Prediction of Water Requirements to Replace Sweat Losses

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ABSTRACT

The Shapiro sweat prediction equation (OSE) was formulated more than two decades ago as: m_{sw} $(g \bullet m^{-2} \bullet h^{-1}) = 27.9 \bullet E_{req} \bullet (E_{max})^{-0.455}$*, where* E_{req} *is required evaporative heat loss and* E_{max} *is maximum evaporative power of the environment. Although OSE was developed for a limited set of conditions, in practice it is often used outside its boundaries to estimate fluid requirements and generate guidance in military, public health, occupational and sports medicine settings. Military (NATO) and public health (IOM) reports have expressed a need for improved sweating rate prediction models that calculate hourly and daily water needs.*

Purpose

The purposes of this study were to 1) determine the accuracy of OSE when widening its boundaries to include cooler environments (2h) and very prolonged exercise (8h), and 2) improve the accuracy of OSE and/or develop a de novo sweat prediction equation with improved accuracy.

Methods

OSE prediction accuracy was determined by comparing measured (m_{sw}) *and predicted sweating rates in 39 volunteers during 15 trials that included intermittent treadmill walking for 2h (300 to 600 W, 15 to 30*^{o}*C; n = 21) or 8h (300 to 420 W, 20 to 40*^{o}*C; n = 18). Accuracy was first assessed by comparing* m_{sw} *and predicted sweating rates (211 observations) using least-squares regression. Mean and 95% confidence intervals for group differences were compared against a ± 0.125 L/h prediction error theshold. The 2h and 8h data were then combined with archived data (total of 101 volunteers, >500 observations), using a variety of metabolic rates over a range of environmental conditions, clothing and equipment combinations and work durations, in an effort to correct OSE and develop a new sweat prediction equation using fuzzy piecewise regression. The corrected and de novo equations were then cross-validated against independent data (30 volunteers; >200 observations).*

Results

OSE accounted for more than 70% of the variance in m_{sw} *and the SEE was small and uniform around the line of best fit. However, the OSE error was always > 0.125 L/h during 2h and 8h of exercise. A corrected equation* (OSE_C)*:* $m_{sw} = 147 \bullet exp\ (0.0012 \bullet OSE)$ *and a new equation* (P_W)*:* $m_{sw} = 147 + 1.527 \bullet (E_{req}) - 0.87 \bullet (E_{max})$ *were derived.* OSE_C *and* P_W *were 58% and 65% more accurate (P<0.01) than OSE, respectively, for conditions both within and outside the original OSE domain of validity.*

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14. ABSTRACT
The Shapiro sweat prediction equation (OSE) was formulated more than two decades ago as: msw (gm-2h-1) = 27.9 Ereq (Emax)-0.455, where Ereq is required evaporative heat loss and Emax is maximum evaporative power of the environment. Although OSE was developed for a limited set of conditions, in practice it is often used outside its boundaries to estimate fluid requirements and generate guidance in military, public health, occupational and sports medicine settings. Military (NATO) and public health (IOM) reports have expressed a need for improved sweating rate prediction models that calculate hourly and daily water needs.

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Conclusion

OSE_C and P_W provide for more accurate sweat predictions over a broader range of conditions. Applications overlap multiple HFM domains and military needs scenarios. Authors' views; not official U.S. Army or DoD policy.

1.0 INTRODUCTION

Effective water management is a key to Force Health Protection and Force Operating Capabilities (5). Health is theatened by fluid deficits (hypohydration), which increase the risk of serious heat illness (1, 5, 6, 7) and fluid surfeits (hyperhydration), which increase the risk of hyponatremia (6, 7, 17). Combat effectiveness declines quickly when water is not available. As a result, drinking water is the largest single potable water planning factor and represents 15% of the total per capita water requirement for all tactical and force structure planning (9). Yet the provision of adequate water is a challenge on the modern battlefield where unit forces are distributed over complex urban terrain extending hundreds of miles (10). As a consequence, smaller units on shorter missions carry their water, which contributes significantly to combat load and reduces fighting effectiveness. Not only do water resupply requirements place support elements at strategic risk, but delivery requires tremendous manpower and vehicle space, making water transport one of the largest logistical supply burdens on the modern battlefield (2, 5, 10). As a result, the ability to accurately predict Warfighter water needs is a key to efficient water consumption planning, Force Health Protection, and Force Operating Capabilities.

The U.S. Army is the DoD executive agent for land-based water resources in a theatre of operations (8). One mission of the U.S. Army Research Institute of Environmental Medicine (USARIEM) has been to develop empirically derived prediction algorithms to estimate water requirements for a variety of situations (2). Although body water is lost though urination and respiration, perspiration (sweat) is the primary avenue for body water losses in populations training and fighting in warm or hot environments. Water losses from sweat increase proportionally with the total thermal load, which includes the heat of metabolism (work intensity × time interaction), macro-environment (climate) and micro-environment (clothing, vehicle) considerations (18). Sweat losses also vary widely among people due to numerous biological factors (acclimatization, fitness, body size, genetics) (18). Careful and extensive research observation and experimentation (14, 16, 19, 20) is the essential starting point for accurate sweat loss prediction algorithms. However, the myriad of complex interactions among variables that influence sweating rates make all-encompassing experiments difficult and impractical, thus prediction models are essential for comprehensive water planning (15).

The current (original) Shapiro equation (OSE) (20), embedded within generations of broader empirical sweat prediction models (2), resolves the interaction between the requirement for evaporative cooling (E_{req}) and the maximum evaporative capacity of the environment (E_{max}). The OSE equation was derived from a matrix of laboratory experiments that included a range of environmental conditions (ambient temperature 20 – 54ºC, and relative humidity 10 – 90%), clothing configurations (insulation or clo = 0.74 to 1.50), and metabolic intensities (approximately 50 – 250 W/m^2) of 2h duration. Actual sweat losses were determined from the change in nude body mass corrected for fluid intake and urine output, but no corrections were made for respiratory or metabolic mass losses. This exclusion will overestimate true sweat losses, especially in cooler environments (3, 4). Clothing insulation (clo) and evaporative potential (i_m/clo) in OSE are for antiquated ensembles using static manikins and do not account for changes in clothing wettedness over time (4, 11). E_{req} in OSE also does not account for the realistic inefficiency of sweat evaporation from the skin (11). When these limitations are considered alongside the fact that OSE is frequently used to model sweat losses and water needs well beyond its 2h domain of validity, there is a clear military (2) and civilian (12) need to quantify and improve OSE performance by expanding its boundaries to include modern protective clothing and realistic work durations (> 2h).

2.0 METHODS

OSE prediction accuracy was determined by comparing measured (m_{sw}) and predicted sweating rates in 39 volunteers during 15 trials (A-O) that included intermittent treadmill walking for 2h (300 to 600 W, 15 to 30°C; n = 21) or 8h (300 to 420 W, 20 to 40°C; n = 18). Accuracy was first assessed by comparing m_{sw} and predicted sweating rates (211 observations) using least-squares regression. Mean and 95% confidence intervals for group differences were compared against a ± 0.125 L/h prediction error theshold. The 2h and 8h data were then combined with archived data 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 conducted at Defence R & D Canada, Toronto. A total of 101 volunteers (80 men, 21 women), and more than 500 observations were made using a variety of metabolic rates (250 to 800W) over a range of environmental conditions (15 to 41°C), clothing and equipment combinations (BDU, body armor, MOPP) and work durations (2h to 8h), in an effort to correct OSE and develop a new sweat prediction equation using fuzzy piecewise regression. The corrected and *de novo* equations were then cross-validated against independent data (30 volunteers; >200 observations). Additional methodological details can be found in Cheuvront et al. (4) and Gonzalez et al. (11).

3.0 RESULTS

OSE accounted for more than 70% of the variance in m_{sw} and the SEE was small and uniform around the line of best fit. However, the OSE error was always > 0.125 L/h during 2h and 8h of exercise (Figure 1). A corrected equation (OSE_C): $m_{sw} = 147 \bullet \exp(0.0012 \bullet OSE)$ and a new equation (P_W): $m_{sw} = 147 + 1.527 \bullet (E_{req}) - 0.87 \bullet (E_{max})$ were derived. OSE_C and P_W were 58% and 65% more accurate ($P<0.01$) than OSE, respectively, for conditions both within and outside the original OSE domain of validity. Additional result details can be found in Cheuvront et al. (4) and Gonzalez et al. (11). Figure 2, from Jay and Webb (13), shows the sweat (water) volume over-estimation error associated with using OSE for 2, 4, 6, and 8h of work over a range of possible E_{req} and E_{max} ratios. For an average sized Warfighter (1.8 m^2) working moderately for 8h (E_{req} = 275 W/m^2) in a hot, arid desert while wearing body armor (E_{max} = 350 W/m^2), use of OSE would over-predict water needs by 2 L (Figure 2). For an individual Warfighter on a 24h mission, this error adds 2 kg to the fighting load. For a battalion-sized unit, the error adds nearly 500 kg (500 L) of unnecessary water transport. This would also have important ramifications for the transport of water into difficult to reach locations, such as mountainous regions (2).

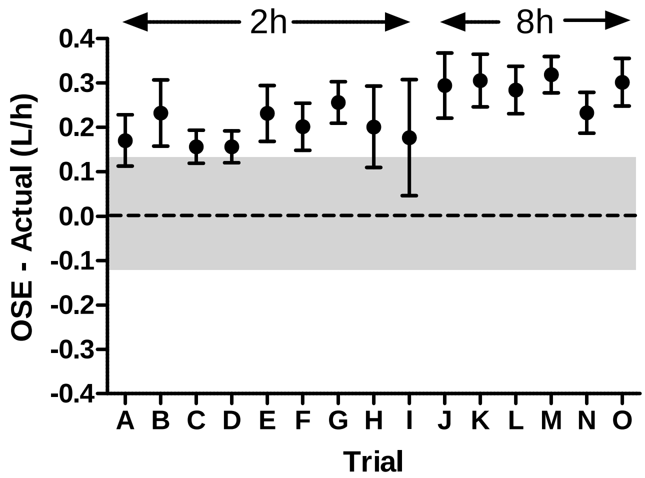

Figure 1: Differences between predicted sweat rate (OSE) and actual sweating rate during 2h (A though I) and 8h (J though O) trials. Data are group (trial) means; bars are 95% confidence intervals. Shaded area represents zone of indifference (± 0.125 L/h) based on the desire to predict sweat losses to within 1L over an 8h work day. From reference 4.

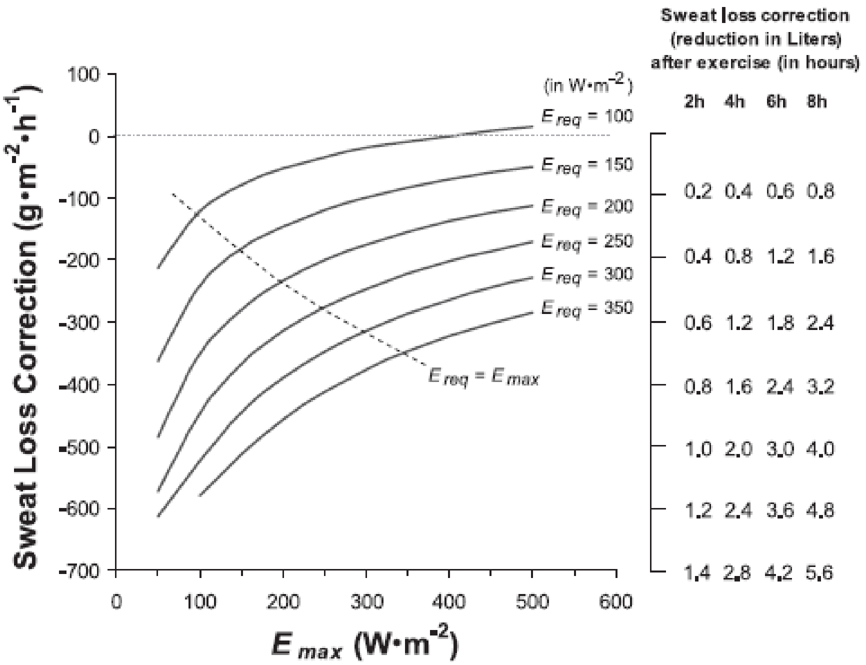

Figure 2: Sweat loss correction (left y-axis) and associated water volume error (right y-axis) observed when using OSE versus OSE_C. Right y-axis volumes represent an overestimate of individual water needs (in liters) over time. From reference 13.

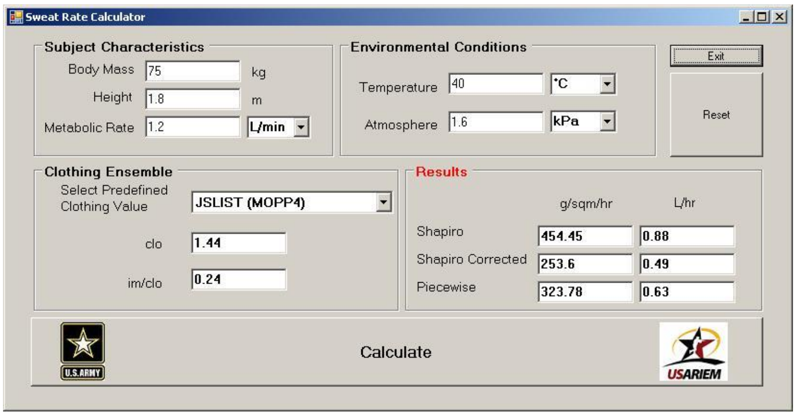

Figure 3: Screenshot of USARIEM executable program run on Microsoft Windows ® which requires minimal user-friendly inputs to predict sweat losses (water needs) comparing OSE, OSE$_C$, and P$_W$.

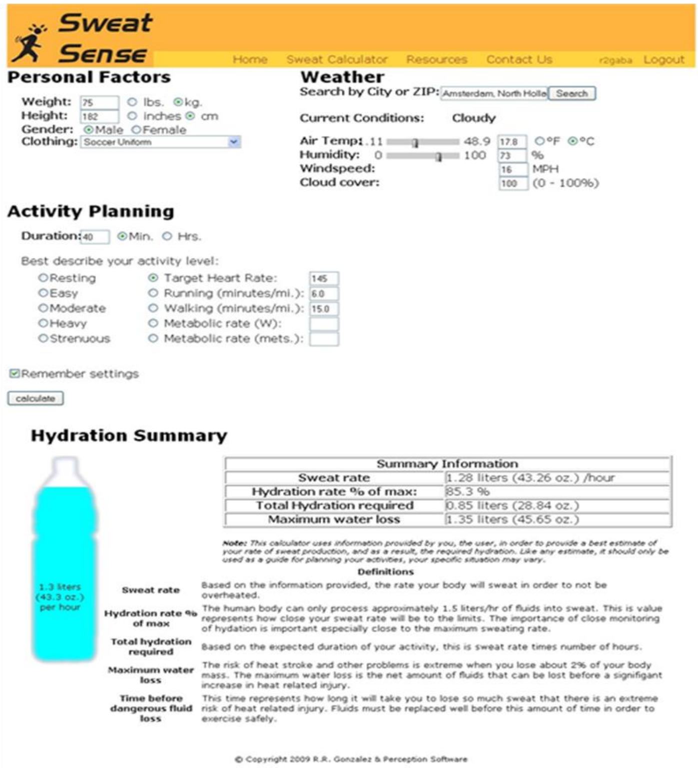

Figure 4: Screenshot of internet program (R.R. Gonzalez & Perception Software, ©2009) incorporating P$_W$ and on-line meteorological data to predict sweat losses (water needs) using minimal user-friendly inputs.

4.0 CONCLUSIONS

OSE$_C$ and P$_W$ provide for more accurate sweat predictions over a broader range of conditions than equations currently in use. Additional validity generalization, extension validity, and bootstrap simulation studies are ongoing and will further improve prediction accuracy. OSE$_C$ is easily migrated into various existing rational and operational thermal prediction models that presently include OSE. Both OSE$_C$ and

P_W can provide Commanders with more accurate forward water planning for larger units and potentially real-time, short term water planning for smaller units. Minimal user-friendly inputs are needed and programs could easily be implemented within various architectures including smartphone, personal digital assistant, or internet applications (Figures 3 and 4). OSE_C and P_W provide greater accuracy in estimating Warfighter water needs, which enhances safety and sustainability and reduces the logistical footprint for water re-supply. Applications overlap multiple Human Factors Medicine domains, military and civilian needs scenarios.

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