USARIEM TECHNICAL REPORT T08-05

PROBABILITY OF SURVIVAL DECISION AID (PSDA)

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March 2008

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE March, 2008	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE Probability of Survival Decision Aid (PSDA).	5. FUNDING NUMBERS
6. AUTHOR(S) Xiaojiang Xu, Mitesh Amin, William R. Santee	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Biophysics and Biomedical Modeling Division U.S. Army Research Institute of Environmental Medicine Building 42 - Kansas Street Natick, MA 01760	8. PERFORMING ORGANIZATION REPORT NUMBER T08-05
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, MD 21702	10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A Probability of Survival Decision Aid (PSDA) is developed to predict survival time for hypothermia and dehydration during prolonged exposure at sea in both air and water for a wide range of environmental conditions. PSDA calculates the survival time of a victim in the water or floating in an emergency craft as a function of human anthropometric parameters, clothing, and environmental variables. PSDA consists of a Six Cylinder Thermoregulatory Model (SCTM) and a Graphic User Interface (GUI) which manages inputs, runs the models, and displays output.

The GUI allows users to easily use PSDA by selecting or entering inputs for ten basic parameters. It is then updated to display predictions for the cold functional time, cold survival time, dehydration survival time, and the empirical dehydration survival time. PSDA was validated using historical survival data, reported cases for accidental water immersions, and limited data for channel swimmers. For ten immersion victims for whom height and weight are known, the predicted survival time for each victim was either very close to or greater than the observed survival time. However, the predictive capability of PSDA is limited by the supporting data.

14. SUBJECT TERMS survival, model, hypothermia, dehydration, immersion, thermoregulation.	15. NUMBER OF PAGES 44
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18 298-102

USAPPC V1.00

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research.

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ACKNOWLEDGMENTS

We would like to thank Mr. C. Turner and Mr. M. Lewandowski, U.S. Coast Guard, whose efforts made the project possible. We would like to acknowledge and thank Dr. E. Wissler for his role as a consultant to this work and his provision of unpublished data, and Mr. J. Giblo for his discussion and immersion clothing values. We would like to thank Dr. R. Hoyt for his leadership, guidance and encouragement during this work. We would like to thank our colleagues in the Division of Biophysics and Biomedical Modeling for their support in various aspects, and especially acknowledge Ms. L. Blanchard for her critical assistance in guiding us through the Information Technology (IT) review process and Dr. M. Yokota for generation of individual anthropometric parameters. Other USARIEM personnel that deserve our thanks are Dr. J. Castellani and Ms. C. O'Brien for their comments and testing of the product, Mr. J. Evans and Mr. C. Joyce for their assistance with budget and business administrative concerns, and Ms. D. Cardinal and Mr. R. Langevin for their assistance in the IT review. Finally, we would like to recognize and thank Ms. S. Hallas for her editorial assistance.

EXECUTIVE SUMMARY

U.S. Army Research Institute of Environmental Medicine (USARIEM) is assisting the U.S. Coast Guard (USCG) by developing a Probability of Survival Decision Aid (PSDA) that predicts survival time for hypothermia and dehydration during prolonged exposure at sea in both air and water for a wide range of environmental conditions. PSDA calculates the survival time of a victim in the water or floating in an emergency craft (e.g., disabled vessel, life raft, surf board) as a function of human anthropometric parameters, clothing, and environmental variables such as water temperature, air temperature, and wind speed.

PSDA consists of (a) a Six Cylinder Thermoregulatory Model (SCTM), (b) an empirical water loss equation developed from physiological data, and (c) a Graphic User Interface (GUI) to manage inputs, run the models, and display output. SCTM combines first principles of the biophysics of heat exchange with a realistic approximation of human physiology, and is applicable to exposure to warm and cold air and water immersion. The empirical water loss model is based on the measured water loss of test subjects in rafts and serves as a secondary or supplemental prediction of water loss. The GUI allows users to easily use PSDA by selecting or entering inputs for ten basic parameters. On command, the GUI runs SCTM and the empirical dehydration model. The GUI is then updated to display predictions for the cold functional time (i.e. time when the core temperature reaches 34°C or 89.6°F), cold survival time (i.e. time when the core temperature reaches 30°C or 86°F), dehydration survival time (i.e. time when water loss reaches 20% of body weight), and the empirical dehydration survival time.

PSDA was validated using historical survival data, reported cases for accidental water immersions, and limited data for channel swimmers. For ten immersion victims for whom height and weight are known, the predicted survival time for each victim was either very close to or greater than the observed survival time. However, the predictive capability of PSDA is limited by the supporting data. To expand the applications of PSDA, more physiological data from case histories and/or controlled studies are needed.

INTRODUCTION

The U.S. Coast Guard (USCG) annually conducts nearly 3000 search and rescue (SAR) missions that involve a person in the water or a victim on an emergency craft. Approximately 750 of these cases are suspended without locating the victim. To improve the success of SAR missions, the USCG needs a sound method to accurately assess the survival times (ST) of victims in distress, either in the water, or in a life raft.

The USCG currently uses the Cold Exposure Survival Model (CESM) developed by Defence R&D Canada, Toronto, to determine the survival time (23;24). As indicated by its name, CESM only applies to cold environments where there is a risk of hypothermia.

The USCG Research and Development Center (R&DC) recognized the need to develop a tool that is applicable for a wider range of environmental conditions. The R&DC also wants to improve the accuracy of survival predictions for cold environments and extend the prediction capability to warm environments. To accomplish this, the prediction tool must incorporate additional modeling of physiological processes that go beyond the biophysics associated with heat generation and loss in cold environments.

Improvements to the USCG survival tool are expected to measurably improve USCG mission effectiveness. When the predicted survival time is short, planners will be able to justify immediate mobilization of other government agencies so that search response units rapidly saturate the search area. Concentrating search effort and resources when the probability of a successful rescue is greatest should shorten the duration of search times, and thus increase the availability of search units to respond to new emergencies. More efficient search operations may save more lives and should reduce inefficient utilization of search resources. Shortening search times and adding search units that can respond more quickly will reduce unnecessary expenditures of search resources and may save lives. The present USCG survival tool provides vague guidance (survival time >36 hours) in cases where water temperature is greater than 20°C (68°F). In some cases, the USCG controller has suspended a search while the victim was still alive and was later rescued after the search was suspended. If the maximum survival time is extended in warm water environments, searches will be continued, and search planners will be able to consider alternate scenarios as part of extended search efforts.

U.S. Army Research Institute of Environmental Medicine (USARIEM) is assisting the USCG by developing a Probability of Survival Decision Aid (PSDA) that will predict survival time for hypothermia. In addition, it will have a capability to predict survival times for dehydration. PSDA will calculate the survival time of a victim in the water or floating in an emergency craft (e.g., life raft, surf board) as a function of human anthropometric parameters, clothing, and environmental variables such as water temperature, air temperature, and wind speed.

METHODS

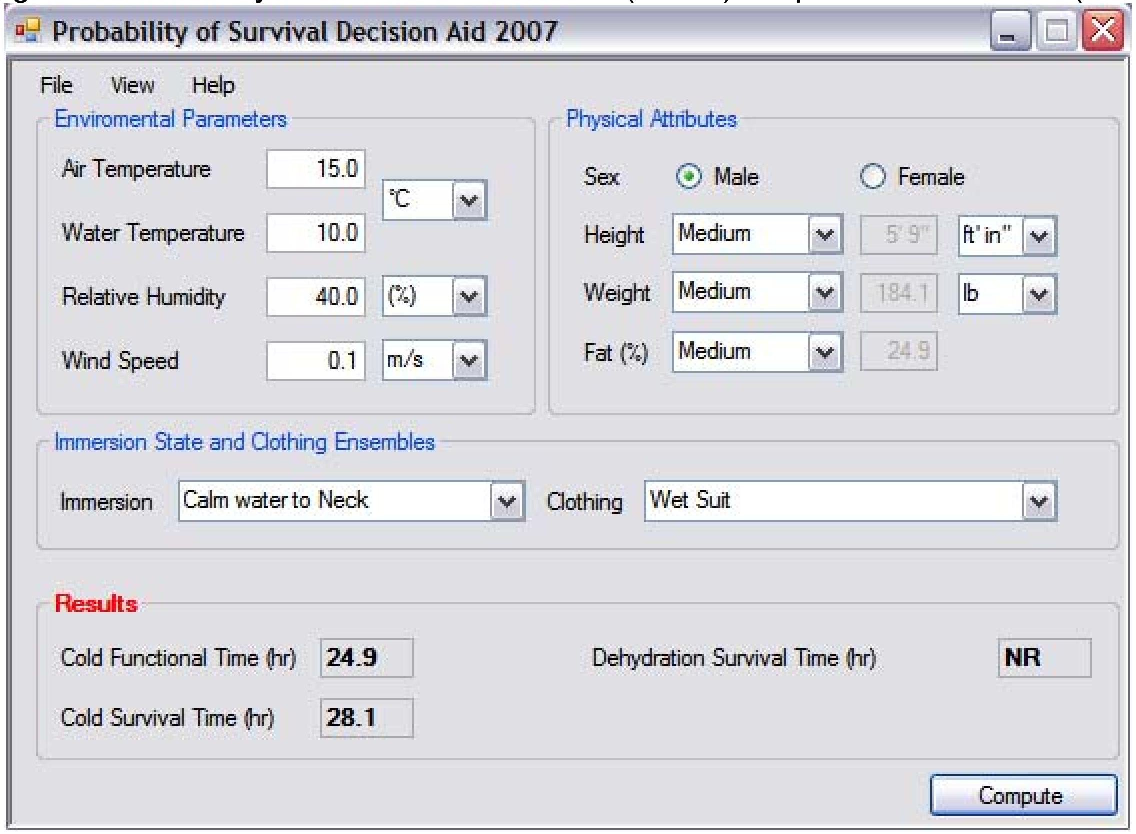
SURVIVAL FACTOR ANALYSIS

Many factors in combination determine the likelihood of survival by mariners/victims in the water or in an emergency craft. The present modeling effort focuses on the contributions of hypothermia and dehydration to survival or the probability of survival. Other factors/risks/hazards, e.g., cold shock, swim failure, injury, and starvation, cannot be ascertained without in-situ observers or reports and may be unique to a specific event or are beyond the scope of the present modeling effort. In other words, this model assumes that victims survive all non-predictable events and survival depends solely on the degree of hypothermia and/or dehydration.

PROBABILITY OF SURVIVAL DECISION AID

PSDA consists of (a) the Six Cylinder Thermoregulatory Model (SCTM), (b) an empirical water loss equation developed from the physiological data, and (c) a Graphic User Interface (GUI). SCTM predicts the core temperature and sweat loss during various exposures and requires about 60 inputs of human physical attributes, environmental condition and clothing properties for six distinct body segments: head, torso, arms, hands, legs, and feet. A second option for predicting water loss, the empirical water loss equation derived from physiological data predicts body water loss as a function of the ambient temperature. A GUI was developed to allow users to run SCTM easily by providing a user friendly interface with the model. It accepts simple inputs of ten parameters, converts the ten inputs into the 60 inputs required by SCTM, calls SCTM to predict human physiological responses, and displays the prediction. The GUI includes other features such as unit conversions, and options to save and print results. The GUI was written in Microsoft Visual Basic 2005. The SCTM was written in Fortran 90 and was ported for use with the GUI via a Dynamic Link Library (DLL). The GUI is shown in Figure 1.

Figure 1. Probability of Survival Decision Aid (PSDA) Graphic User Interface (GUI)



Enviromental Parameters

Air Temperature 15.0 °C

Water Temperature 10.0 °C

Relative Humidity 40.0 (%)

Wind Speed 0.1 m/s

Physical Attributes

Sex ● Male ○ Female

Height Medium 5' 9" ft' in"

Weight Medium 184.1 lb

Fat (%) Medium 24.9

Immersion State and Clothing Ensembles

Immersion Calm water to Neck

Clothing Wet Suit

Results

Cold Functional Time (hr) 24.9

Cold Survival Time (hr) 28.1

Dehydration Survival Time (hr) NR

SIX CYLINDER THERMOREGULATORY MODEL (SCTM)

SCTM is a thermoregulatory model for heat exposure and prolonged cold exposure in the air or water. It takes into account physiological mechanisms, including metabolic heat production, sweating heat loss, respiratory heat loss, and blood circulation. It is able to predict both core and regional temperatures, and evaporative water loss through the skin and lungs, which can then be used to estimate the degree of dehydration.

SCTM was derived from an earlier version of a thermoregulatory model developed by Werner and Webb (27) which was, in turn, based on the pioneering work of Stolwijk and Hardy (22). The SCTM is a six cylinder model, with each cylinder originally consisting of core and shell layers. Subsequently, we added muscle, fat, and clothing layers (33) and incorporated a conceptual model for shivering intensity and fatigue into the current SCTM configuration (32). This has improved the model prediction of human responses to long-term cold exposure. Each cylinder is now divided into concentric compartments representing the core, muscle, fat, and skin. The outer cylinder has an optional clothing layer. Circulation is represented as a one-loop circulatory system and is an independent compartment. Thus, the human body is represented by 25 compartments; i.e., six cylinders with four layers and one blood pool.

The size of each compartment is derived using height, weight, and body fat percentage (30).

In the active or controlling system of the model, an integrated thermal signal to the thermoregulatory controller is composed of weighted thermal inputs from thermal receptors at various sites distributed throughout the body. The integrated body temperature is weighted using the core, muscle, and skin compartment temperatures. The afferent signal is the difference between this temperature and its threshold, which activates thermoregulatory mechanisms including vasomotor changes, sweat production, and metabolic heat production (33). Shivering thermogenesis (i.e., part of metabolic heat production) is a function of core and mean skin temperatures, and includes an intensity adjustment, maximal capability, shivering exhaustion, and inhibition due to a low core temperature (32). The maximal shivering intensity was estimated from the height, weight, $\dot{V}O_{2\ max}$ and age (7). Water loss is the sum of predicted sweat loss, predicted respiratory loss (30) and constant urine daily loss of 0.5 L/day.

SCTM inputs include individual characteristics (i.e., height, weight, body fat percentage, age, $\dot{V}O_{2\ max}$) and level of activity, as well as environmental (i.e., temperature, humidity, and wind velocity) and clothing (i.e., clothing insulation (clo), and moisture permeability index (i_m) properties).

EMPIRICAL WATER LOSS ESTIMATION

For resting humans in normal environmental conditions, dehydration is a slow process. At rest in neutral or cold environments, it takes several days to reach a dehydration level associated with a decrement in physical work capacity and more time to reach a fatal dehydration level. Prediction of long-term sweat loss or water loss is complicated, as (1) many factors affecting sweat rates may change over time, e.g., dynamic weather conditions; (2) human physiology may change as fatigue sets in; and (3) the collection of physiological data to validate the prediction is difficult, particularly under long-term or realistic ocean conditions. Therefore, a secondary or alternative approach was developed to predict the long-term water loss.

Water loss of men on life rafts was studied systematically by Brown and his colleagues (4). To the best of our knowledge, this was the only study that specifically ascertained the rates of water loss on life rafts at sea. This study was conducted in the sea near the mouth of Choctawhatchee Bay, Florida, adjacent to the Gulf of Mexico. The subjects consisted of eight enlisted men plus, on occasion, other volunteers. They were exposed in various ways to the sun/shade and wind with dry/wet clothing, and sat or reclined on the bottom of the raft. Their water loss and urine loss were periodically measured. The following are some of the conclusions from this study: the water loss in the ocean is principally influenced by air temperatures, body water could be conserved by shade and by keeping the clothing wet, and water needed to replace losses can be provided from several sources, e.g., rain catchments or devices which produce emergency drinking water. The results were used to compute maximal water needs for a considerable sustained period of time and to estimate the extent to which men become dehydrated under a variety of conditions. As the exposure conditions were similar to the Air/boat menu option for exposure state in the PSDA GUI (see Fig.1), results from this study were used to develop an empirical method to predict water loss for PSDA. The water loss per day was estimated as:

$$WD = 1.86 + 0.008 \cdot e^{0.177 \cdot T_a} \tag{1}$$

where WD is % weight loss per day, and T_a is the ambient temperature in °C. This equation is only applicable in a range of air temperatures from 5°C to 35°C.

INPUT PARAMETERS

Environmental Parameters

SCTM requires the following environmental parameters: air and/or water temperature, humidity, wind speed, and sea state. The environmental values for each body segment are determined from user inputs for air temperature, water temperature, humidity, wind speed, and immersion state. The temperatures for submerged body segments will be assigned as the specified water temperature. The temperature, relative humidity, and wind speed for body segments in air will be assigned specified air values.

Physical Attributes

PSDA provides options to input human anthropometric parameters; i.e., height, weight and body fat percentage as actual values or, alternately, as descriptive categories such as very short or tall for height and very light to very heavy for body weight. The default height and weight numeric values were based on the survey data for U.S. population in the National Health and Nutrition Examination Surveys (NHANES) database (16). Body fat percentage is estimated from height and weight, using formulas developed from ~665 black and white men and women ranging from 17 to 65 years in age by Jackson et al. (13).

Average Man and Woman. The height and weight of the average American adult man or woman over 20 years old in the NHANES database are listed in Table 1.

Table 1. Height and weight of average American

	Height (m)	Height (inches)	Weight (kg)	Weight (lbs)
Male	1.76	69	86	190
Female	1.62	64	74	163

Height. The definitions of descriptive height categories presented in Table 2 (i.e., very short, short, medium, tall and very tall) are based on height distributions in the NHANES database. Very short (5%) means that 5% of the population is shorter than 1.63 m for males and 1.51 m for females. Medium (50%) means that 50% of the population is less than 1.76 m for males and 1.62 m for females.

Table 2. Definitions of the descriptive height categories and height (m)

Description	Very Short	Short	Medium	Tall	Very Tall
Percentile	5th	25th	50th	75th	95th
Male	1.63	1.71	1.76	1.81	1.88
Female	1.51	1.57	1.62	1.67	1.73

Weight. The definitions of the descriptive weight categories presented in Table 3 (i.e., very light, light, medium, heavy and very heavy) are also based on weight distributions in the NHANES database. Very light (5%) means that 5% of the population is lighter than 60.4 kg for males and 49.8 kg for females. Medium (50%) means that 50% of the population is lighter than 83.5 kg for males and 70.2 kg for females.

Table 3. Definitions of descriptive weight categories and weight (kg)

Description	Very Light	Light	Medium	Heavy	Very Heavy
Percentile	5th	25th	50th	75th	95th
Male	60.4	73.6	83.5	96.2	121.2
Female	49.8	60.1	70.2	83.7	110.2

Range of Height, Weight and BMI. Some combinations of height and weight are not realistic, e.g., a 6' tall male weighing 90 lbs. To avoid unreasonable inputs of heights and weights that may cause erroneous predictions, a range of heights and weights, and body mass index (BMI, kg/m^2, defined as weight/(height x height), were set according to the NHANES database. The ranges cover more than 90% of U.S. adult populations, and the GUI is set to reject input values outside of this range listed in Table 4.

Table 4. Range of height, weight and body mass index

	Height (m)	Weight (kg)	BMI (kg/m^2)
Male	1.60 – 1.92	58.0 – 123.0	17.0 – 43.0*
Female	1.48 - 1.76	48.0 – 112.0	17.0 - 45.0*

*NHANES BMI limits, modified by results from Jackson et al (13).

Body Fat Percentage Estimation. Body fat percentage is an important parameter that affects the human response to thermal environments, especially during cold exposure. Body fat percentage is typically determined by direct measurement and must be inferred at the start of an SAR case. Formulas for estimating body fat percentage from height and weight developed by Jackson et al. (13) were used in PSDA:

Male:

$$fat\% = 3.76 \cdot BMI - 0.04 \cdot BMI^2 - 47.80 \quad (r^2 = 0.78, SE = 4.63\%) \tag{2}$$

Female:

$$fat\% = 4.35 \cdot BMI - 0.05 \cdot BMI^2 - 46.24 \quad (r^2 = 0.68, SE = 4.90\%) \tag{3}$$

where SE is the standard error of estimation. A lower limit was set for males at 5.0%, which was determined in a physiology study (8) and for females at 12.0% (15). In applications such as search and rescue operations, the victim's body fat percentage is usually unknown. The descriptive categories for body fat percentage presented in Table 5 are therefore provided as an option to estimate body fat percentage.

The definitions in the Table 5 were tested against body fat measurements for young male subjects taken during various USARIEM physiology studies (N = 45). It was found that 67% of the subjects fit the categories between lean and fat, and 91% of subjects fell between very lean and very fat. To a degree, this presents the relationship between descriptive categories and population distribution. However, USARIEM subjects are generally young, fit individuals.

Table 5. Definition of descriptive categories for body fat percentage

Description	Very Lean	Lean	Medium	Fat	Very Fat
Fat%	fat% - 2SE	fat% - SE	fat%	fat% + SE	fat% + 2SE

Immersion State

The immersion state is divided into three categories: air/boat, calm water immersion, and rough water immersion. The choices for immersion level, (i.e., neck, chest, or waist) indicate how much of the body was immersed. Selecting the Neck option means PSDA will be run with only the head out of water. Selecting chest level means the head, 20% of the chest, arms, and hands are out of water, and for waist level, the head, 80% of the chest, the arms, and the hands are out of the water. The default values for unknown immersion level and sea conditions are "Neck level" and "Rough Sea," as listed in the menu of Immersion State.

The convective heat transfer coefficient for calm seas, 160 $W/m^2°C$, is derived from measurements taken during a laboratory human immersion study (unpublished results). The convective heat loss coefficient for rough sea conditions, 460 $W/m^2°C$, was obtained from the literature (25).

Clothing Ensembles

SCTM requires inputs for the following clothing parameters for each cylinder: intrinsic thermal resistance and vapor permeable index (i_m). For informational purposes, the representative (descriptive) values of the clothing ensembles are reported as average values, since the actual insulation values may vary slightly between cylinders. The thermal resistances in air/boat conditions were measured at USARIEM and are listed in Table 6. The vapor permeability index was set at 0.4. Examples of Fall/Spring suit and Winter clothing are shown in Figure 2.

Table 6. Representative thermal insulation of dry clothing during Air/Boat exposure

No.	Clothing Ensembles	Intrinsic Insulation (clo)
1	Nude/swimsuit	0.00
2	Summer suit, T-shirt/Pant	0.37
3	Fall/Spring suit	0.97
4	Winter clothing	2.90

Figure 2. Fall/Spring suit (left) and Winter clothing (right)

Thermal resistances for immersion in calm sea conditions listed in Table 7 were primarily adapted from the literature (21;23). The thermal resistances of two ensembles were provided by the Navy Clothing & Textile Research Facility, Natick, MA (Mr. Joseph Giblo, personal communication). Thermal resistance values for clothing during immersion in rough seas were reduced to 60% of the insulation values reported for calm sea, according to the measurement results of humans and manikins (21).

Table 7. Representative thermal insulation of wet clothing during Calm Sea Immersion

No.	Ensembles	Intrinsic Insulation (clo)
1	Nude/swimsuit	0.00
2	Summer suit, T-shirt/Pant	0.00
3	Fall/Spring suit	0.05
4	Light marine suit	0.18
5	Moderate marine suit	0.24
6	Heavy marine suit	0.39
7	Wet suit	0.50
8	Wet vest suit	0.18
9	Dry suit, shirt, vest, & work jacket	0.50
10	Dry suit, single pile,& vest	0.81
11	Dry suit, double pile &vest	1.01

Examples of marine suits are described as follows (21):

Light marine suit: one piece, close cell foam insulated coverall with fully gusseted front and lower leg zippers. The front zipper has a storm flap. There is an inner elastic cuff at the wrist, ankles, and waist with velcro closures on the outer wrist and ankles sleeves, There are cinch type closures on the thighs and upper arms secured with Velcro. The hood is uninsulated.

Moderate marine suit: one piece, close cell foam insulated coverall with gusseted front and lower leg zippers and a storm flap covering the front zipper. There are Velcro closures on the wrists and thighs and an insulated hood.

Heavy marine suit: one piece, close cell foam insulated coverall with a storm flap covering the front zipper, a waist belt and gusseted lower leg zippers. The suit has Velcro closures on the wrist and ankles and a cinch strap on each thigh. The hood is insulated and there is an inflatable pillow to support the head.

COMPUTED RESULTS

As shown in Figure 1, PSDA predicts the cold functional time (FT), cold survival time (ST), and dehydration survival time. The cold FT is the time that the predicted core temperature reaches 34°C or 89.6°F and the victim’s capacity to perform useful external work ceases. Cold ST is the time that predicted core temperature reaches 30°C or 86°F. The dehydration ST is the time predicted for water loss to reach 20% of body weight. When air temperature is between 5° and 35°C, the time for the water loss to reach 20% of body weight is estimated by the empirical equation described earlier.

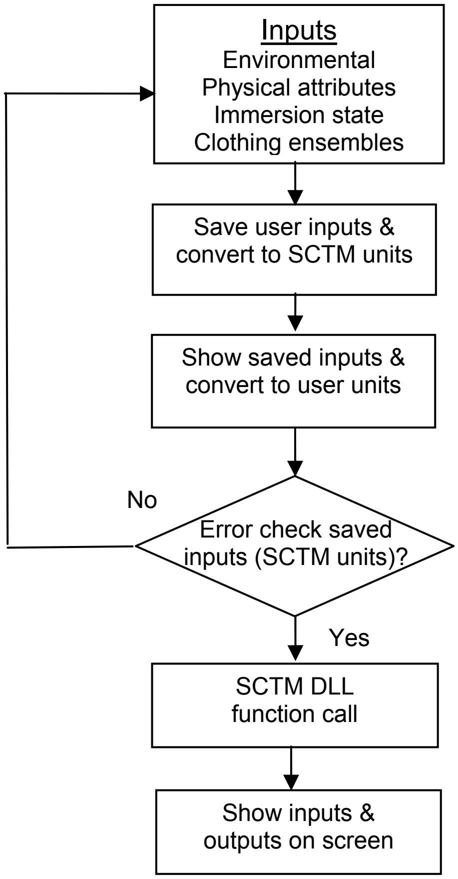
MAXIMAL PREDICTED SURVIVAL TIME

Predictions of long-term victim survival are poorly supported by documented cases, as either changing environmental conditions or other poorly understood processes may impact the results. For this reason, PSDA sets time limits for the duration of the simulations: 80 hours for immersion, and 240 hours for air exposure. Molnar reviewed U.S. Navy reports on sea rescues from 1942 to 1945 (17). He found some cases where victims survived for up to 50-60 hours. Aside from Molnar's work, based on our best knowledge at the time that this report was prepared, there are a few rare documented cases where victims survived for more than 60 hours. The USCG has a record of at least one case where the victim survived for 89 hours (Chris Turner, private communication). Thus, we decided to set the SCTM limit at 80 hours for immersion cases. During exposure to air, on a life raft or other floatation platform, it is even more difficult to obtain data to validate long-term predictions. The 240 hour limit was set to coincide with the survival curve created by Brown and his colleagues (4).

GUI CALL TO DYNAMIC LIBRARY LINK (DLL) OF SCTM

When data entry is competed and the compute button is clicked, all input variables are checked for errors, stored, and converted to the proper units used by the computational model. The input variables are then passed to the Dynamic Library Link (DLL), which calculates the predicted results and returns them to the GUI. Then the GUI displays the results and gives the user the option to save and print the input and output variables. The GUI flowchart is shown in Figure 3.

Figure 3. Graphic User Interface (GUI) Flowchart



The GUI only accepts anthropometric parameters within the range listed in Table 4. When the input values are out of range, the GUI marks the out-of-range value with a warning label/information and SCTM will not run. The GUI input check process consists of the following steps: (a) check to ensure the entered height and weight are within the allowable ranges; (b) check to ensure that the BMI value calculated from height and weight is within the allowable range; (c) when body fat percentage is entered as a descriptive category, the GUI will use the equations presented earlier in the paper to calculate body fat percentage; (d) when body fat percentage is known, i.e., inputted, the GUI will check to ensure that fat% value is within a range of ± 2 SE of the body fat percentage calculated, using the equations described above; (e) ensure that the body fat percentage is above 5% for males and 12.0% for females; (f) after the completion of the above checks, the GUI will run SCTM.

VALIDATION

Physiological data collected at USARIEM and the University of Manitoba were used to validate SCTM. In a USARIEM study, 10 subjects walked on treadmills at 0.44

m/s and 0.88 m/s in 10°C and 15°C water up to chest and waist levels for approximately 2 hours (5;31). In a University of Manitoba study, up to 10 subjects sat in 8°C water for up to 6 hours (32). Comparisons between predicted and measured core temperature (T_c) indicated that the prediction fell within the range of measured $T_c \pm$ SD. PSDA was also validated using accidental water immersion cases reported in the published literature. When this report was prepared, we could not identify any reports of victims on rafts, boats, or other platforms out of the water containing sufficient data to use to validate the model for long-term exposure in air.

ACCIDENTAL WATER IMMERSION (GUAYMAS, MEXICO)

The accidental data used to validate PSDA involved a group of 6 individuals who were immersed in 17°C water after their dive vessel capsized off Guaymas, Mexico (26). One victim (No. 1, Table 8) was wearing a kapok life vest and swam for 35 hours to get help. The other five victims (Nos. 2-6) clung to a wooden door. One victim (No. 2) was wearing a full wet suit, but the other victims were wearing only pajamas. A rescue vessel arrived on the accident scene 38 hours after the incident and found only one survivor (No. 2). As the other four victims slipped away, No. 2 recorded the time. Table 8 provides the basic characteristics of the victims and their recorded and predicted survival times (assuming nude immersions), as well as the predicted survival time victim No. 2 adjusted to include the insulation provided by the wetsuit. The predicted ST was based on the time required for the core temperature to drop below 30°C. The predicted ST for victims Nos. 3-6 were close to their observed survival time. For victim No. 2, the difference in ST with and without a wet suit was approximately 19 hours. The predicted ST in the wet suit is close to his observed exposure time and actual ST in the water. It is likely that the wet suit saved his life.

Table 8. Guaymas casualty characteristics and observed and predicted survival time

No.	Height (m)	Mass (kg)	Obs ST (hr)	Pred ST (hr)
1	1.75	100	35	32.1
2	1.78	91	38	41.2*
3	1.83	83	14	13.1
4	1.80	86	12	17.0
5	1.68	73	11	13.0
6	1.64	68	9	11.4

* with wet suit. Prediction without wetsuit was 22.3 hours.

PROLONGED IMMERSION CASE (NEW ZEALAND)

An experienced diver wore a wetsuit and survived 75 hours of immersion in 16°C water. The wind speed was about 2.1 m/s. He reported feeling delirious and disoriented toward the end of his third day in the water. This is consistent with a core body temperature drop to 32°C to 33°C (down from the normal 37°C). A further loss of 2°C or 3°C would have resulted in unconsciousness and drowning (http://www.divenewzealand.com/articles.asp?sid=721, accessed on Mar 3, 2008). His height and weight were 1.75 m and 105 kg (Chris Turner, private communication). He wore a New Zealand Navy wetsuit including gloves and hood. PSDA predicted his cold functional time of 72.3 hours and cold survival time of 81.3 hours. The predicted core temperature at 75 hours was 32.5°C which appears to be close to the observed core temperature.

CHANNEL SWIMMERS (ENGLAND-FRANCE CHANNEL)

Swimming increases both heat production and heat loss, and thus exerts a strong but uncertain influence on the heat balance of a human body during immersion. From a physiology perspective, it is not yet clear whether swimming ultimately increases or reduces survival time. Although PSDA in its present format cannot account for these conflicting effects, it is still useful to see if PSDA can predict survival times for swimmers with reasonable accuracy. Physiological data for nine channel swimmers (1955 & 1956, England-France)(20) were used to validate PSDA predictions. Table 9 includes the following data: height, weight, time in water, predicted functional time, observed rectal and mouth temperature at the end of swimming. Predicted functional times were used instead of the predicted survival time, as all swimmers survived. Swimmers 5 through 7 were female. The water temperature was 18°C for swimmers 1 through 7, and 16°C for swimmers 8 and 9. The predicted functional times for all swimmers except swimmer No. 1 were longer than the time spent in the water. The question is how long they might be able to continue swimming? Predicted core temperatures for 6 of 9 swimmers were close to (difference less than 1.0°C) or higher than the observed core temperature; this indicated that the predicted survival times were probably conservative for these six swimmers. However, the predicted core temperatures for the remaining three swimmers were lower than the observed core temperature, and the predicted survival times would thus not be conservative. A Student t-test indicated that the differences between observed and predicted core temperatures at the end of swimming were not significant ($p>0.05$).

Despite the fact that PSDA was not designed to accommodate the complicated interaction between increased heat production and increased heat loss while swimming, PSDA predictions made using a simpler set of assumptions still predicted the cold functional time and cold survival time with an acceptable degree of accuracy. Based on these results, it would therefore seem acceptable to use “resting” conditions to simulate the thermal state of swimmers/“swimming” conditions. Whether these results for well-trained swimmers can be applied to cases involving untrained swimmers will need to be studied further when additional data becomes available. From the data, it appears that both swimmers 1 and 4 were able to produce sufficient metabolic heat to raise their core temperatures. As presently configured, PSDA assumes that the subjects are resting and produced heat only by involuntary shivering heat production and, thus, cannot simulate this phenomenon.

Table 9. Immersion time, predicted functional time, observed and predicted core temperatures at the end of swimming for Channel swimmers

No	Height (m)	Mass (kg)	TIW (hr)	Pred FT (hr)	Obs T_c (°C)	Pred T_c (°C)
1	1.72	82	23.5	17.8	37.8	28.7
2	1.79	86	11.7	17.2	36.1	35.9
3	1.73	82	12.1	18.5	34.0	36.0
4	1.83	103	9.7	29.7	38.3	36.2
5f	1.58	69	7.8	18.3	37.0	35.9
6f	1.58	63	3.8	14.2	36.3	35.8
7f	1.70	71	4.0	13.1	35.0*	35.7
8	1.60	77	12.5	17.2	35.5	35.8
9	1.70	87	18.0	19.8	34.8	35.1

TIW: time in water; Pred FT: predicted functional time;
Obs T_c: observed rectal temperature except where noted by an asterisk;
Pred T_c: predicted core temperature; * mouth temperature;

ACCIDENTAL WATER IMMERSION (CHAMBERLAIN LAKE, MAINE)

Three people went fishing and their boat sank in water at a temperature of about 10°C (50°F) (3). The three victims wore life jackets. One victim was rescued and survived, but the two other victims died of hypothermia within ~2 hours. Table 10 showed the characteristics of the victims, ST, and predicted ST. The survivor, i.e., No. 1, was about to lose consciousness when rescued. It would be reasonable to believe that he would not have survived for more than a few more hours. Thus, his survival time would have been more than the observed ST of approximately 2 hours, but probably less than the predicted ST of 12.4 hours. Heights and weights are in English units, demonstrating that PSDA allows the use of both metric and English unit systems. Prediction for this accident appeared to be conservative.

Table 10. Chamberlain Lake victim characteristics, observed and predicted survival time

No	Height (ft)	Mass (lbs)	Obs ST (hr)	Pred ST (hr)
1	6	220	~2	12.4*
2	6	170	1	5.0
3	5’10	158	1-2	4.2

*survivor

ACCIDENTAL WATER IMMERSION (PACIFIC OCEAN, NORTHERN CALIFORNIA)

A fishing vessel capsized and sank in 14.4°C water of the Pacific Ocean off the coast of northern California (18). After approximately 9.7 hours, two crew members were rescued. One crew member, who was able to don a survival suit, experienced only a minimal decrease in core temperature and was discharged from the Emergency Department. The other crewman was not able to don a survival suit. He was not observed to be shivering immediately after rescue, but shivering began during transport to the hospital. His rectal temperature was 30°C on initial examination at the Emergency Department.

The height, weight, body fat percentage, observed and predicted STs, and observed and predicted core temperatures were shown in Table 11. Because height and weight for the first crew member were unknown, height and weight for an average American male, as listed in Table 3, were used in the simulation, and body fat percentage was calculated. It was further assumed that he wore a Heavy Marine Suit, as listed in Table 9. The predicted core temperature of 36°C was close to observed core temperature.

The second crewmember's height, weight and body fat percentage were measured. His body fat percentage was low - even lower than the "very lean" person. Predicted survival and functional times were 19 hours and 16 hours, respectively; longer than his actual time in the water. The predicted T_c after 9.7 hour immersion was 35.6°C, which was higher than the core temperature measured at the Emergency Department. Based on the model, the T_c measured at rescue should have been higher than 30°C. However, due to the afterdrop phenomena, the temperature can be lower than the T_c value predicted at the time of rescue. Afterdrop is when T_c continues to drop after victims are removed from the cold water, because blood redistribution and conductive heat transfer from the core to the skin (9). Even so, the predicted T_c was several degrees higher than the measured T_c. However, the second crewmate was not shivering when rescued. This suggested that his T_c would have dropped rapidly and he would have died of hypothermia within a short time. It was unlikely that he would have been able to stay alive in the water for another 9-10 hours. Thus, the predicted ST for the second crewmate appeared to be a probable over-prediction of survivable time in water which errors on the side of caution by allowing a longer search time.

Table 11. Northern California casualty characteristics, observed and predicted survival times

No	Height (m)	Mass (kg)	Fat (%)	Obs ST (hr)	Pred ST (hr)	Obs T_c (°C)	Pred T_c (°C)
1	1.86*	86*	25.6*	9.7	24.3	~37.0	36.0
2	1.79	102	19.6	9.7	19	30.0	35.6

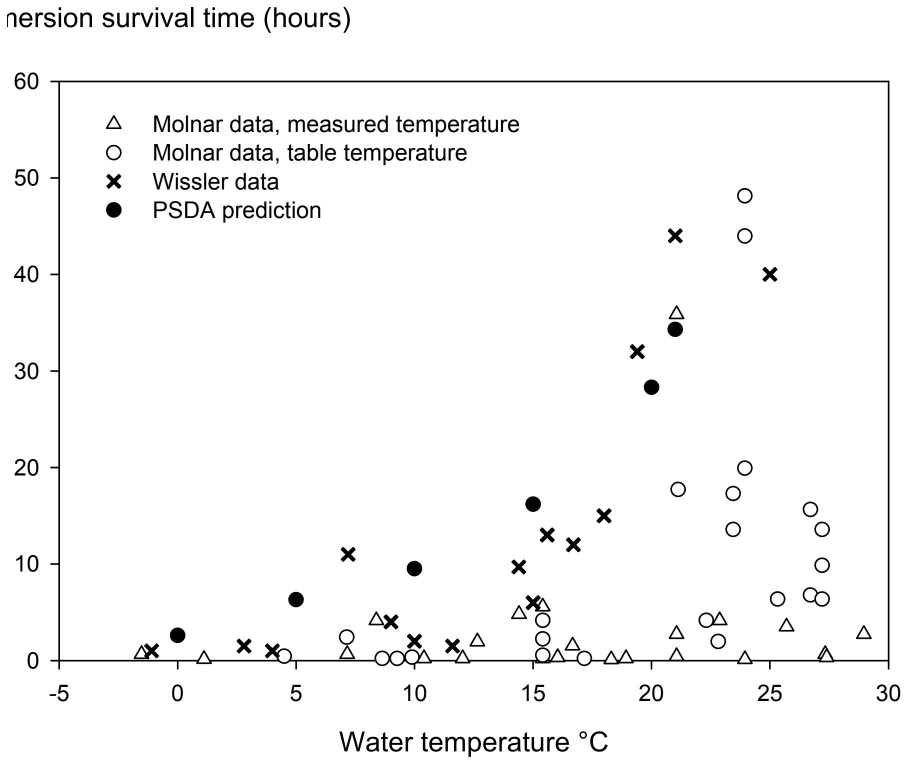
* average American, predicted body fat percentage

MOLNAR SURVIVAL DATA

Molnar analyzed the survival data during WWII and generated a survival curve, i.e., Molnar curve (17). This has been the basis for many cold prediction efforts. Recently Wissler augmented the Molnar survival data with survival data he collected (Wissler, private communication). PSDA prediction was compared with the Molnar and

Wissler data. Figure 4 shows data from Molnar's original study, together with subsequently reported data. Molnar's data are designated by open circles where water temperature was recorded, and triangles where temperature was obtained from tables of typical water temperatures. Wissler data points are designated by "x." Black circles show PSDA predictions for an average America of 1.76 m and 86 kg with normal body fat percentage and wearing bathing suits. When the water temperature was below 20°C, only two cases survived longer than PSDA predicted survival time. PSDA prediction appears to be consistent with these data. The individual differences in height, weight, fat%, and clothing influences the survival time significantly, but are not reported in the data.

Figure 4. Molnar's survival data augmented by recent data, and PSDA prediction. Open triangles (Δ) and circles (○) for Molnar data, x for recent data by Wissler, and black circles (●) for PSDA prediction for average American of 1.76 m height and 86 kg body weight



LONG-TERM DEHYDRATION, CAR ACCIDENT CASE (SEATTLE, WASHINGTON)

A woman was trapped in her car during a car accident in September 2007 for 7-8 days (2). She was found alive but dehydrated and in critical condition with kidney failure. The average air temperature for that period, obtained from www.accuweather.com, was about 13°C. Actual physical parameters for the victim were unavailable. The average American woman has a height of 1.62 m and weight of 74 kg, as shown in Table 3. Using those parameters, her predicted cold survival time was 107 hours or 4.5 days if she was wearing regular spring/fall clothing and hypothermia was the main issue. The predicted dehydration survival time was 192 hours or 8 days if she was wearing winter clothing. Dehydration, not hypothermia, was the main issue.

SUMMARY

Heights and weights were available for a total of 10 victims of accidental water immersion cases that did not involve swimming. The predicted survival time for each victim was either very close to, or greater than, the observed survival time. The values predicted by PSDA appear to be conservative. Additional data are needed to make further comparisons.

DISCUSSION

BEST AND WORST CASE SCENARIOS

Many factors play a role in determining survival time. PSDA uses a set of simple conditions and assumptions, such as shown in Figure 1, to simulate survival times. To further complicate the situation, it is often impossible to obtain accurate information – a critical requirement to optimize the accuracy of simulations. Consequently, some input has to be estimated or simply based on speculation. Uncertainties in the model inputs lead to inaccuracies in the predictions. To overcome the potential errors associated with inaccurate inputs, ideally PSDA should be run multiple times to produce a range of ST outcomes. One approach for dealing with these uncertainties is to run all reasonable combinations or scenarios of parameters. However, this approach may simply require too much time. A less intensive computational approach would be to simulate the best- and worst-case scenarios. To accomplish this, the inputs most likely to simulate the best and worst outcomes must be identified. PSDA inputs, as shown in Figure 1, influence ST in predictable patterns. Generally speaking, ST increases when the following happens:

1. air/water temperature increases;
2. immersion state changes from the neck level to waist levels, or from rough sea to calm sea, or from sea to air;
3. body weight, for a given height, increases;
4. clothing insulation increases.

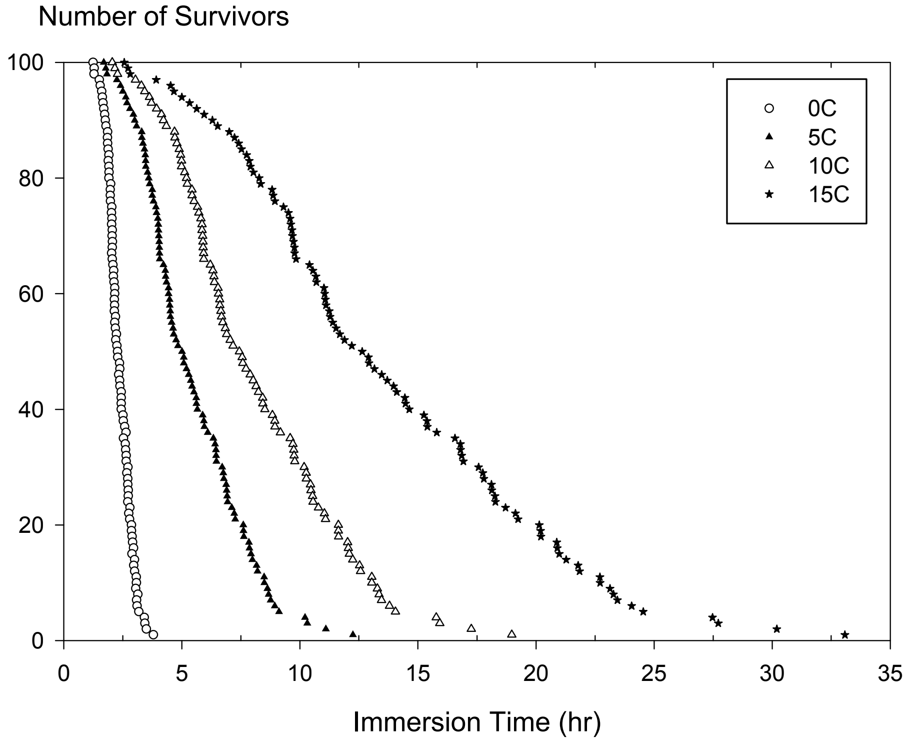
ST is reduced when the parameters described above change in the opposite direction. Body fat percentage, which is dependent upon height and weight, may increase or decrease ST. Since insulation of fat is proportional to the body fat percentage, but shivering is inversely proportional to body fat percentage, it would be necessary to manipulate body fat percentage to see how it affects ST for certain combination of height and weight. Therefore, for the best possible scenario, the input parameters that are unknown or not well defined should be selected to reflect the condition most likely to increase ST. For the worst possible scenario, the suspect input parameters should be changed to reduce ST.

The following example demonstrates how the best or worst possible scenario can be created. Known inputs are environmental conditions (e.g., air temperature 10°C, water temperature 7°C), immersed state "Rough Sea to Neck level", and the height and weight of the victim (1.76 m and 86.0 kg). Inputs with uncertainty are body fat percentage and clothing. Predicted ST was 7.5 hours if the fat level of the victim was "medium" and the victim wore a swimming suit. ST was reduced to 5.3 hours if the body fat level of the victim changed to "very lean," and increased to 8.5 hours if the fat level changed to "very fat." ST increased to 25.1 hours when the victim with medium body fat wore "Dry Suit, Double Pile, & Vest." As noted above, clothing insulation increases ST significantly, thus, it is critical to pay attention to what clothing the victim might be wearing.

INDIVIDUAL DIFFERENCE IN PREDICTED SURVIVAL TIME

Individual differences in survival times are high. Even under similar conditions, some people survive only for a few hours, while other victims survive much longer. One factor affecting ST is body build, i.e., height, weight, and body fat percentage. PSDA was used to simulate survival times for 100 computer generated "individuals" to demonstrate how individual anthropometric variability may alter ST. Height was first generated by a Monte Carlo method using the height distribution. Weight was then generated by a Monte Carlo method using the weight distribution corresponding to a given height interval or range (Yokota, M., Monte Carlo simulation program for human body dimensions version 0.5. STATA8.0 September 9 2007, USARIEM). Body fat percentage was then calculated from height and weight using BMI. The survival times for immersion at water temperatures of 0°C, 5°C, 10°C, and 15°C for a population of 100 subjects was predicted by PSDA. The results are shown in Figure 5. Predicted STs demonstrated significant variance in the probability of survival. About 50% of the test population should survive hypothermia for 2.8, 5.0, 7.4, and 12.6 hours at water temperatures of 0°, 5°, 10°, and 15°C, respectively. At 0°C, ST varied from 1.2 to 3.8 hours. That range of predicted ST values appeared to be consistent with events during the Titanic shipwreck, where water temperature was near 0°C and virtually no survivors were present after 2 hours (29).

Figure 5. Predicted survival times for 100 victims during immersion at 0°C, 5°C, 10°C, 15°C water



The results in Figure 5 can also be interpreted as the population-based probability of survival. This method provides a means to predict the number of survivors during accidents that involve a large number of victims, such as a shipwreck. The results indicate that the number of survivors or survival rate, essentially another way of expressing the probability of survival, is reduced over time. However, in contrast to this approach, Wissler's model is for an individual victim and predicts the individual based probability of survival. It should be made clear that population-based and individual based probabilities of survival are different concepts, and that the relationship between the two probabilities of survival will need to be studied further. This version of the PSDA predicts the individual (Wissler) based probability of survival.

INTERPRETATION OF RESULTS

As mentioned before, predicted survival time is the time for core temperature to reach 30°C, or dehydration level to reach 20% of body weight. Predicted cold functional time is the time when core temperature reaches 34°C and represents the point when the capability to participate in self-rescue or the ability to perform effective external work stops. Selection of these thresholds was based on common knowledge of hypothermia or dehydration, but these thresholds are dependent on individual tolerances. Some victims may survive more extreme core temperature or dehydration levels than those assumed for the model. In addition, an individual's physiological responses may vary in response to the specific circumstances of a given emergency situation. Given the nature of data collected during life-threatening emergencies, it is virtually impossible to identify relatively subtle differences between conditions, victims, or other factors. Thus, the predicted results should always be explained with "likely." For example, if predicted ST is 30 hours, it should be understood that the hypothermic ST is likely to be about 30 hours.

When the predicted cold ST or FT is predicted to be 80 hours, this indicates that the core temperature was not expected to reach the functional (34°C or 89.6°F) or survival (30°C or 86°F) temperature thresholds during 80 hours of immersion. Under these conditions, other factors such as fatigue, the will to survive, and survival skills may affect survival time. As these factors are not incorporated into the model, the expertise of search and rescue personnel provides an important reality check. Thus PSDA should be used only as a decision aid to provide additional information. In the decision-making process, the final decision ultimately must rely on experienced search and rescue personnel. For example, a recent study of search and rescue operations in Oregon, that included land, mountain, and lake cases, concluded that the probability of finding victims alive was high during the first 17 hours, moderate between 17-50 hours, and low after 51 hours (1). This type of experience-based knowledge provides search and rescue personal with a good point of reference for incorporating thermal modeling into the overall search and rescue operational planning.

Either hypothermia or dehydration may limit survival during air and boat exposure cases in warm conditions. When the dehydration survival time result is given as 240 hours, it means that dehydration level is not expected to reach 20% of body weight. When dehydration is the factor limiting survival (predicted ST is 240 hours), it should be noted that the accuracy of the prediction is expected to be low. Few, if any, exposure cases of this duration have been documented. Survival is also affected by changes in weather. For example, the occurrence of rain during this period would significantly increase survival time (4).

When water loss estimated from the empirical equation (Eq. 1) and predicted by SCTM are not in agreement, it is advisable to consult experienced personnel during the decision-making process, as mentioned above. The empirical equation was only based on the physiological data under experimental conditions, whereas SCTM was a rational model, based on physiological mechanisms. Based on our best knowledge, there are not any data for long-term water loss or dehydration available for use. Thus, it was difficult to determine whether the empirical equation or SCTM was more accurate for water loss prediction.

PSDA calculates the probability of survival by Wissler's method (29) as described in Appendix B. Wissler's original method was developed for hypothermia in immersion conditions, but the method was extended to cover hypothermia during air exposure and dehydration. Wissler's fatality function (Appendix B, Eq. 6) was developed to ensure that the half-life time predicted by his model approximated the Molnar curve (see

Appendix B). Due to the lack of any observed physiological data, the fatality function for hypothermia during air exposure (Appendix B, Eq. 7) and the function for dehydration (Appendix B, Eq. 8) are based on theoretical assumptions. Therefore, the probability of survival should be considered strictly as a theoretical value, and users should be aware of this limitation when they use the probability of survival in applications.

LIMITATIONS

PSDA was developed from the SCTM and an empirical sweat prediction equation. PSDA uses ten inputs for environmental conditions, human physical parameters, immersion state, and clothing to simulate the survival conditions of victims on or in the water. Obviously, defining survival on the basis of only ten parameters does not capture the complexity, nor fully describe all of the conditions that coalesce to determine actual survival. During actual incidents, additional factors, such as wave height, trauma sustained by the victims, and alcohol use, can influence survival outcome. All models are a simplification of true reality. Survival is a complicated physiology process that can only be studied through accident analysis. Thus, the circumstances surrounding each accident or incident are unique. Well-documented case histories are rarely available to use for validation and/or development of survival models. These limitations make model development a difficult task, as the lack of sufficient data for an in-depth validation ultimately means that the model should be considered, to a degree, untested. With the unavoidable limitations and compromises with respect to model development and validation, it should be clear that the PSDA model, or any survival model, should be used with a degree of caution.

RECOMMENDATIONS

(1) All users must read this technical report and understand how PSDA works and what it predicts.
(2) When PSDA is used, inputs should be collected as precisely as possible. Accuracy of inputs affects the predicted results directly. For situations where the inputs are unknown or incomplete, establish reasonable ranges for each parameter and then see how they affect the results. Run multiple scenarios, including best and worst case scenarios, rather than relying on a single run. Results from multiple scenarios will provide a better basis for decision-making than the results obtained from a single set of conditions.
(3) PSDA development is a continuing process. When PSDA is used, information such as inputs should be recorded, along with information regarding the actual information and outcome of the search process. This will help users to better understand how PSDA prediction should be used to support the decision-making process. Ultimately, this type of information will help to improve future revisions of PSDA and lead to better ways to integrate PSDA into the overall decision-making process.
(4) When an adequate number of cases of PSDA applications have accumulated, it will be essential to evaluate PDSA performance using information from the cases. Based on the outcome of the review, further improvement can be made to PSDA.

(5) Due to lack of sufficient data for validation, the PSDA model should be considered, to a degree, untested and, thus, used with caution. PSDA is a tool that allows the USCG user to analyze possible survival scenarios and to better assess the situation. PSDA can be used to assist the USCG search and rescue personnel in making decisions, but cannot be used as the primary basis for making search and rescue operation decisions. Any decision to suspend a search and rescue mission should be made by USCG search and rescue personnel.

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APPENDIX A
USER'S GUIDE – PROBABILITY OF SURVIVAL DECISION AIDE (PSDA)

INTRODUCTION

The purpose of the Probability of Survival Decision Aid (PSDA) is to provide U.S. Coast Guard (USCG) personnel assistance in estimating possible survival times during Search and Rescue (SAR) operations. PSDA requires inputs of environmental parameters, human physical attributes, immersion state and clothing ensembles, and predicts cold functional time, cold survival time, and dehydration survival time. During SAR operations the information required for the inputs may be limited or simply unavailable. To assist the user, some pull down menus list general categories that can be selected when more specific information is unavailable. PSDA outputs are described in detail in the main text and briefly below under the heading **RESULTS**.

USING PSDA

The Graphic User Interface (GUI) display screen is organized into zones for entering environmental parameters (Figure 6, box 2), physical attributes of missing individuals (box 3), and immersion state and clothing (box 4). Results (box 5) are computed after the operator button (box 6) labeled **COMPUTE** in the lower right corner is clicked to run the PSDA program. Box 1 also shows the location for the **FILE, VIEW** and **HELP buttons**. It is strongly recommend that users read the technical report before using PSDA.

Entering Environmental Parameters

Input environmental conditions: **AIR TEMPERATURE, WATER TEMPERATURE, RELATIVE HUMIDITY** (RH), and **WIND SPEED**, as shown in box 2, Figure 6. Clicking on the arrow on the buttons displaying the units to the right of the value input boxes allows the user to select unit options for temperature (°C or °F) and wind speed (m/s, knots, mph). The range of these parameters are Air Temperature -45°C to 45°C; Water Temperature: 0°C to 35°C; RH 1-100%, and wind speed: 0.09 to 41.0 m/s. If values are outside the assigned ranges, when the "compute" box is clicked, exclamation points inside the red circle will appear to the right of the out-of-range values. Initially these error symbols will blink on and off. If victims are in air, or on a boat or raft, the water temperature is not needed.

Physical Attributes – Description of Missing Person(s)

Input physical attributes-- **SEX, HEIGHT, WEIGHT,** and body **FAT** -- as shown in Figure 6, box 3. After picking the **SEX** (gender) of an individual by clicking on the appropriate circle, the user can either enter the missing person's height or select a descriptive terms from a menu of descriptive terms by clicking on the arrow on the right margin of the **HEIGHT** box. There are three boxes in the row for height. The middle box faintly displays the height associated with the descriptive term or the value handentered by the user. The units for height can be changed by clicking the arrow on the right box to select the desired units (feet and inches, cm, or m). The values associated with the descriptive categories differ for males and females. In a similar manner, **WEIGHT** may be entered for the missing individual. The unit options are lbs or kg. The height and weight of average Americans are 1.76 m and 86 kg for male and 1.62 m and 74 kg for female. Select or input the body fat percentage "**FAT,**" e.g., 17.0%. If the body fat percentage is unknown, select a descriptive term that is appropriate.

Immersion State and Clothing Ensembles

The box for **IMMERSION STATE** has an arrow on the right margin, as shown in Figure 6, box 4,. Click to display a list of descriptive categories. The choices are either out of the water on a raft, boat, or other platform (**AIR/BOAT**), or being immersed in either calm or rough water at a depth equal to neck, chest, or waist level. The Air/Boat option is for victims in a boat or raft who are not immersed. When victims are in water, immersion state should be "to Neck." When victims cling to a capsized boat or other, immersion state could be "to Chest or Waist." Default for immersion state in water is **Rough Water to Neck**.

The box for **CLOTHING** also has an arrow on the right for five descriptive categories ranging from virtually no clothing to winter weight clothing for Air/Boat condition, or for eleven descriptive categories ranging from virtually no clothing to a dry suit for immersion conditions, as shown in box 4.

Compute – Run the Model

Once all input fields are addressed, click on the button labeled **COMPUTE** in the lower right corner of the GUI, as shown in Figure 6, box 6, The GUI will quickly display the following output in the **RESULTS** section (box 5): **COLD FUNCTIONAL TIME, COLD SURVIVAL TIME, and DEHYDRATION SURVIVAL TIME**.

Results

COLD FUNCTIONAL TIME is the time that the predicted core temperature reaches 34°C or 89.6°F, and **COLD SURVIVAL TIME** is the time that predicted core temperature reaches 30°C or 86°F. **DEHYDRATION SURVIVAL TIME** is the time predicted for water loss to reach 20% of body weight. When air temperature is between 5°C and 35°C, the time for water loss to reach 20% is also calculated by an empirical equation as a secondary estimation and can be seen using the "**VIEW**" button (Figure 6, box 1).

File

SAVE RESULTS: to save results for a record, click on this option. **PRINT RESULTS**: to print out the results, as shown in Figure 6, box 1. **EXIT**: exit the PSDA.

View

Clicking on **VIEW** (Figure 6, box 1) will display the **EMPIRICAL DEHYDRATION ESTIMATION** option. When air temperature is between 5°-35°C, the time for water loss to reach 20% is also calculated by the empirical equation as a secondary estimation and can be seen by clicking **VIEW**.

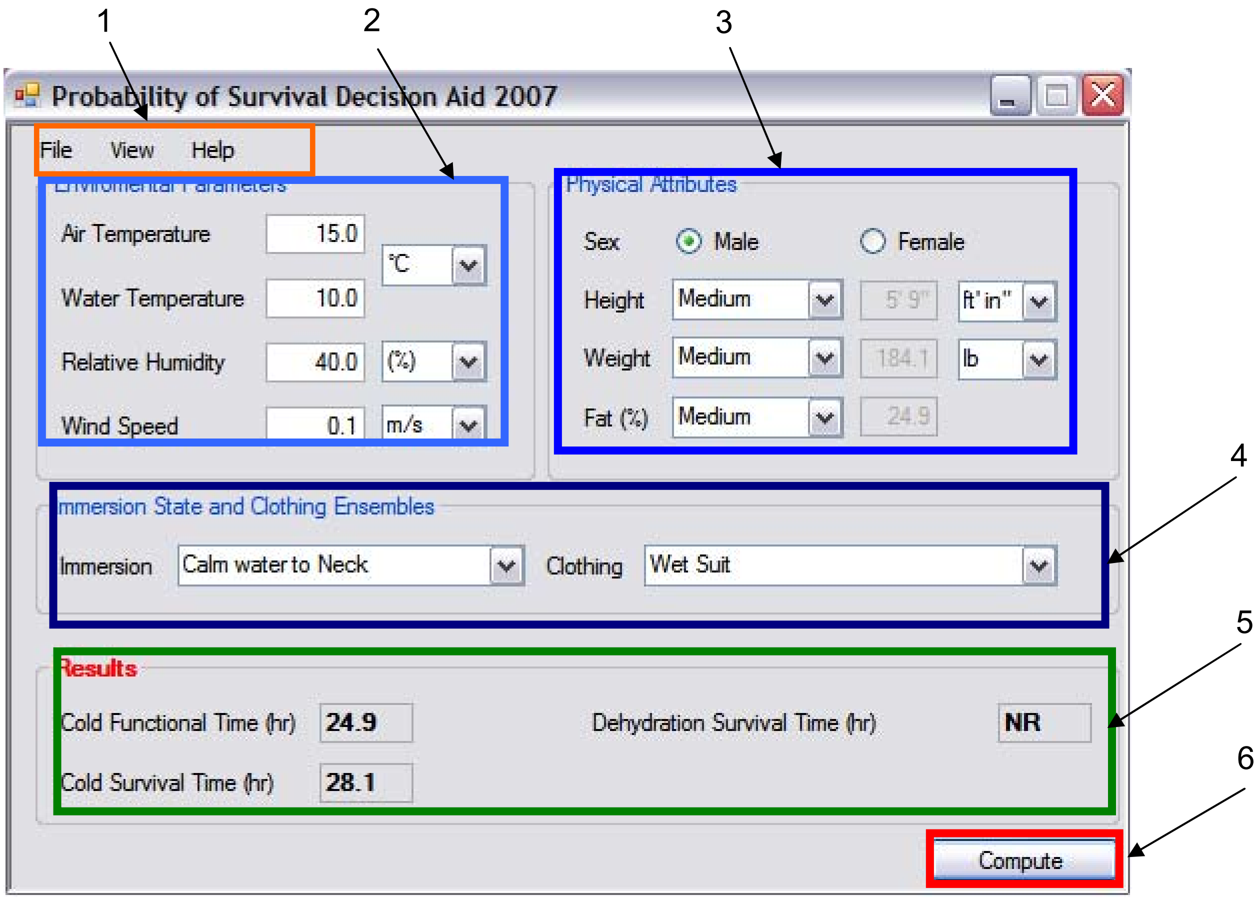
Help

Clicking on the HELP option (Figure 6, box 1) will display the following choices:

HELP/HELP In this version of the GUI, only a limited number of definitions and other guidance are provided. At a later date, an abbreviated version of a User's Guide will be included.

HELP/DISCLAIMER – displays USARIEM logo, the full legal disclaimer and contact information.

Figure 6. Graphic User Interface for Probability of Survival Decision Aid



Probability of Survival Decision Aid 2007

Enviromental Parameters

Air Temperature 15.0 °C

Water Temperature 10.0

Relative Humidity 40.0 (%)

Wind Speed 0.1 m/s

Physical Attributes

Sex ● Male ○ Female

Height Medium 5' 9" ft' in"

Weight Medium 184.1 lb

Fat (%) Medium 24.9

mmersion State and Clothing Ensembles

Immersion Calm water to Neck

Clothing Wet Suit

Results

Cold Functional Time (hr) 24.9

Dehydration Survival Time (hr) NR

Cold Survival Time (hr) 28.1

APPENDIX B
THEORETICAL PROBABILITY OF SURVIVAL

Probability of survival (POS) is the likelihood of survival for a particular victim at a given point in time during accidental immersion. Several potential threats to survival, including initial cold shock, swimming failure, hypothermia, and dehydration, may cause death, injury, or trauma. Survival means that a person survives the combined hazards of initial cold shock, swimming failure, hypothermia, and/or dehydration. Non-survival (death) means that this person does not survive at least one of these four threats. From the perspective of probability, it would be convenient to consider them as independent events. Due to lack of supporting evidence and data, initial cold shock and swimming failure are hard to predict and are probably very dependent on individual characteristics and/or the circumstances of the specific incident. Therefore, our efforts focus on the POS the hazards of hypothermia (event A) and dehydration (event B). POS could be calculated as:

$$POS = P(A) \cdot P(B) \tag{4}$$

POS=1 indicates the person survives, and P=0 indicates that the person died. Death may be caused by either A or B. P(A)=1 indicates the person survives the hypothermia, and P(A)=0 indicates the person died due to hypothermia. P(B)=1 indicates the person survives dehydration, and P(B)=0 indicates the person died due to dehydration. “Alive” means the person survives both A and B.

Wissler developed a theoretical method to estimate POS from the core temperature (28). A detailed explanation of Wissler’s methodology was described in his paper. His method was adapted in this work to estimate POS. The probability that a fatal event occurs in the short time interval Δt is equal to the product of the probability that the victim survives to time t and the probability that a fatal event occurs in Δt. Thus, POS follows the equation:

$$\begin{gathered} \frac{dP}{dt} = -P \cdot f \\ P = 1.0 \quad t = 0.0 \end{gathered} \tag{5}$$

where P(t) is probability of survival function, t is the time in hour, and f is fatality function in 1/hour. The initial condition assumes that P is 100% before immersion. The fatality function, a function of time, is defined as:

$$\begin{aligned} f &= 0.0 && T_c > 36.0 \\ f &= 0.01167 \cdot e^{(2.089 \cdot (36.0 - T_c))} && T_c \le 36.0 \end{aligned} \tag{6}$$

The difference (36.0-T_c) was limited to a max of 2.0°C.

Eq. 4 is applicable to the water immersion condition. To extend it to cold air condition, where the reduction in T_c is a slower process, it was modified as following:

$$f = 0.01167 \cdot e^{(1.253 \cdot (36.0 - T_c))} \quad T_c \leq 36.0 \tag{7}$$

The probability of survival function and fatality function were extended to dehydration survival conditions. Eq. (5) is assumed to be applicable to dehydration survival condition, but the fatality function for dehydration is defined as:

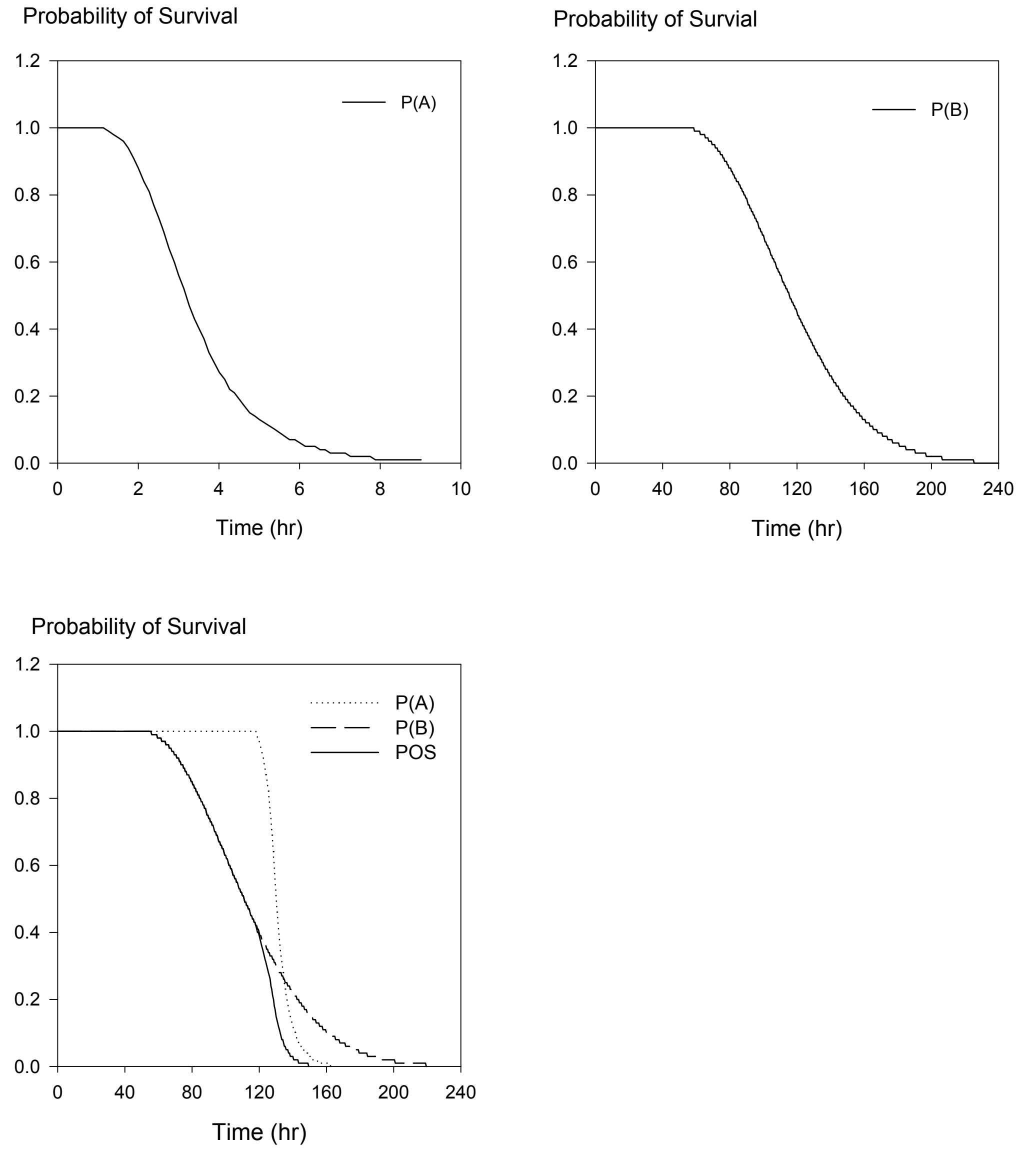
$$f = 0.38 \cdot (WL - 0.05) \tag{8}$$

WL is the weight loss percentage, which includes normal water loss in urine and water loss as sweat.

While SCTM calculates T_c and WL, the predicted T_c and WL go into Eq. 4 thru 8 and are used to calculate POS. P(A) is equal to 1 when T_c is above 36°C, and starts to drop when T_c fall below 36°C. Usually POS is below 10% when T_c is below 30°C. In the similar way, P(B) is 1 when WL is less than 5%, and starts to decline gradually as WL increases to 20%, until it approaches 0 when WL is over 20%. Figure 7 shows POS during cold water immersion, warm air exposure, and cold air conditions. During immersion at 9°C water, i.e., top left, T_c falls to below 30°C in about 7.5 hours, and POS falls gradually from 1 to 0, accordingly. Within this short time period, P(A) is the domain component and, thus, POS is equal to P(A). During exposure in 30°C air, i.e., top left, WL increases to 20% of body weight in about 225 hours, and POS reduces from 1 to 0 gradually. As T_c is stable and over 36°C, P(B) is the domain component and, thus, POS equals P(B). During exposure to 20°C air, i.e., bottom left, POS was influenced by both hypothermia and dehydration.

Following an accident or other emergency, the circumstances that contribute to a threat to personal survival are a complicated and virtually unique set of conditions. The probability of survival model is a mathematical way to simulate/describe the physiological processes that determine the probable outcome for a given life-death situation. Unfortunately, the physiological data needed to validate the model are often limited to post-hoc case histories based on the recollections of survivors and SAR personnel. Consequently, POS predictions should be considered a theoretical number. Further research is needed to fully establish methodologies for interpreting POS that will provide an answer that is operationally meaningful to USCG.

Figure 7. Probability of Survival. top left: immersion at 9°C water, P(A), i.e. probability of survival due to hypothermia, is a domain component and POS is equal to P(A); top right, exposure to air at 30°C, P(B), i.e. probability of survival due to dehydration, is a domain component and POS is equal to P(B); bottom left, exposure to air at 20°C, POS is influenced by P(A) and P(B).



APPENDIX C
MODEL SELECTION AND EVALUATION OF SWEAT RATE PREDICTION

In this section, USARIEM models have been validated with experimental data and compared to determine the accuracy of sweat prediction of each models.

USARIEM THERMAL MODELS

USARIEM has been developing thermal models to predict human thermal responses to heat, cold, and water immersion for several decades. At present, the three major USARIEM models are the Six Cylinder Thermoregulatory Model (SCTM)(32;33), SCENARIO(14), and the Heat Strain Decision Aid (HSDA)(10;11;19). The SCTM and SCENARIO models combine the application of the first principles of the biophysics of heat exchange with a realistic approximation of human physiology, whereas HSDA is an empirical model. SCTM is applicable to cold, heat, and water immersion, while SCENARIO and HSDA are applicable to heat exposure. A description of each model is provided below:

SCTM is a six cylinder thermoregulatory model for heat exposure and prolonged cold exposure in the air or water. It takes into account physiological mechanisms, including metabolic heat production, sweating heat loss, respiratory heat loss, and blood circulation. It is able to predict both core and regional temperatures, and evaporative water loss through the skin and lungs, which can then be used to estimate dehydration.

SCTM was derived from an earlier version of a thermoregulatory model developed by Werner and Webb (27), which was, in-turn, based on the pioneering work of Stolwijk and Hardy (22). It is a six-cylinder model, with each cylinder originally consisting of core and shell layers. Recently, we added muscle, fat, and clothing layers (33) and incorporated a conceptual model for shivering intensity and fatigue into the current SCTM configuration. This has improved the model prediction of human responses to long-term cold exposure (32). Each cylinder is now divided into concentric compartments representing the core, muscle, fat, and skin. The outer cylinder has an optional additional clothing layer. Circulation is represented as a one-loop circulatory system and is an independent compartment. Thus, the human body is represented by 25 compartments. The size of each compartment is derived using height, weight, and body fat percentage (30).

In the active system of the model, an integrated thermal signal to the thermoregulatory controller is composed of weighted thermal inputs from thermal receptors at various sites distributed throughout the body. The integrated body temperature is weighted using the core, muscle, and skin compartment temperatures. The afferent signal is the difference between this temperature and its threshold, which activates thermoregulatory mechanisms including vasomotor changes, sweat production, and metabolic heat production (33). Shivering thermogenesis, i.e., part of metabolic heat production, is a function of core and mean skin temperatures, and includes an intensity adjustment, maximal capability, shivering exhaustion, and inhibition due to a low core temperature (32). The maximal shivering intensity was estimated from the height, weight, VO_{2max}, and age (7).

SCTM inputs include individual characteristics (i.e., height, weight, body fat percentage, age, VO_{2max}) and exercise intensity, as well as environmental (i.e., temperature, humidity, and wind velocity) and clothing (clothing insulation clo, moisture permeability index i_m) properties for each of the six cylinders.

SCENARIO was developed to predict human responses to heat stress, work loads, acclimation, and weather conditions. It is also a rational human thermoregulation model based on first principles of physiology, heat transfer, and thermodynamics. The model represents the human as six lumped parameter tissue compartments, five of which are concentric layers representing core, muscle, fat, vascular skin, and outer skin. The sixth compartment is blood, which interacts and exchanges heat directly with all of the compartments except the outer skin. At activities above resting, the increased energy is generated in the muscle compartment. The environment exchanges heat and moisture through the clothing and exposed skin and also exchanges heat and moisture with the core through respiration. The main mechanisms for active physiological body temperature control are in regulating sweating, and blood flow to skin.

The HSDA incorporates the biophysics of heat exchange, but it is an empirically based model that draws upon an extensive database of human studies conducted at USARIEM. It predicts core temperature, maximum work times, sustained work-rest cycles, water requirements, and estimated probability of heat injuries. HSDA takes into account various weather factors such as air temperature, wind speed, humidity, and solar radiation. Different versions of HSDA were developed, including a version for a hand-held calculator, tactical decision aids (TDA), and a simplified version for a personal digital assistant (PDA). One version has also been implemented as a weather product of the Army Integrated Meteorological System (IMETS).

SWEAT RATE PREDICTIONS

Water loss, i.e. dehydration, is one of two factors that PSDA uses to determine survival time. Thus, obtaining accurate predictions of water loss is important. As the SCTM, SCENARIO, and HSDA models all predict sweat rate, it is valuable exercise to compare accuracy of their predictions. This evaluation, along with other information on model performance, will provide a rational basis to select which model(s) will be used to predict survival times in warm environments. A recent study at USARIEM collected physiological data, i.e. sweat rate, in various environmental conditions and exercise intensity (6). These data were used to evaluate and compare predictions from these three models.

Experimental Data

Thirty-nine healthy Soldiers participated in 2- and/or 8-hour experiments in this study. The clothing ensemble was the U.S. Army woodland Battle Dress Uniform (BDU) with field cap, with sleeves down (clo = 1.08, i_m/clo = 0.49 at wind speed 1 m/s), and athletic shoes. Twenty-one volunteers (five women) participated in the 2-hour experiments. Descriptive characteristics for this group were: age 23 ± 4 yr, height 174 ± 8 cm, mass 76 ± 11 kg, and BSA 1.9 ± 0.2 m^2 (mean ± SD). Eighteen different volunteers (one woman) were enrolled in the 8-hour experiments. Their characteristics were: age 22 ± 4 yr, height 177 ± 4 cm, mass 80 ± 13 kg, and BSA 2.0 ± 0.2 m^2 (mean ± SD). The number of volunteers that completed each trial is provided in Tables 1 and 2, along with trial letter designations, environmental conditions, exercise cycle (work/rest), and other associated data. In the 2-hour study trials, volunteers were not heat acclimated, whereas in 8-hour experiments, volunteers were heat acclimated.

Table 12. Descriptive data for 2-hour experiments.

Trial	n	T_a (°C)	rh (%)	Work:Rest (min)	Metabolism (W/m^2)	SR (L/h)
A	15	15	50	2x (50:10)	261 ± 19	0.307 ± .129
B	15	15	50	2x (50:10)	348 ± 25	0.465 ± .159
C	15	20	50	2x (50:10)	178 ± 15	0.220 ± .089
D	19	20	50	2x (50:10)	248 ± 23	0.397 ± .162
E	17	20	50	2x (50:10)	349 ± 39	0.610 ± .191
F	13	25	50	2x (50:10)	178 ± 19	0.337 ± .110
G	10	25	50	2x (50:10)	256 ± 22	0.482 ± .226
H	11	25	50	2x (50:10)	348 ± 37	0.737 ± .244
I	11	30	50	2x (50:10)	345 ± 31	0.914 ± .309

Abbreviations: n (number of volunteers), T_a (air temperature), rh (relative humidity), SR (actual measured sweating rate). Values are mean ± SD.

Table 13. Descriptive data for 8-hour experiments.

Trial	N	T_a (°C)	rh (%)	Work:Rest (min)	Metabolism (W/m^2)	SR (L/h)
J	13	40	40	3x (60:20) 3x (60:20)	181 ± 29	0.647 ± .131
K	16	35	30	6x (60:20)	233 ± 33	0.559 ± .073
L	15	35	30	3x (60:20) 3x (60:20)	176 ± 15	0.452 ± .058
M	15	27	40	6x (60:20)	236 ± 24	0.397 ± .100
N	13	27	40	3x (60:20) 3x (60:20)	173 ± 15	0.260 ± .057
O	13	20	50	6x (60:20)	230 ± 19	0.224 ± .085

Abbreviations: n (number of volunteers), T_a (air temperature), rh (relative humidity), SR (actual measured sweating rate). Values are mean ± SD.

Predicted Sweat Loss

The SCTM, SCENARIO and HSDA models were used to predict the sweat loss (L/h) for the 15 conditions described in Tables 1 & 2. Inputs included mean heights and weights, clothing insulation, and moisture permeability index values that were measured on manikins, environmental conditions, and mean metabolic rates.

Predicted sweat losses were compared to the observed sweat losses in Figure 8. When the observed sweat loss is less than 0.8L/h, the predicted values for sweat loss for the three models are all in close agreement with the observed values. However, the deviation from the observed values increases when the sweat loss is greater than 0.8L/h. The measured water loss can be compared with the predicted water loss, using the root mean square deviation (RMSD). RMSD quantifies the average difference between predicted and observed measurement across time (12;14). The average standard deviation (SD) of observed sweat loss is 0.14 L/h, the RMSD for HSDA is 0.092 L/h, RMSD for the SCTM is 0.088 L/h, and the RMSD for SCENARIO is 0.135 h/L. These RMSD values are all less than the corresponding observed SD. When compared with results of 2-hour trials (A-I), the measured SR was 0.5 ± 0.18 L/h, while predicted SR by HSDA, SCTM, and Scenario were 0.47, 0.39, and 0.5 L/h, respectively. In comparison with results of 8-hour trials (J-O), the measured SR was 0.42 ± 0.14 L/h, while predicted SR by HSDA, SCTM, and Scenario were 0.54, 0.42, and 0.48 L/h, respectively. All predicted SR were close to the measured SR and within the range of mean ± standard deviation. Thus, for the data described above, water loss predictions from all three models were within acceptable limits. Water loss predicted by SCTM is acceptable for PSDA application.

Figure 8. Predicted (by three models) and observed sweat loss
during 2- and 8-hour exposure warm/hot environments during exercise/rest.