

# Expanded prediction equations of human sweat loss and water needs

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**Gonzalez RR, Cheuvront SN, Montain SJ, Goodman DA, Blanchard LA, Berglund LG, Sawka MN.** Expanded prediction equations of human sweat loss and water needs. *J Appl Physiol* 107: 379–388, 2009. First published April 30, 2009; doi:10.1152/jappphysiol.00089.2009.—The Institute of Medicine expressed a need for improved sweating rate ( $\dot{m}_{sw}$ ) prediction models that calculate hourly and daily water needs based on metabolic rate, clothing, and environment. More than 25 years ago, the original Shapiro prediction equation (OSE) was formulated as  $\dot{m}_{sw} (\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}$ , where  $E_{req}$  is required evaporative heat loss and  $E_{max}$  is maximum evaporative power of the environment; OSE was developed for a limited set of environments, exposures times, and clothing systems. Recent evidence shows that OSE often overpredicts fluid needs. Our study developed a corrected OSE and a new  $\dot{m}_{sw}$  prediction equation by using independent data sets from a wide range of environmental conditions, metabolic rates (rest to  $\leq 450 \text{ W/m}^2$ ), and variable exercise durations. Whole body sweat losses were carefully measured in 101 volunteers (80 males and 21 females;  $>500$  observations) by using a variety of metabolic rates over a range of environmental conditions (ambient temperature, 15–46°C; water vapor pressure, 0.27–4.45 kPa; wind speed, 0.4–2.5 m/s), clothing, and equipment combinations and durations (2–8 h). Data are expressed as grams per square meter per hour and were analyzed using fuzzy piecewise regression. OSE overpredicted sweating rates ( $P < 0.003$ ) compared with observed  $\dot{m}_{sw}$ . Both the correction equation (OSE<sub>C</sub>),  $\dot{m}_{sw} = 147 \cdot \exp(0.0012 \cdot \text{OSE})$ , and a new piecewise (PW) equation,  $\dot{m}_{sw} = 147 + 1.527 \cdot E_{req} - 0.87 \cdot E_{max}$  were derived, compared with OSE, and then cross-validated against independent data (21 males and 9 females;  $>200$  observations). OSE<sub>C</sub> and PW were more accurate predictors of sweating rate (58 and 65% more accurate,  $P < 0.01$ ) and produced minimal error (standard error estimate  $< 100 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ ) for conditions both within and outside the original OSE domain of validity. The new equations provide for more accurate sweat predictions over a broader range of conditions with applications to public health, military, occupational, and sports medicine settings.

thermoregulation; modeling; fluid balance; hydration; fluid replacement

DAILY WATER NEEDS can be determined from “minimal” water losses and expected increases in different water flux avenues (11, 22). Metabolic water production and respiratory losses often offset each other, and fecal losses are usually small (11, 22). Urinary losses primarily depend on hydration status and osmolar load, but sweat represents the largest potential avenue of body water loss. Knowledge of sweat losses is therefore critical for calculating water needs for active populations, particularly when exposed to heat stress (11, 22). For example,

military potable water planning relies on water tables generated from existing prediction equations (15, 25), and similar nomograms have been generated for public health purposes (11). Although the sports medicine community recognizes the variability of human sweat losses and the need for individualized fluid replacement guidance (23), realistic sweating estimates for sporting scenarios enable the same water planning capability as in military logistics and facilitate accuracy of phenomenological modeling in sport (14). There also are applications for occupational settings (12) and disaster relief efforts.

The Institute of Medicine (IOM) recently set U.S. Dietary Reference Intake (DRI) standards for water and electrolytes (11). The IOM used the original Shapiro equation (OSE) (28) to estimate sweating rates and calculate daily water needs, as well as daily sodium losses, over a broad range of activity levels and environmental conditions. The OSE was selected because it was the best equation available at the time, but, because of its limitations, the IOM panel determined a need for improvements in the “development of capabilities to predict hourly and daily water requirements based on metabolic rate, climatic conditions, and clothing” (11). The OSE (28) is a sequel to the Givoni-Goldman model to predict core temperature (6). It was developed from laboratory experiments on men for energy expenditures ranging from  $\sim 75 \text{ W}$  (rest) up to  $475 \text{ W}$  (moderate metabolic intensity) over a range of environmental conditions [20–54°C and 10–94% relative humidity (RH)] while wearing shorts and a T-shirt or what is now obsolete military clothing and equipment (27, 28). The original derived equation is shown below:

$$\text{OSE: sweating rate } (\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455} \quad (1)$$

where  $E_{req}$  is the evaporation required to maintain heat balance at any given core temperature and  $E_{max}$  is the maximal evaporative capacity of the environment. Equation 1 has been used widely to predict water needs, assuming the fluid intake (l/h) replaces the expected water lost by sweating in a heat-acclimated person [sweating rate  $\times$  body surface area (BSA)  $\times 10^{-2}$ , l/h].

Although  $E_{req}$  is a final outcome solved by the solution of heat balance and is a determinant of those parameters involved in thermoregulation (i.e., skin and core temperature, skin wettedness, and heat production), this variable is not wholly equal to thermoregulatory sweating. Equivalence is based on the efficiency of the sweat secreted to cool the skin. For 100% effectiveness, all sweat must be evaporated at the skin, and any variance in efficiency or heat storage or imbalances or inconsistencies in heat exchange properties can affect the sweat rate equation predictability.

The OSE often overpredicts sweating rates for conditions both within and outside the original experimental  $E_{req}$  and  $E_{max}$  domains of validity (3). Recent tests of its robustness during

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more prolonged exercise bouts ( $>2$  h), higher exercise intensities, cooler temperatures, or modern protective clothing indicate poor agreement between predicted and measured sweat losses (3). Cheuvront et al. (3) found that the overpredictions from use of the OSE were also likely associated with complications attributed directly to non-sweat losses of body mass (NSL). In addition, variability in estimations of dry heat losses (radiant,  $R$  + convective,  $C$ ) and  $E_{\max}$  from a clothed individual can lead to incorrect calculations whenever imprecise heat and vapor transfer coefficients through clothing, determined by use of static manikins, are subsequently applied to dynamic conditions based on variable wind and walking conditions (1, 7, 8, 10). It is imperative that improved equations be developed and validated that predict sweating rates over wider thermal environments, with and without outdoor solar loads, higher metabolic rates, longer work durations, and with contemporary military clothing including the new combat uniform and other modern protective uniforms and equipment (11, 12, 15, 23, 25).

The purposes of this study were 1) to compare the accuracy of OSE with measured sweating rates during extended exercise ( $>2$  h) with higher metabolic rates, contemporary clothing systems including modern body armor, and a broader range of environmental conditions; 2) to develop a new equation that more accurately predicts sweating rates compared with OSE; and, if possible, 3) to develop a correction to OSE, designated as OSE<sub>C</sub>, that is applicable and easily migrated into various existing rational and operational thermal prediction models. The first hypothesis was that OSE overestimates sweating rates over extended periods of exercise and, therefore, leads to excessive estimates of water needs. The second hypothesis was that new and corrected equations, based on a more comprehensive database, would provide a more accurate estimation of water needs to encompass most military (15, 25), occupational (12), and public health scenarios (11), as well as many situations within the sports medicine community (23).

## METHODS

The database consisted of 101 volunteer subjects (80 men and 21 women) with  $>500$  observations included in the data set used to develop the algorithms. Experiments were conducted for the purpose of precisely measuring sweating rates over a broad range of conditions. Each protocol was approved by the appropriate institutional human use review boards, and all volunteers were informed both verbally and in writing of the objectives and procedures of the respective study. No identifications of a given volunteer's personal records were present in the spreadsheet database.

Raw data were obtained from four separate environmental chamber studies and one field study conducted at the U.S. Army Research Institute of Environmental Medicine (USARIEM) and from one environmental chamber study previously conducted at Defence R&D Canada, Toronto (DRDC) (8). Actual sweat losses were carefully measured in all studies by weighing volunteers and accounting and correcting for non-sweat losses of mass, food, and fluid intakes (NSL) (2, 3). In brief, sweat losses were measured by accounting for the change in individual nude body mass (kg) measured on a electronic precision balance scale (Toledo 1D; Worthington, OH; accuracy  $\pm 20$  g) before and after each experiment. Water from premeasured bottles was available to drink at will during all experiments, and a small meal ( $\sim 500$  kcal) was provided during the 8-h experiments. The weights of all food and water consumed and urine voided were measured on an electronic scale (Ohaus E1M210; Nanikon, Switzerland; accuracy  $\pm 1$  g). The weight of any fecal mass was determined from body mass changes before and after void. Total sweat losses

were determined from mass balance using the Peters-Passmore equation (3) and then time weighted to derive rate. The measurements assume that 1 ml of sweat is equal to a mass of 1 g. To summarize, sweat loss (kg) = change in body mass + (solids in – solids out) + (fluids in – fluids out) – (gases in – gases out), where gases refer to CO<sub>2</sub>-O<sub>2</sub> exchange.

These data sets are summarized briefly below. *Data sets I–IV* were used to develop the new and corrected sweating rate prediction equations, whereas *data sets V and VI* were used for cross-validation.

*Data set I.* Details can be found in Montain et al. (15). Data were obtained from 19 previously heat-acclimatized individuals (13 men and 6 women) who completed all experiments dressed in hot weather battle dress uniforms [BDU; with a clo (clothing insulation coefficient) value of 1.08 and a  $i_{m/clo}$  (evaporative impedance coefficient) value of 0.49]. Volunteers completed 12 randomized exercise-heat stress trials in which they walked at three exercise intensities characterized as easy, moderate, and heavy work intensities set at 250, 425, and 600 W in three humid environments ( $T_a = 28^\circ\text{C}/P_w = 2.8$  kPa,  $T_a = 32^\circ\text{C}/P_w = 3.57$  kPa, and  $T_a = 36^\circ\text{C}/P_w = 4.45$  kPa, where  $T_a$  is ambient temperature and  $P_w$  is water vapor pressure). In the other three heat stress trials, volunteers walked at 425 W in three dry environments ( $T_a = 36^\circ\text{C}/P_w = 1.47$  kPa,  $T_a = 41^\circ\text{C}/P_w = 1.95$  kPa, and  $T_a = 46^\circ\text{C}/P_w = 2.53$  kPa). Dry heat stress trials were completed following a humid test condition. Appropriate work-rest cycles for each exercise task were initially determined using a current model (19) for a predicted 2-h total exposure. In the minority of heat/exercise trials where mean skin temperature ( $T_{sk}$ ) was not available,  $T_{sk}$  was estimated using Saltin's (20) equation:  $T_{sk} = 0.215T_a + 26.6$  ( $\pm 0.5$  SEE), where SEE is standard error estimate, to calculate the pertinent heat balance equation parameters essential for model algorithms.

*Data set II.* Details can be found in Cheuvront et al. (3). Thirty-nine healthy volunteers participated in this study specifically designed to obtain data for the development of an improved sweat rate prediction equation. The clothing ensemble was the U.S. Army woodland BDU with field cap, sleeves down [ $clo = 1.08$ ,  $i_{m/clo} = 0.49$  at wind speed ( $V$ ) = 1 m/s], and athletic shoes. Test sessions lasted either 2 or 8 h. Twenty-one volunteers (16 men and 5 women) participated in the 2-h trials, and physical characteristics for this group are shown in Table 1. Eighteen different volunteers (17 men and 1 woman) completed the 8-h trials, and their characteristics are shown in Table 2. Tables 1 and 2 also describe the seven different levels of environmental stress, work-rest cycles, metabolic rate at each exercise intensity, and measured sweat loss. In the 2-h trials, volunteers were not heat acclimated, whereas in the 8-h trials, volunteers were heat acclimated.

*Data set III.* Details can be found in Cheuvront et al. (2). Thirteen men participated in this study specifically designed to obtain data for the development of an improved sweating rate prediction equation. Each subject completed three trials consisting of 4 h of treadmill walking ( $\sim 500$  W) in a hot, dry environment ( $T_a = 35^\circ\text{C}$ ,  $P_w = 1.7$  kPa,  $V = 1$  m/s). The U.S. Army BDU was worn in all three trials: alone (trial BDU:  $clo = 1.12$ ,  $i_{m/clo} = 0.44$  at  $V = 1$  m/s), combined with interceptor body armor (trial IBA:  $clo = 1.35$ ,  $i_{m/clo} = 0.27$  at  $V = 1$  m/s), or combined with IBA and a spacer vest (trial SP:  $clo = 1.28$ ,  $i_{m/clo} = 0.32$  at  $V = 1$  m/s). In the BDU trial, the BDU was worn with field cap, sleeves down, and athletic shoes. The IBA vest included front and rear ballistic protective inserts (throat and groin protection excluded). The total weight of the vest as used was 7.5 kg, and it covered  $\sim 25\%$  of the total BSA. In trial SP, the spacer was a 1-cm-thick vest of proprietary knit fabric worn between the IBA and uniform. The spacer vest is designed to produce an air channel that theoretically increases the potential for ventilation and evaporative cooling of the torso.

*Data set IV.* Details can be found in Chinevere et al. (4). One woman and five men did continuous treadmill exercise ( $\sim 400$  W) for 2 h while dressed in BDU plus IBA, as in *data set III* (IBA:  $clo = 1.35$ ,  $i_{m/clo} = 0.27$  at  $V = 1$  m/s). Environmental conditions were  $T_a = 30^\circ\text{C}/P_w = 2.1$  kPa,  $T_a = 35^\circ\text{C}/P_w = 4.27$  kPa, and  $T_a = 40^\circ\text{C}/P_w = 1.47$  kPa. All other procedures and details were as outlined in *Data set III*.

Table 1. Key descriptive and physiological data for 2-h experiments in data set II-B used in developing the present equation

Trial	T <sub>a</sub> , °C	P <sub>w</sub> , kPa	Work:Rest Cycles, #(min)	n	BSA, m <sup>2</sup>	Body Weight, kg	T <sub>sk</sub> , °C	V̇O <sub>2</sub> , l/min	SR, l/h
A1	15	0.85	2× (50:10)	12M	1.94±0.15	77.6±8.8	29.3±1.0	0.94±0.14	0.135±0.079
				4F	1.70±0.03	64.3±4.2	28.2±0.82	0.79±0.17	0.188±0.086
A	15	0.85	2× (50:10)	13M	1.96±0.14	79.7±9.3	28.7±0.8	1.49±0.17	0.305±0.136
				2F	1.68	60.4	28.7	1.3	0.319
B	15	0.85	2× (50:10)	13M	1.96±0.14	79.7±9.3	29.1±1.0	1.99±0.21	0.472±0.170
				2F	1.68	6.4	27.5	1.57	0.424
C	20	1.17	2× (50:10)	14M	1.96±0.14	80.7	31.1±0.8	1.08±0.15	0.220±0.089
				1F	1.63	56.9	31.34	0.81	0.165
D	20	1.17	2× (50:10)	15M	1.98±0.13	80.9±8.9	30.2±1.08	1.45±0.19	0.410±0.177
				4F	1.67±0.04	62.6±5.7	30.4±0.47	1.14±0.13	0.346±0.084
E	20	1.17	2× (50:10)	15M	1.97±0.14	80.5±9.4	30.3±1.15	2.03±0.26	0.625±0.199
				2F	1.69	63.5	29.6	1.49	0.498
F	25	1.59	2× (50:10)	11M	1.96±0.11	80.2±8.9	31.8±0.55	1.03±0.16	0.321±0.102
				2F	1.68	60.35	31.1	0.84	0.421
G	25	1.59	2× (50:10)	9M	1.95±.12	80.0±9.5	31.5±0.92	1.47±0.20	0.479±0.171
				1F	1.73	63.8	30.9	1.26	0.515
H	25	1.59	2× (50:10)	10M	1.95±0.11	80.5±8.9	32.1±0.62	1.99±0.27	0.755±0.237
				1F	1.63	56.9	31.6	1.54	0.558
I	30	2.12	2× (50:10)	10M	1.95±0.11	80.5±8.9	33.5±0.75	1.98±0.26	0.935±0.317
				1F	1.63	56.9	33.1	1.45	0.702

Values are means ± SD except when  $n < 3$ ;  $n$  = no. of subjects (M, male; F, female) completing the experiment. T<sub>a</sub>, air temperature; P<sub>w</sub>, ambient water vapor pressure; T<sub>sk</sub>, mean skin temperature; SR, observed sweating rate. Wind speed for all experiments was 1 m/s. Trial letters are as presented in Cheuvront et al. (3).

**Data set V.** An archival raw data set was obtained from a US-ARIEM field study conducted at Ft. Bliss, TX, to determine sweating rates during walking exercise in mild to moderate solar load conditions. Details can be found in Santee et al. (21). In brief, eight males [average body mass = 80.5 ± 15.2 kg (SD); BSA = 1.97 ± 0.18 m<sup>2</sup> (SD)] walked at 2 miles/h for 12 miles (24 min of continuous exercise with a 6-min break) on a calibrated track for 6 h. Subjects carried a 22-kg pack, and average heat production was maintained at ~350 W. Standard chemical protective clothing designated as mission-oriented protective posture (MOPP) was worn during the walks. The clothing system configurations consisted of *MOPP 0* (BDU: clo = 1.34 and  $i_{m/clo}$  = 0.31 at  $V$  = 1 m/s), *MOPP 1* (clo = 1.97 and  $i_{m/clo}$  = 0.17 at  $V$  = 1 m/s), and *MOPP 4* (clo = 2.44 and  $i_{m/clo}$  = 0.12). Volunteers walked at night and day in the various MOPP clothing configurations. Daytime ambient conditions were T<sub>a</sub> = 23°C/P<sub>w</sub> = 0.2 kPa, with a mixed solar load (diffuse and direct) estimated by the effective radiant field (ERF) at 500 W/m<sup>2</sup>, resulting in an operative temperature (T<sub>o</sub>) of 49.5°C (1, 5, 9, 27).

**Data set VI.** Raw data from an international cooperative data sharing program (8) were used to test the developed equations. Data from 13 males and 9 females (the latter in the follicular phases of their menstrual cycle) were compiled to compare the various equations. Physical characteristics (±SD) were body mass = 82.7 ± 12.5 kg and BSA = 2.01 ± 0.16 m<sup>2</sup> for males and body mass = 60.4 ± 8.9 and

BSA = 1.66 ± 0.15 m<sup>2</sup> females. The ambient conditions were T<sub>a</sub> = 40°C and P<sub>w</sub> = 1.47 kPa at  $V$  = 0.4 m/s. Subjects exercised for 2 h (4 exercise-rest cycles of 15:15 min) or until their rectal temperature reached a peak value of 39.5°C or heart rate became elevated higher than 180 beats/min for 3 min. Average metabolic rate was ~365 and ~338 W for the male and female groups, respectively. Subjects were dressed in the Canada nuclear, biological, chemical (NBC) protective clothing system previously evaluated using USARIEM manikin procedures and found to have heat transfer characteristics of clo = 1.88 and  $i_{m/clo}$  = 0.18 at  $V$  = 1 m/s (1).

**Heat transfer analyses.** Each element of the comprehensive heat balance equation (5) was determined from the raw data and concatenated together in a unified spreadsheet (Microsoft Excel) for later analysis. The techniques documented by Gagge and Gonzalez (5) and Breckenridge (1) were applied to the raw spreadsheet values to determine respective heat and mass transfer coefficients for calculating dry heat exchange ( $R + C$ ),  $E_{max}$ , and other variables in the heat balance equation. Clothing heat and evaporative potential parameters were determined on a regionally heated, articulated manikin at various wind speeds. A heat balance analysis was carried out for each individual response.

In general, heat balance (in W/m<sup>2</sup>) of the human body surface area can be expressed by

Table 2. Key descriptive and physiological data for 8-h experiments in data set II-B used in developing the present equation

Trial	T <sub>a</sub> , °C	P <sub>w</sub> , kPa	Work:Rest Cycles, #(min)	n	BSA, m <sup>2</sup>	Body Weight, kg	T <sub>sk</sub> , °C	V̇O <sub>2</sub> , l/min	SR, l/h
J	40	2.95	6× (60:20)	12M	2.03±0.14	84.7±12.4	35.9±0.61	1.11±0.21	0.667±0.114
				1F	1.63	55.3	36.2	0.775	0.404
K	35	1.69	6× (60:20)	15M	1.97±0.12	80.2±9.8	34.4±0.5	1.39±0.21	0.569±0.062
				1F	1.62	54.8	34.12	0.92	0.405
L	35	1.69	6× (60:10)	15M	1.99±0.15	81.7±12.9	33.9±0.5	1.05±0.15	0.452±0.058
M	27	1.43	6× (60:20)	14M	1.98±0.15	81.7±12.9	32.3±0.6	1.44±0.23	0.406±0.096
				1F	1.63	55.7	31.83	0.96	0.263
N	27	1.43	6× (60:20)	12M	1.98±0.16	81.1±13.9	32.7±0.64	1.05±0.14	0.269±0.05
				1F	1.63	55.6	33.0	0.770	0.153
O	20	1.17	6× (60:20)	12M	1.97±0.16	80.9±14	30.6±1.15	1.39±0.22	0.229±0.087
				1F	1.63	55.1	30.3	0.847	0.162

Values are means ± SD except when  $n < 3$ ;  $n$  = no. of subjects completing the experiment. All subjects were previously heat acclimated. Wind speed for all experiments was 1 m/s. Trial letters are as presented in Cheuvront et al. (3).



$S$  = net metabolic heat flux – skin insensible heat flux  
– skin sensible heat loss, (2)

$$S = (M \pm Wk) - E \pm (R + C + K) \quad (3)$$

where  $S$  is the time rate of change of body heat (gain or loss). If positive, the body is increasing its core and skin temperature, and these can be estimated using  $M$ , the rate of metabolic heat production;  $Wk$ , the rate of accomplished mechanical work;  $E$ , the rate of evaporative heat loss via regulatory sweating from eccrine sweat glands, diffusion ( $E_{dif}$ ), respiration ( $E_{res}$ ), and metabolic heat loss ( $m_r$ );  $C$ , the rate of convective heat loss from the total body surface and respiration;  $R$ , the rate of radiant heat loss (or gain from) the surrounding surfaces, and  $K$ , the rate of conductive heat flux to or from the environment.

**Radiation exchange.** In any thermal environment, a linear radiation transfer coefficient ( $h_r$ , in  $W \cdot m^{-2} \cdot ^\circ C^{-1}$ ) may be derived (1, 5) by

$$h_r = 4\alpha\sigma(A_r/A_D) \cdot f_{cl} \cdot (5.67 \times 10^{-8}) [(T_o + T_{surf})/2 + 273.15]^3 \quad (4)$$

where  $\alpha$  is the skin or clothing absorptance for the radiation exchange to the ambient,  $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8}$ , in  $W \cdot m^{-2} \cdot K^{-4}$ ), and the factor  $A_r/A_D$  is the ratio of the effective radiating area of the human body to the total body surface area as measured by the Dubois surface area formula (0.72 for standing individuals). The interior environmental temperature is composed of an average of the operative temperature ( $T_o$ ) plus all the surface temperatures ( $T_{surf}$ ) including any clothing surface temperature ( $T_{cl}$ );  $f_{cl}$  represents a factor that increases the effective  $A_r$  of the body surface by some 15–20% per clo (1, 5). Mean clothing surface is derived from  $T_{sk}$  in the relationship  $[T_o + F_{cl}(T_{sk} - T_o)]$ . For shorts and a T-shirt,  $F_{cl} = 1$  and  $T_{cl} = T_{sk}$ .

**Convective exchange.** This heat exchange factor is represented by free convection and forced convection via increased metabolic activity or increased room air movement artificially. Two equations for estimating the convective heat transfer coefficient ( $h_c$ , in  $W \cdot m^{-2} \cdot ^\circ C^{-1}$ ) have been formulated based on a composite of free and forced convection (1, 5, 9):

$$h_c = 1.2 [(M - 50)(P_B/760)]^{0.39} \quad (5)$$

where  $M$  is metabolic heat production (in  $W/m^2$ ) and  $P_B$  is the barometric pressure in Torr (1 kPa is equivalent to 7.5 Torr at sea level). Alternatively,  $h_c$  for fan-generated forced convection, in which ambient air movement ( $V$ , m/s) is the main factor affecting convective heat exchange, can be expressed by either

$$h_c = 8.6 [V \cdot P_B/760]^{0.53}, \quad (6)$$

when persons are dressed in shorts and a T-shirt, or by

$$h_c = 12.7 [V \cdot P_B/760]^{0.50}, \quad (6')$$

when persons are clothed (5).

**Insensible heat loss.** Procedures applicable to clothing heat transfer were used to calculate environmental heat exchange and applied to the respective data for each individual (1, 5, 6, 9). These methods consider the skin, clothing, and environment as a total system and the constants defining insulation and water vapor transfer as functions of effective air movement ( $V_{eff}$ ). The term  $V_{eff}$  is the sum of air motion around a stationary object plus the speed at which the object is moving.  $I_T(V_{eff})$  is the total resistance to heat flow by radiation and convection (in clo units, 1 clo is equivalent to  $0.155 m^2 \cdot K \cdot W^{-1}$  or thermal conductance of  $6.45 W \cdot m^{-2} \cdot ^\circ C^{-1}$ ), and  $i_m(V_{eff})$  is the relative total resistance to evaporative heat transfer (zero to one, dimensionless). In heat balance calculations,  $i_m$  is not used alone but as a latent heat transfer coefficient ( $i_m/I_T$ ), separately evaluated using an articulated, moving, sweating manikin; this latter quantity is considered as a key dynamic constant incorporating both heat and mass transfer via “pumping” through cuffs, vents, and walking;

enthalpic evaporation (7, 10); and relative permeation from skin to each subsequent intrinsic clothing layer, and ultimately to the ambient temperature important in total latent heat transfer efficiency of military clothing present in this study. These factors were not considered in development of the legacy  $E_{max}$  of the Shapiro et al. (28) study and will likely improve the efficacy of the OSE.

Values for  $I_T$  and ( $i_m/I_T$ ) as a function of  $V_{eff}$  were calculated for each clothing system in each calculation of  $E_{req}$  in the heat balance output during each exercise condition or use of body armor and transient dynamic effects. These clothing parameters were ascertained from the following power curves automatically estimated on the sweating, articulated manikin used to evaluate clothing ensembles (1):

$$I_T = A \cdot (V_{eff})^B \quad (7)$$

and

$$(i_m/I_T) = C \cdot (V_{eff})^D \quad (8)$$

where the coefficients  $A$  and  $C$  are the values for  $I_T$  and ( $i_m/I_T$ ) when  $V_{eff} = 1.0$  m/s, and the coefficients  $B$  and  $D$  are slopes of plots of  $\ln(I_T)$  and  $\ln(i_m/I_T)$  vs.  $\ln(V)$ .

The intrinsic thermal insulation value,  $I_{int}(V)$ , was obtained by subtracting the value of the insulation of the air boundary layer,  $I_{acl}$ , from  $I_T$ :

$$I_{int} = I_T - \frac{1}{(f_{acl}) \cdot (0.61 + 1.87 \sqrt{V_{eff}})} \quad (9)$$

where  $f_{acl}$  in Eq. 9 is the increase in surface area due to clothing that is estimated (1, 5) using

$$f_{acl} = 1 + (0.2 \cdot A_D). \quad (10)$$

The algebraic sum of the total (dry) heat loss by radiant and convective heat exchange ( $R + C$ ), in watts (1, 9), therefore, is

$$\text{Dry} = (R + C) = \frac{6.45 \cdot A_D \cdot f_{acl}}{I_{int}} \left[ \frac{0.61(\bar{T}_{sk} - \bar{T}_r) + \sqrt{V} \cdot (T_{sk} - T_a)}{\frac{1}{I_{int}} + f_{acl}(0.61 + 1.87 \sqrt{V})} \right] \quad (11)$$

Insensible heat loss ( $E$ ) was determined by the rate of sweat secretion ( $\dot{m}_{sw}$ ) and the maximal rate of evaporative heat loss from a fully wetted skin surface ( $E_{max}$ ).  $E_{max}$  is a function of the vapor pressure gradient between the fully wetted skin surface and the air ( $P_{s,sk} - P_w$ ), the evaporative heat transfer coefficient ( $h_e$ ), and  $i_m$ , Woodcock's dimensionless factor for permeability of water vapor through clothing (1, 5, 6). The evaporative heat transfer coefficient,  $h_e$ , is directly related to the convective heat transfer coefficient,  $h_c$ , by the Lewis relationship (LR;  $2.2^\circ C/Torr$  or  $16.5 K/kPa$ ) (5, 7, 10).

When evaporation is not restricted by clothing or the environment, then

$$E_{sk} = \dot{m}_{sw} \cdot \lambda \quad (12)$$

where  $\dot{m}_{sw}$  is in grams per hour and  $\lambda$  is the heat of vaporization for sweat at  $35^\circ C$  ( $0.68 W \cdot h \cdot g^{-1}$ ), as determined by Wenger (31). The expression for skin evaporative heat loss ( $E_{sk}$ ) under conditions where evaporation of sweat is restricted, particularly during exercise with impermeable clothing (1, 5, 7, 10) and where there is frank dripping ( $E_{drip}$ ) or wasted sweat due to skin wettedness ( $\omega > 1.0$ ) (5, 7), is

$$E_{sk} = (0.06 + 0.94\omega) \cdot A_D E_{max} = (LR \cdot 6.45) A_D \cdot (i_m/I_T) \cdot (P_{s,sk} - P_w), \quad (12')$$

when  $E_{max} \leq -\dot{m}_{sw} \cdot \lambda$ , where  $A_D$  is the DuBois surface area ( $m^2$ ) (1, 5) and  $P_{s,sk}$  (in Torr) is the vapor pressure of saturated air at skin temperature.  $P_{s,sk}$  is related to  $T_{sk}$  by the Antoine equation (5, 7):

$$P_{s,sk} = \exp\left(18.6686 - \frac{4030.183}{T_{sk} + 235}\right) \quad (13)$$

Respiratory heat loss is also a part of the NSL avenue.  $C_{res}$  and  $E_{res}$  are directly related to ventilation rate and vary as a function of aerobic exercise intensity ( $M_{tot}$ ) up to maximal levels. The combined equation for estimating respiratory loss by convection and evaporation ( $C_{res} + E_{res}$ , g/min) was taken from Mitchell et al. (18), applicable for high levels of exercise as

$$C_{res} + E_{res} = 0.019 \cdot \dot{V}_{O_2}(44 - P_w) \quad (14)$$

or

$$(C_{res} + E_{res}) = A_D \cdot M_{tot} [0.0014 \cdot (34 - T_a) + 0.0023 (44 - P_a)] \quad (14')$$

$E_{res}$  is also modified by a constant (F) for high levels of exercise (20) so that if  $\dot{V}_{O_2} < 2.6$  l/min,  $F = 1$ , and if  $\dot{V}_{O_2} > 2.6$ ,  $F = 1 + 0.106(\dot{V}_{O_2} - 2.6)^2$ .

Evaporative heat loss corrected for metabolic heat losses by  $CO_2$  and  $O_2$  ( $\dot{m}_{res}$ , g/min) was calculated using the following assumptions (20). If the respiratory exchange ratio (R) is equal to 1,

$$\dot{m}_{res} = \dot{V}_{O_2}(R \cdot \rho_{CO_2} - \rho_{O_2}) \quad (15)$$

where  $\rho_{CO_2}$ , the density of  $CO_2$ , = 1.96 g/l STPD;  $\rho_{O_2}$ , the density of  $O_2$ , = 1.43 g/l STPD, and  $\dot{m}_{res} = 0.53(\dot{V}_{O_2})$ . If  $R > 1$ ,

$$\dot{m}_{res} = \dot{V}_{O_2}(R \cdot 0.53) \quad (15')$$

**Statistical procedures and quasi-Newton analyses.** All concatenated data from the spreadsheet were analyzed using fuzzy piecewise linear and nonlinear regression analyses (29, 30) with various statistical modules (Statistica, version 7; Tulsa, OK) to establish appropriate change points in sweat loss per time points in the data set, coded by trial, sex, and individual subject number, and to obtain intercepts for independent parameters derived from the heat balance equation ( $E_{req}$ ,  $E_{max}$ ). A quasi-Newton method was employed to derive regression parameters. In this method, the slope of a function at a particular locus is computed as the first-order derivative of the function (at that locus). The "slope of the slope" is the second-order derivative, which documents how fast the slope is changing at the respective point and in which direction. The quasi-Newton method will, at each step, evaluate the function at different points to estimate the first-order and second-order derivatives. It will then use this information to follow a path toward the minimum of the loss function (29). The fuzzy piecewise routine is more robust than conventional methods, is not sensitive to outliers, and tracks transient responses or irregular data especially found in this data set due to heavy-intensity exercise and disparate sweating patterns. The technique, as constructed for this study, is also suitable for long-term time series predictions of specific variables (29).

OSE-predicted sweating rates were initially compared against observed data to obtain residual analyses to ascertain how much OSE deviated from the observed data. Next, the new fuzzy piecewise (PW) equation (29) was compared with OSE and the observed raw data secured for each separate trial. Corrections to OSE (designated as OSE<sub>c</sub>) were derived by independent piecewise regression analyses incorporating an iterative approach to obtain the most optimum equation (exponential, log fit) and test the significance of the derived regression coefficients (Wald statistic) that fit the database (17). The conditions were that the standard error estimate (SEE) of a new equation (PW) should not deviate from the observed data or the independently determined fuzzy piecewise equation by more than  $\pm 125$  g·m<sup>-2</sup>·h<sup>-1</sup> (roughly less than  $\pm 0.24$  l/h for a person with 1.9 m<sup>2</sup> BSA). This is a more liberal criterion than the one used previously by Cheuvront et al. (3), which assigned an a priori "zone of indifference" of  $\pm 0.125$  l/h (i.e.,  $\sim 65.8$  g·m<sup>-2</sup>·h<sup>-1</sup> for a 1.9 m<sup>2</sup> BSA) resulting in

band differentiation of some  $\pm 2$  g/min over an extended period. The higher level relaxes the prediction of  $E_{req}$  that can be calculated from the heat balance equation. This decision is based on the fact that the calculation of evaporative heat exchange parameters in clothed individuals are not exact, and indeed, the latent heat of evaporation is variable, particularly during cold ambient conditions (10), and a model's accuracy predicting sweating rate is not always tied in with evaporative cooling efficiency (7, 9, 10), particularly when  $\omega$  is 100% for an extended period.

Data are expressed as means  $\pm$  SD, means  $\pm$  SE, or means  $\pm$  95% confidence interval (CI). The differences in observed sweating rate, heat production, and the output from the various prediction equations were analyzed using a factorial ANOVA design to include main effects and interactions for categorical predictors (sex, all trials). Both univariate (using a given single continuous dependent variable) and multivariate designs (multiple continuous dependent variables) were analyzed. If a significant  $F$  value was found for a given dependent variable, the more conservative Bonferroni adjustment procedure (17) was used as a post hoc approach to locate critical differences at  $P < 0.01$  and considered statistically significant; correlations with a  $P$  value  $> 0.01$  (including those with  $P$  values between 0.01 and 0.05) were considered nonsignificant.

We determined the prediction accuracy of a given equation, compared with observed sweating rates from composite trial data, using analyses of differences of mean error rates as described by Lim et al. (13). For each trial data set, the algorithm with the lowest error rate compared with the observed sweating rate is assigned rank one, the second lowest rank two, and so on, with average ranks assigned in case of ties as formulated by Lim et al. (13). The Friedman ANOVA nonparametric test (17) was then used to test differences in mean error rate ranks for each algorithm.

Finally, an independent cross-validation analysis of the fuzzy piecewise equation was executed against two independent archival data sets: a field study in which a group of men walked in NBC clothing (at MOPP levels 0, 1, and 4) (19, 21) and a laboratory study in which men and women walked in NBC protective clothing conducted at DRDC (8); experimental details are presented above.

## RESULTS

Table 3 provides the calculated mean heat production ( $M$ , W/m<sup>2</sup>) and observed (measured) sweating rates (g·m<sup>-2</sup>·h<sup>-1</sup>)  $\pm$  SE for *data sets I–IV* (METHODS) separated by sex. After ANOVA tests, a Bonferroni post hoc (17) analysis was performed. The only significant difference in measured sweating rates between men and women occurred with the moderate-intensity exercise trials in *data set I* ( $P < 0.01$ ).

Figure 1 plots the individual sweating rates (Fig. 1A) for *data sets I–IV* and the calculated residuals (Fig. 1B) used to evaluate OSE and develop a new prediction equation. Noticeable are the high points and depressions in sweating rates (Fig. 1A) due to variation in exercise intensity and environmental conditions (particularly cooler environments) among *data sets I–IV*. The residual values in Fig. 1B (comparing measured minus predicted sweating rates for each data point) demonstrate that some predicted values were overestimated by 100% or more, especially during higher exercise intensities (*data set I*), and underestimated by 80% during cooler trials (*data set II*). However, for many of the data sets, OSE was within  $\pm 20\%$  of observed data with residuals distributed symmetrically around the zero line, particularly during low exercise intensities and mild heat stress conditions.

The data set was next examined to develop optimum regression parameters that would satisfy all data sets sufficiently (within a SEE of  $\pm 125$  g·m<sup>-2</sup>·h<sup>-1</sup> criterion and coefficient of

Table 3. Heat production and observed sweating rate

Description	Data Set	Sex	<i>M</i> , W/m <sup>2</sup>		OSR, g·m <sup>-2</sup> ·h <sup>-1</sup>		<i>n</i>
			Mean	±SE	Mean	±SE	
Easy work	I-L	M	163.04	8.87	295.21	18.35	32
	I-L	F	148.60	12.18	208.31	25.17	17
Moderate work	I-M	M	224.00	5.84	407.13	12.06*	74
	I-M	F	252.24	8.37	332.59	17.29*	36
Heavy work	I-H	M	329.18	8.25	443.96	17.06	37
	I-H	F	357.61	11.83	356.88	24.46	18
BDU	II-B	M	252.42	3.53	224.72	7.30	202
	II-B	F	231.82	10.04	210.19	20.75	25
Moderate work, BDU	III-B	M	284.66	13.92	353.21	28.78	13
	III-B	F	NA	NA	NA	NA	1
Moderate work, BDU+ body armor	III-I	M	287.79	13.92	407.64	28.78	13
Moderate work, BDU+ body armor	III-I	F	NA	NA	NA	NA	1
Moderate work, BDU+ body armor with vest	III-S	M	289.52	13.92	420.47	28.78	13
Moderate work, BDU+ body armor with vest	III-S	F	NA	NA	NA	NA	1
Easy work, BDU+ body armor with vest	IV	M	213.07	12.96	362.12	26.79	15
Easy work, BDU+ body armor with vest	IV	F	193.80	28.98	483.49	59.91	3

Values are least-squares means between males and females for combined data, followed by SE values; *n* = no. of observations. *M*, heat production; OSR, observed sweating rate; BDU, battle dress uniform; NA, not estimated due to small sample in trial. \**P* < 0.01 (Bonferroni; post hoc test within trial cells).

determination  $R^2 \geq 0.8$ ) as shown in Fig. 2, A–C. Figure 2A shows that OSE accounted for 74% of the variance but had a high SEE (181 g·m<sup>-2</sup>·h<sup>-1</sup>). Since the data were collected at different times and contained disparate conditions, a nonlinear fuzzy piecewise regression employing a quasi-Newton solution provided the best resolution (29, 30). Fuzzy piecewise regression using the  $E_{\text{req}}$  and  $E_{\text{max}}$  values as input parameters produced the following equation (PW):

$$\text{Sweating rate (g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 147 + 1.527 \cdot E_{\text{req}} - 0.87 \cdot E_{\text{max}} \quad (16)$$

Figure 2B provides the comparison of output from PW with respect to observed sweating rates for *data sets I–IV*. PW accounted for 78% of the variance for the same data with a much smaller SEE (72 g·m<sup>-2</sup>·h<sup>-1</sup>). For this analysis,  $E_{\text{req}}$  and  $E_{\text{max}}$  were determined from the individual heat balance equation by using new heat and mass transfer coefficients as explained in METHODS and were transformed to sweating rate by division of  $\text{W} \cdot \text{m}^{-2} / (0.68 \text{ W} \cdot \text{h} \cdot \text{g}^{-1})$  (31).

Since it was determined that the output from OSE would probably not completely unify the data set and predict adequately because of the imprecise clothing coefficients determined from a static manikin and the low wind speeds (10) applied to the heat balance analyses in OSE (28), a similar iterative approach was run to correct the OSE by using individual analysis of  $E_{\text{req}}$  and  $E_{\text{max}}$  using modern analytic approaches to the clothing coefficients in the data sets (METHODS). An exponential correction to Eq. 1 was successfully obtained after various statistical algorithm solutions were attempted. This solution produced the following correction applied to the OSE equation to predict sweating rates:

$$\text{OSE}_C (\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 147 \cdot \exp^{(0.0012 \cdot \text{OSE})} \quad (17)$$

where OSE in Eq. 17 is the uncorrected output from the original Eq. 1 (28).

$E_{\text{req}}$  and  $E_{\text{max}}$  signify the new values obtained with the new clothing coefficients. Figure 2C plots the comparison of output from  $\text{OSE}_C$  with respect to observed sweating rates for all data sets.  $\text{OSE}_C$  accounted for ~64% of the variance but with a

small SEE ( $\pm 98.3 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ ). Noticeably, the regression coefficient (0.603) is significantly smaller (*P* < 0.01, Wald statistic) than the OSE output equation.

Figure 3 provides a histogram comparing mean outputs for OSE,  $\text{OSE}_C$ , and PW equations against measured sweating rates for *data sets I–IV*. The OSE demonstrated the widest variability compared with the measured data and was markedly elevated for the moderate- and high-intensity exercise experiments. However,  $\text{OSE}_C$  and PW prediction equations tracked measured sweating rates remarkably well.

**Cross-validation analyses.** To evaluate the prediction equations against averaged responses from independent data sets, we made comparisons with two additional data sets: one an outdoor field study (*data set V*) and another conducted in an environmental chamber (*data set VI*). In both studies, volunteers wore a variety of clothing configurations, including NBC protective clothing (see METHODS). Figure 4 plots the mean observed sweating rates and mean predicted values during a field study test (*data set V*) (21). In general, PW and  $\text{OSE}_C$  equations were not significantly different from the experimentally observed sweating rates. The OSE, however, consistently predicted responses too high within and between the various trials except for the day with solar load and night trials when subjects wore the MOPP level 1 clothing configuration. Figure 5 plots the mean observed sweating rates and mean predicted values during the environmental chamber study (*data set VI*). The OSE predicted sweating rates higher than measured data consistently within the two male and female groups of subjects (*P* < 0.01).

## DISCUSSION

This study compared the accuracy of OSE to a new equation (PW) for predicting sweating rate during extended exercise (2 to 8 h) with higher metabolic rates and contemporary clothing systems including body armor and developed a correction to OSE ( $\text{OSE}_C$ ) that is applicable and easily migrated into various existing rational and operational thermal models. The hypotheses, based on current research and literature results (3, 15), were that OSE overestimates sweating rates and that improved



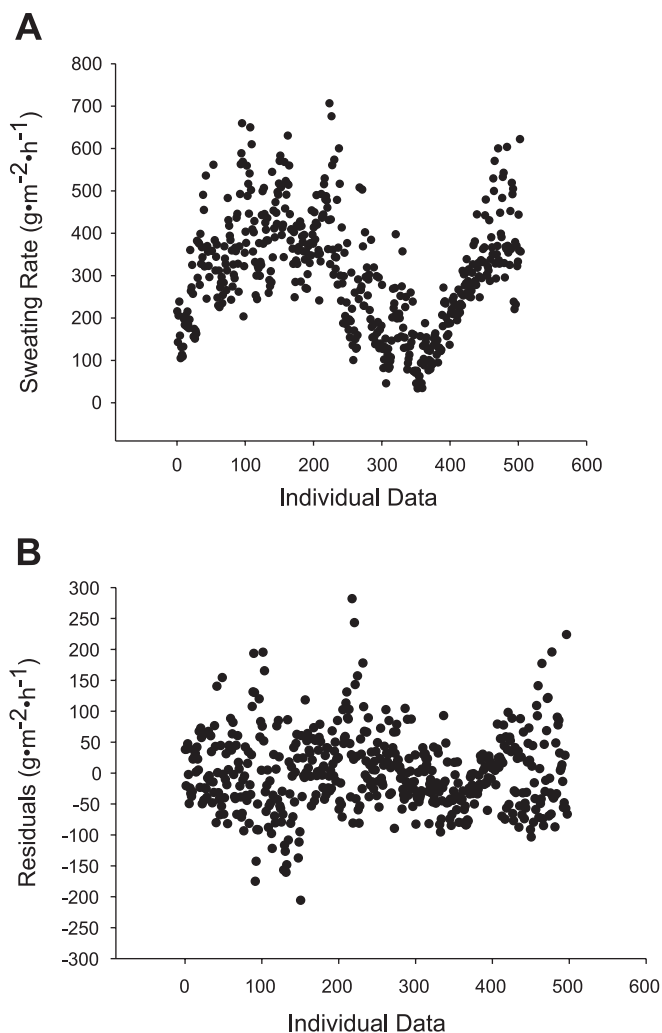


Fig. 1. A: individual sweating rate measurements from data sets I–IV. B: residual plot of original Shapiro equation output (OSE) (28) vs. observed data for each individual ( $n = 504$ ).

prediction equations could be developed. The newly developed  $\text{OSE}_c$  and PW equations were better predictors of sweating rates (58 and 65% more accurate,  $P < 0.01$ ) and produced minimal error ( $\text{SEE} < 100 \text{ g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) for conditions both within and outside the original OSE domain of validity, which include cooler environments, higher metabolic rates, longer work durations, and modern protective clothing and equipment ensembles.

The rationale to develop a predictive equation for sweating rate (and, thereby, water needs) was a unique concept at the time that OSE was developed and one that had not been expanded on until this effort. The OSE predicts sweat losses, and thus water needs, over wide thermal environments by knowledge of only two key variables,  $E_{\text{req}}$  and  $E_{\text{max}}$ , which

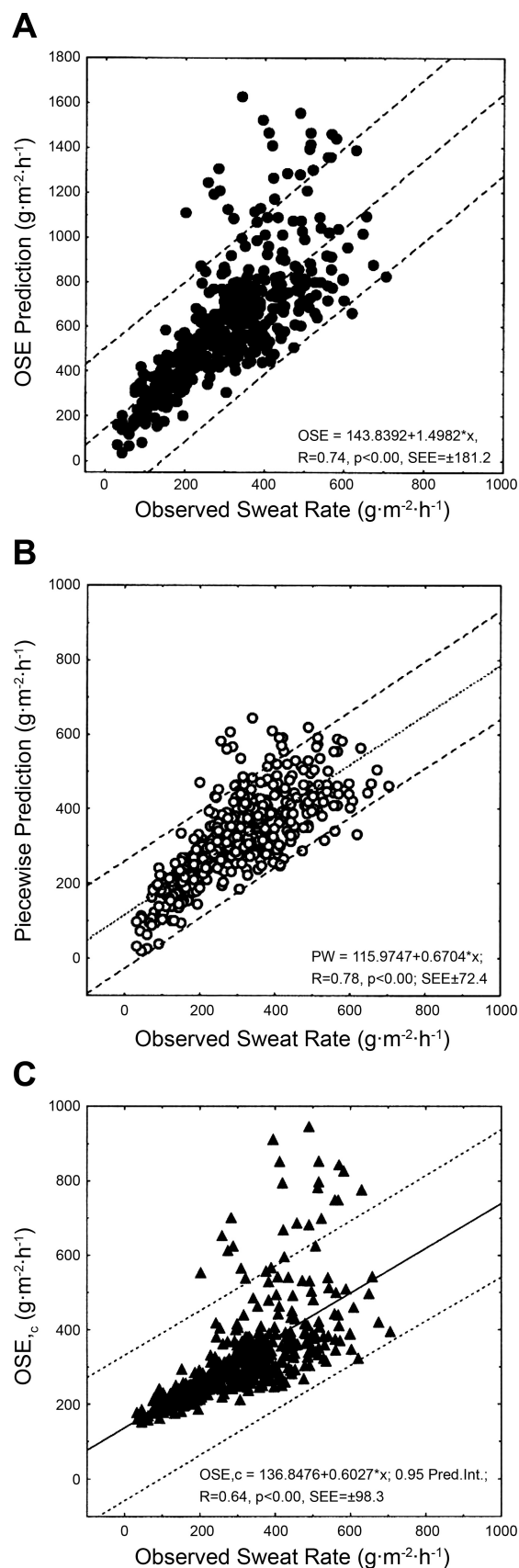


Fig. 2. Linear plots of prediction equation output vs. observed sweating rates. A: original Shapiro equation (OSE). B: piecewise equation (PW). C: corrected OSE ( $\text{OSE}_c$ ). The correlation between measured sweating rates and predicted sweating rates from each equation is indicated in each panel. Fuzzy PW is a nonlinear transient analysis; linear correlations are shown only for relative comparison of accuracy between the various output algorithms. SEE, standard error of the estimate.

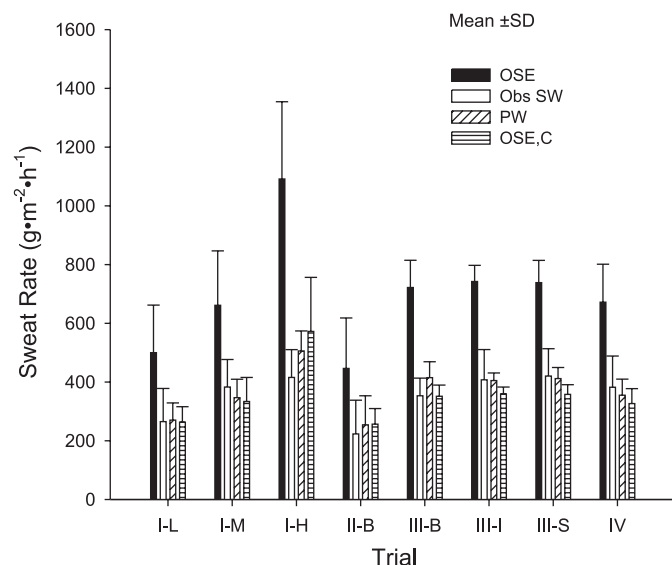


Fig. 3. Sweating rate output (means  $\pm$  SD) from the various equations compared with measured (observed, Obs SW) data plotted for data sets I-IV. Data set designations are the same as in Table 3. Prediction accuracy and significance was determined by analyses of mean error rate of each equation vs. observed data (see Table 4 and text).

directly or indirectly integrate the effects of the internal factors (metabolic rate, skin and core temperature) and external factors (clothing, operative temperature, wind, and humidity). OSE has been shown to often overestimate sweating rates for a variety of conditions within and outside the original equation's domain of validity (3).

The original equation was not meant to predict responses at high metabolic rates. Elevated heat production is accompanied by higher levels of core and skin temperatures (20) and generally higher sweating rates that can saturate the microcli-

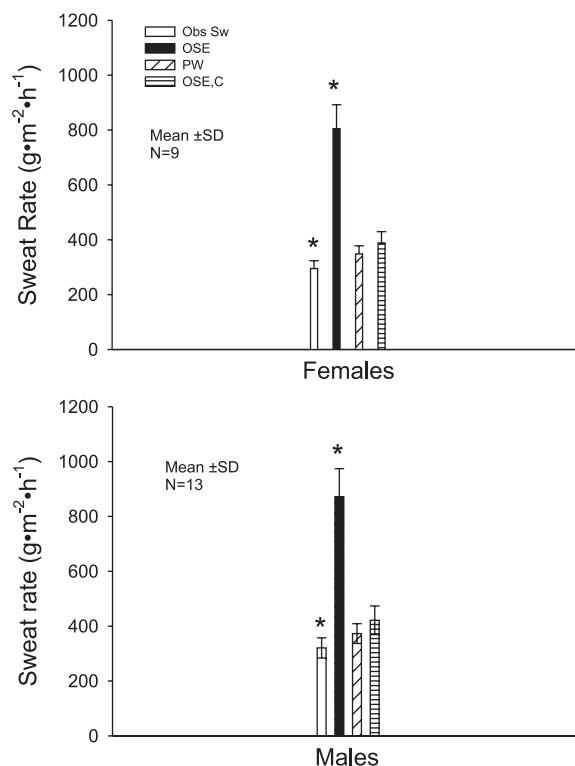


Fig. 5. Comparison of output from the various prediction equations and measured (observed) sweating rate plotted for each group (9 females and 13 males) in an experimental cross validation study (study VI). Values are means  $\pm$  SD. NS differences between genders; \* =  $P < 0.01$  within group.

mate (and invariably  $E_{drip}$ ), both of which become limiting factors in a person's ability to achieve steady-state heat balance. Although core temperatures are not shown in this study, this variable is indirectly related to the analysis of the heat

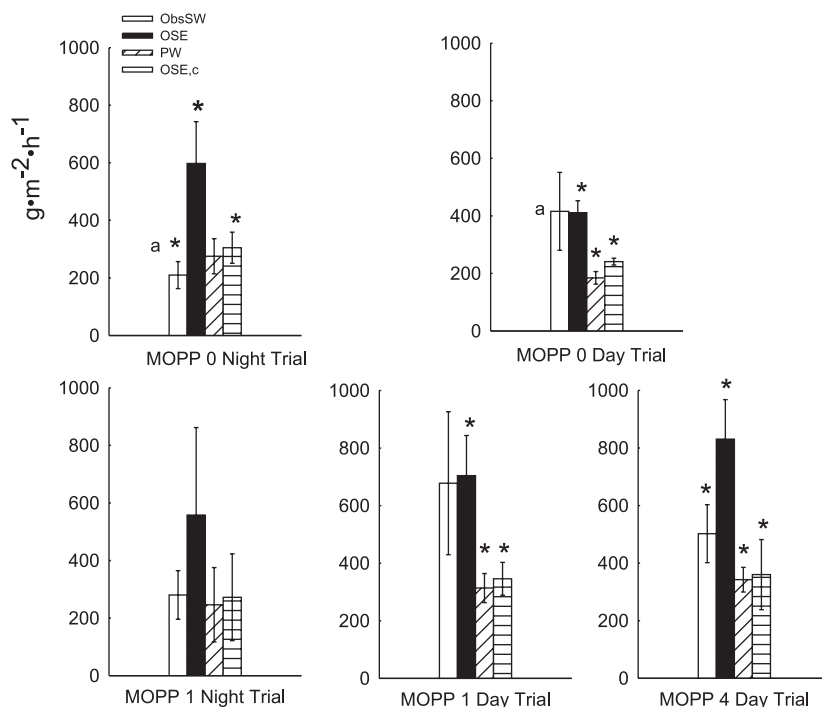


Fig. 4. Comparison of output from each of the prediction equations and measured (observed) sweating rate plotted for each group walking in the outdoor cross-validation study (data set V) clothed in various NBC clothing. MOPP, mission-oriented protective posture. Values are means  $\pm$  SD. \* $P < 0.01$  within each specific trial. a =  $P < 0.01$  between night and day trials in MOPP O.



balance and reflected directly by any changes in  $S$ . The latter is affected by core and skin temperature drive so that  $S/hF_{cl} = (dT_b/dt)[(0.97mb/A_D)]/hF_{cl}$ , where  $T_b$  is integrated mean body temperature,  $mb$  is body mass (kg),  $A_D$  is body surface area ( $m^2$ ),  $0.97$  is body specific heat ( $W \cdot h / (kg \cdot ^\circ C)$ ), and  $hF_{cl}$  is the combined heat transfer coefficient times Burton's clothing factor,  $F_{cl}$  (5, 26).

Also, steady-state skin temperature levels add errors in determining dry heat flux ( $R + C + K$ ) through clothing and insensible heat loss, and variable latent heat of evaporation (10) also can introduce errors in  $E_{max}$  calculations leading to wide discrepancies in prediction accuracy of sweating rates using OSE.

In this study, OSE consistently overestimated measured sweating rate (Fig. 2, A–C), particularly at the higher measured sweating rates. A correction to OSE using the present extensive database (101 subjects, longer work durations from 4 to 8 h, and a variety of clothing systems) extended accurate prediction of actual sweating rates from  $\sim 200$  to  $\sim 500 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ . The most significant finding of the current study was the development of a new and improved equation PW:  $\dot{m}_{sw} (\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 147 + 1.527 \cdot E_{req} - 0.87 \cdot E_{max}$ .

The improved equation PW is based on fuzzy piecewise regression analysis that incorporates the combined effects of a broader range of metabolic rates, wearing of body armor (commonly employed by military and law enforcement), and other aspects of modern military clothing systems. This equation is essentially applicable for both men and women working for time periods up to 8 h. Most importantly, this equation still incorporates attributes of OSE documenting two essential physiological mechanisms (5, 26) necessary in thermoregulatory function, one coupled with eccrine sweat gland function, itself associated with internal and skin body temperatures necessary in the regulation of heat balance ( $E_{req}$ ), and the other needed whenever heat transfer mechanisms must be characterized in terms of clothing worn and environmental impact ( $E_{max}$ ). In the latter cases, the factor  $E_{req}/\dot{m}_{sw}$  is a direct correlate of  $M$  (metabolic heat production), since  $E_{req}$  is based on the solution of the comprehensive heat balance equation comprising  $S = (M \pm Wk) - E \pm (R + C + K)$  (10).

The relative accuracy of PW and  $OSE_C$  has only been implied so far in this discussion. The concern is that any equation's output should accurately predict sweating rates within a given boundary level because, over an 8-h period, it has an impact on water requirements needed by an individual. Cheuvront et al. (3) estimated that this should be  $\pm 0.125 \text{ l/h}$  (some  $65.8 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  for a person  $1.9 \text{ m}^2$  BSA). Our results in this study showed via the SEE (Fig. 2, A–C) that the various equations' domains of accuracy were  $\pm 72.4 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  for PW,  $\pm 98.3 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  for  $OSE_C$ , and  $\pm 181.3 \text{ g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$  using the original OSE. These translate for the  $1.9 \text{ m}^2$  BSA person to  $\pm 0.137 \text{ l/h}$  (new),  $0.186 \text{ l/h}$  (corrected), and  $0.340 \text{ l/h}$  (original) for the whole database considered in this study. It is doubtful that the  $\pm 0.137 \text{ l/h}$  found using the new equation is physiologically meaningfully compared with the  $\pm 0.125 \text{ l/h}$  criterion, which would result in  $\sim 1,096 \text{ ml}$  over 8 h compared with the 1,000-ml criterion recommended by Cheuvront et al. (3).

A sweating rate predictive model that is operational for wide uses such as determining water requirements over various environments, activities, and time domains is only as good as

the accuracy it possesses compared with the true (or experimentally observed) outcome. Within the scope of this study's intent, any equation developed must exhibit a tight association between the model's outcome predictions and the group outcomes of the test population. The equation serves as a surrogate of actual observed sweat responses based on one or more independent factors ( $E_{req}$ ,  $E_{max}$ ) driving the outcome (measured  $\dot{m}_{sw}$ ). The analysis of mean error rates for all combined trials resulted in a rejection of the null hypothesis that all three equations are equally accurate.

Table 4 shows that PW was almost 65% more accurate in predicting sweating rate compared with the OSE. However, using  $OSE_C$  would still be 58% more accurate than using OSE. Therefore, using either PW or  $OSE_C$  could be considered mathematically equivalent over the range of environments, time domains, or metabolic activities studied. Furthermore, integration with the OSE that resides in many rational and operational thermal models is now possible by applying  $OSE_C$ :  $\dot{m}_{sw} (\text{g} \cdot \text{m}^{-2} \cdot \text{h}^{-1}) = 147 \cdot \exp(0.0012 \cdot OSE)$ , where OSE is output from OSE (28) that leaves the exponential regression coefficients  $[27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}]$  intact but modifies the  $E_{req}$  and  $E_{max}$  to conform with more robust and modern heat and evaporative transfer coefficients and dynamic manikin thermal resistance values.

The limits of the corrected predictive equations comprise the original  $E_{req}$  and  $E_{max}$  limits ( $50 < E_{req} < 360 \text{ W/m}^2$  and  $20 < E_{max} < 525 \text{ W/m}^2$ , respectively), but these limits are extended so that the equation is applicable for higher metabolic intensities ( $M = 400 \text{ W/m}^2$ ,  $\sim 700\text{--}800 \text{ W}$ ), lower ambient conditions ( $T_a = 15^\circ\text{C}$ ), and longer time periods (up to 8 h).

PW and  $OSE_C$  were derived principally from environmental chamber experiments. The limited results from the field test reported in Fig. 4 (data set V) indicate that PW and  $OSE_C$  appear valid in predicting sweating rate during mild effective radiant loads. Although solar load in terms of ERF did include daytime tests as high as  $500 \text{ W/m}^2$ , a more extensive database incorporating wider thermal conditions with more intense and variable solar loads (27) and further testing or modification of the equations studied is needed in the future.

**Conclusions.** The present study developed both a new (PW) and a corrected ( $OSE_C$ ) sweating rate (and fluid needs) prediction equation that provides a more accurate estimate of measured sweating rates, and therefore also water needs, for a variety of military, occupational, and sports medicine scenarios. PW and  $OSE_C$  have wide application to public health, military, occupational and sports medicine communities. Future studies should develop sweating rate databases for other

Table 4. Summary of mean error rate analyses for each equation compared with data over all trials

Variable	Mean $\pm$ SD
OSE rank	9.75 $\pm$ 2.31*
$OSE_C$ rank	5.37 $\pm$ 3.50†
PW rank	4.12 $\pm$ 2.16

OSE, original shapiro equation;  $OSE_C$ , corrected OSE; PW, piecewise equation. Rank analysis was performed using Friedman ANOVA. \* $P < 0.01$ , PW vs. OSE (64.5% difference). † $P < 0.01$ ,  $OSE_C$  vs. OSE (57.9% difference). There is no significant difference comparing PW vs.  $OSE_C$  (15.6% difference).

conditions to test the extension validity of the new equation for more intense and variable solar load conditions.

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