied Human Science*. 1997;16(2):61-75.
47. Gagge A, Stolwijk J, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. Memoirs of the Faculty of Engineering, Hokkaido University. 1972;13(Suppl):21-36.
48. Gagge AP, Stolwijk J, Hardy J. Comfort and thermal sensations and associated physiological responses at various ambient

temperatures. *Environmental Research*. 1967;1(1):1-20.
49. Gagge AP, Stolwijk JAJ, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*. 1971;77(1):247-62.
50. Wissler E. Comparison of computed results obtained from two mathematical models: a simple 14-node model and a complex 250-node model. *Journal de Physiologie*. 1971;63(3):455.
51. Wissler EH. A mathematical model of the human thermal system. *The Bulletin of Mathematical Biophysics*. 1964;26(2):147-66.
52. Woodcock AH. Moisture permeability index - a new index for describing evaporative heat transfer through fabric systems. 1961. Report No.: EP-149.
53. Woodcock AH. Moisture transfer in textile systems, Part I. Textile Research Journal. 1962;32:628-33.
54. Woodcock AH. Moisture transfer in textile systems, Part II. Textile Research Journal. 1962;32:719-23.
55. Woodcock AH, Breckenridge JR. A model description of thermal exchange for the nude man in hot environments. *Ergonomics*. 1965;8:223-35.
56. Woodcock AH, Breckenridge JR. A new method for completely describing man's thermal environment. In: Wexler A, editor. Humidity & Moisture: Measurement & Control in Science and Industry. New York, NY: Reinhold Publishing Corporation; 1965. p. 17-23.
57. Breckenridge JR. Effect of wet insulation in vapor barrier cold-weather boots. *Textile Research Journal*. 1967;37(9):809-11.
58. Breckenridge JR, Goldman RF. Human solar heat load. *ASHRAE Transactions*. 1972;78:110-9.
59. Breckenridge JR, Pratt RL. Effect of clothing color on solar heat load. Quartermaster Research and Engineering Command Center, Natick, MA. 1961.
60. Goldman RF, editor Biophysical factors in the design and uses of clothing - today and tomorrow. New York, NY1971.
61. Goldman RF. Clothing, its physiological effects, adequacy in extreme thermal environments and possibility of future improvements. *Archives Des Science Physiologiques*. 1973;27:137-47.
62. Goldman RF. Clothing design for comfort and work performance in extreme thermal environments. *Transactions New York Academy of Sciences*. 1974;36:531-44.
63. Goldman RF, editor Environment, clothing and personal equipment, and military operations. West Point, NY: U.S. Military Academy; 1974.
64. Goldman RF. The role of clothing in modifying the human thermal comfort range. *Inserm*. 1977;75:163-76.
65. Goldman RF, Breckenridge JR, Reeves E, Beckman EL. "Wet" versus "Dry" suit approaches to water immersion protective clothing. *Aerospace Medicine*. 1966;37:485-7.
66. Goldman RF, Green EB, Iampietro PF. Tolerance of hot, wet environments by resting men. *Journal of Applied Physiology*. 1965;20:271-7.
67. Tan AP, Cheong CH, Lee T, Seng KY, Teo CJ. Computer modelling of heat strain responses of exercising personnel in tropical climate. *Computers in Biology and Medicine*. 2021:104530.
68. Du Bois D, Du Bois EF. Clinical calorimetry: tenth paper a formula to estimate the approximate surface area if height and weight be known. *Archives of Internal Medicine* 1916;XVII(6_2):863-71.
69. Looney DP, Sanford DP, Li P, Santee WR, Doughty EM, Potter AW. Formulae for calculating body surface area in modern US Army Soldiers. *Journal of Thermal Biology*. 2020;92:102650.
70. Buono M, Sjoholm N. Effect of physical training on peripheral sweat production. *Journal of Applied Physiology*. 1988;65(2):811-4.
71. Nadel ER, Bullard RW, Stolwijk J. Importance of skin temperature in the regulation of sweating. *Journal of Applied Physiology*. 1971;31(1):80-7.
72. Montain SJ, Latzka WA, Sawka MN. Control of thermoregulatory sweating is altered by hydration level and exercise intensity. *Journal of Applied Physiology*. 1995;79(5):1434-9.
73. Furlong J, Gonzalez R. Enhancement and integration of thermal strain modeling tools to support objective force warrior: SCENARIO-J

v1. 0 and SCENARIO-MC v 6.0 DAMD17-98-d0022. Science Applications International Corporation (SAIC), McLean, VA. 2003.
74. Doherty T. Fileread: Software Module for Reading Scenario Model Inputs and Observed Data from Text Files. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report; 2000.
75. Doherty TJ, Coyne MD, Kesick CM, Stephenson LA. CIRCAD: Automated analysis of circadian core temperature data. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, TN00-2; 2000.
76. Matthew WT, Santee WR, Berglund LG. Solar load inputs for USARIEM thermal strain models and the solar radiation-sensitive components of the WBGT Index. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T01-13; 2001.
77. Matthew WT, Berglund LG, Santee WR, Gonzalez RR. USARIEM Heat Strain Model: New Algorithms Incorporating Effect of High Terrestrial Altitude. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T03-9; 2003.
78. Berglund LG, Yokota M. Comparison of human responses to prototype and standard uniforms using three different human simulation models: HSDA, Scenario_J and Simulink2NM. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T05-08; 2005.
79. Yokota M, Berglund B, Santee WR, Buller MJ, Hoyt RW. Predicting individual physiological responses during marksmanship field training using an updated SCENARIO-J model. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T04-09; 2004.
80. Yokota M, Matthew WT, Berglund LG, Buller MJ, Hoyt RW. Characterization of uncertainties in a thermal strain prediction model for military applications. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T04-03; 2003.
81. Welles AP, Tharion WJ, Potter AW, Buller MJ. Novel Method of Estimating Metabolic Rates of Soldiers Engaged in Chemical Biological Defense Training. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Report; 2016.
82. Welles AP, Xu X, Santee WR, Looney DP, Buller MJ, Potter AW, et al. Estimation of core body temperature from skin temperature, heat flux, and heart rate using a Kalman filter. *Computers in Biology and Medicine*. 2018;99:1-6.
83. Gonzalez R, Halford C, Keach E. Environmental and physiological simulation of heat stroke: A case study analysis and validation. *Journal of Thermal Biology*. 2010;35(8):441-9.
84. Yokota M, Berglund LG, Bathalon GP. Monte Carlo simulations of individual variability and their effects on simulated heat stress using thermoregulatory modeling. *Journal of Thermal Biology*. 2010;35(3):154-9.
85. Berglund LG, Yokota M, Santee WR, Endrusick TL, Potter AW, Goldman SJ, et al. Predicted thermal responses of military working dog (MWD) to chemical, biological, radiological, nuclear (CBRN) protective kennel enclosure. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T11-03; 2011.
86. Potter AW, Berglund LG, O'Brien C. A canine thermal model for simulating temperature responses of military working dogs. *Journal of Thermal Biology*. 2020;91:102651.
87. O'Brien C, Tharion WJ, Karis AJ, Sullivan HM. Predicting military working dog core temperature during exertional heat strain: Validation of a Canine Thermal Model. *Journal of Thermal Biology*. 2020.
88. O'Brien C, Berglund LG. Predicting recovery from exertional heat strain in military working dogs. *Journal of Thermal Biology*. 2018;76:45-51.
89. Looney DP, Santee WR, Blanchard LA, Karis AJ, Carter AJ, Potter AW. Cardiorespiratory responses to heavy military load carriage over complex terrain. *Applied Ergonomics*. 2018;73:194-8.
90. Looney DP, Buller MJ, Gribok AV, Leger JL, Potter AW, Rumpler WV, et al. Estimating resting core temperature using heart rate.

Journal for the Measurement of Physical Behaviour. 2018;1(2):79-86.
91. Looney DP, Santee WR, Hansen EO, Bonventre PJ, Chalmers CR, Potter AW. Estimating Energy Expenditure during Level, Uphill, and Downhill Walking. *Medicine & Science in Sports & Exercise*. 2019;51(9):1954-60.
92. Looney DP, Santee WR, Karis AJ, Blanchard LA, Rome MN, Carter AJ, et al. Metabolic costs of military load carriage over complex terrain. *Military Medicine*. 2018;183(9-10):e357-e62.
93. Potter AW, Santee WR, Mullen SP, Karis AJ, Blanchard LA, Rome MN, et al. Complex Terrain Load Carriage Energy Expenditure Estimation Using GPS Devices. *Medicine & Science in Sports & Exercise*. 2018; 50(10):2145-9.
94. Richmond PW, Potter AW, Looney DP, Santee WR. Terrain coefficients for predicting energy costs of walking over snow. *Applied Ergonomics*. 2019;74:48-54.
95. Richmond PW, Potter AW, Santee WR. Terrain factors for predicting walking and load carriage energy costs: review and refinement. *Journal of Sport and Human Performance*. 2015;3(3):1-26.
96. Larose J, Boulay P, Sigal RJ, Wright HE, Kenny GP. Age-related decrements in heat dissipation during physical activity occur as early as the age of 40. *PLoS One*. 2013;8(12):e83148.
97. Larose J, Boulay P, Wright-Beatty HE, Sigal RJ, Hardcastle S, Kenny GP. Age-related differences in heat loss capacity occur under both dry and humid heat stress conditions. *Journal of Applied Physiology*. 2014;117(1):69-79.
98. Kenny GP, Jay O. Sex differences in postexercise esophageal and muscle tissue temperature response. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*. 2007;292(4):R1632-R40.
99. Gagnon D, Jay O, Lemire B, Kenny GP. Sex-related differences in evaporative heat loss: the importance of metabolic heat production. *European Journal of Applied Physiology*. 2008;104(5):821-9.
100. Notley SR, Poirier MP, Hardcastle SG, Flouris AD, Boulay P, Sigal RJ, et al. Aging impairs whole-body heat loss in women under both dry and humid heat stress. *Medicine & Science in Sports & Exercise*. 2017;49(11):2324-32.
101. Notley SR, Meade RD, D'Souza AW, Friesen BJ, Kenny GP. Heat loss is impaired in older men on the day following prolonged work in the heat. *Medicine & Science in Sports & Exercise*. 2018; 50(9):1859-1867.
102. Xu X, Santee WR. Sweat loss prediction using a multi-model approach. *International Journal of Biometeorology*. 2011;55(4):501-8.
103. Potter AW, Hunt AP, Cadarette BS, Fogarty A, Srinivasan S, Santee WR, et al. Heat Strain Decision Aid (HSDA) accurately predicts individual-based core body temperature rise while wearing chemical protective clothing. *Computers in Biology and Medicine*. 2019;107:131-6.
104. Waldock K, Lee B, Powell S, Wardle S, Looney D, Greeves J, et al. Field validation of the Heat Strain Decision Aid during military load carriage. *Computers in Biology and Medicine*. 2021;134:104506.
105. Tharion WJ, Yokota M, Karis AJ, Potter AW. Accuracy of the Heat Strain Decision Aid (HSDA) during Ranger Training Brigade's road march exercise. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Report, T21-06.; 2021.
106. Givoni B, Goldman RF. Predicting rectal temperature response to work, environment and clothing. *Journal of Applied Physiology*. 1972;32(6):812-22.
107. Potter AW, Gonzalez JA, Karis AJ, Rioux TP, Blanchard LA, Xu X. Impact of estimating thermal manikin derived wind velocity coefficients on physiological modeling. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Report, T14-7; 2014.
108. Potter AW. Method for estimating evaporative potential (im/clo) from ASTM standard single wind velocity measures. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Report, T16-14; 2016.
109. Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, et al. Development

and validation of the predicted heat strain model. *Annals of Occupational Hygiene*. 2001;45(2):123-35.

110. Fiala D, Lomas KJ, Stohrer M. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *International Journal of Biometeorology*. 2001;45(3):143-59.
111. Havenith G. Individualized model of human thermoregulation for the simulation of heat stress response. *Journal of Applied Physiology*. 2001;90(5):1943-54.
112. Raimundo A, Quintela D, Gaspar A, Oliveira A, editors. Development and validation of a computer program for simulation of the human body thermophysiological response. 2012 *IEEE 2nd Portuguese Meeting in Bioengineering (ENBENG);* 2012: IEEE.
113. Wan X, Fan J. A transient thermal model of the human body–clothing–environment system. *Journal of Thermal Biology*. 2008;33(2):87-97.
114. Kuznetz LH. A two-dimensional transient mathematical model of human thermoregulation. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*. 1979;237(5):R266-R77.
115. Castellani MP, Rioux TP, Castellani JW, Potter AW, Xu X. A Geometrically Accurate 3 Dimensional Model of Human Thermoregulation For Transient Cold and Hot Environments. *Computers in Biology and Medicine*. 2021:104892.
116. Unnikrishnan G, Hatwar R, Hornby S, Laxminarayan S, Gulati T, Belval LN, et al. A 3-D virtual human thermoregulatory model to predict whole-body and organ-specific heat-stress responses. *European Journal of Applied Physiology*. 2021:1-20.
117. Yermakova I. Mathematical modeling of thermal processes in man for development of protective clothing. 한국생활환경학회지. 2001;8(2):127-33.
118. Potter AW, Hunt AP, Pryor JL, Pryor RR, Stewart IB, Gonzalez JA, et al. Practical method for determining safe work while wearing explosive ordnance disposal suits. *Safety Science*. 2021;141:105328.
119. Santee WR, Berglund LG, Cardello AV, Winterhalter CA, Looney DP, Gonzalez JA, et al. Physiological assessment of Soldiers wearing military uniforms of different fabrics during intermittent exercise. *Journal of Sport and Human Performance*. 2020;8(1).
120. Potter AW, Gonzalez JA, Karis AJ, Blanchard LA, Rioux TP, Santee WR. Biophysical Characteristics of Chemical Protective Ensemble With and Without Body Armor. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Report, T15-8; 2015.
121. Friedl KE, Buller MJ, Tharion WJ, Potter AW, Manglapus GL, Hoyt RW. Real time physiological status monitoring (RT-PSM): accomplishments, requirements, and research roadmap. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA, Technical Note, TN16-02; 2016.
122. Friedl KE. Predicting human limits-the special relationship between physiology research and the Army mission. Military Quantitative Physiology: Problems and Concepts in Military Operational Medicine: Problems and Concepts in Military Operational Medicine. 2012:1-38.