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Equations for predicting diver regional skin temperatures as a function of mean skin temperature

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Johnson CE, Collins JD, Piantadosi CA. Equations for predicting diver regional skin termperatures as a function of mean skin temperature. Undersea Biomed Res 1982; 9(1):59–74.—A series of linear algebraic equations have been derived from those of Kerslake (Flying Personnel Research Committee Memo 213, R.A.F. Institute of Aviation Medicine, 1964) for predicting the regional skin temperatures of a quasi-euthermic diver having pronounced vasoconstriction. The equations were developed by numerically analyzing twelve regional skin temperatures recorded from five resting subjects exposed to a hyperbaric chamber environment of 20°C, 95% helium, and 5% oxygen pressurized to the equivalent of 200 msw (650 fsw). The independent variable of the basic correlation is an arbitrarily defined mean skin temperature; the empirical equations were developed for the purpose of assisting a designer in estimating regional supplementary heating requirements for a diver wearing a thermal protection garment of known composition. The developed equations were authenticated by comparing the predicted normalized regional temperature with the respective experimental normalized temperature obtained from several sets of physiological data collected during the evaluation of the Naval Coastal System Center's diver thermal protection garment (DTP). The results of these comparisons of nondimensionalized temperatures indicated that the derived correlations should accurately predict the skin temperature of the principal regions as a function of mean skin temperature with a nominal error of no more than 15%.

skin temperature **mean skin temperature**
predictive equations **modeling of diver heat loss**
skin temperature in a hyperbaric environment

The observation is well established that the preferred mean weighted skin temperature of the human being at rest in a euthermic environment is 33°C ± 1°C. Associated with the resting state is a metabolic rate of about 55 W/m², most of which is emitted as waste heat and the remainder utilized for metabolic processes (1–3). Physiological laboratory studies have defined specific regional skin temperatures and rates of heat loss that are associated with the cited preferred skin temperature (3).

Kerslake (4) developed an algebraic model for predicting the temperature of any of 8 different regions, as a function of mean skin temperature, from extensive experimental studies of human subjects in a nearly steady thermal state. The equations that he developed were of the form:

$$T(i) = \overline{T}_{sk} \pm A(i) \cdot R \qquad (1)$$

where T(i) = regional skin temperature, $\overline{T}_{sk}$ = mean skin temperature, A(i) = distribution fraction for region i (Table 1), R = temperature difference between trunk and hands and feet, and i = regional index.

Piironen and Takalo (5) conducted a series of physiological experiments using an instrumented suit calorimeter with which they determined both regional heat fluxes and skin temperatures for a variety of work rates and degrees of vasoconstriction. In their three experimental subjects they found maximum vasoconstriction in the mean skin temperature range of 31°C–32°C and observed a 10% increase in metabolic heat production whenever minimum tissue conductance was attained. This observed increase in metabolic rate did not correlate with the onset of shivering thermogenesis. Shivering appeared only with a further lowering of the mean skin temperature below that required to attain the minimum tissue conductance. When shivering did occur, an associated increase of tissue conductance was indicated by the instrumented suit. Plots of the total-body and regional experimental conductances for three resting subjects indicated that minimum tissue conductance occurs at a mean skin temperature of 31.5°C (5).

In designing an actively heated diver thermal protection garment having a limited supply of energy it would seem reasonable to allow peripheral vasoconstriction but to avoid the onset of shivering and its associated increase of tissue conductance. Limits of thermal equilibrium are usually specified in terms of a minimum mean skin temperature and minimum temperatures for hands and feet (6). Supplementary heating of a diver may be required to maintain the specified mean skin temperature, most probably at varying regional rates for particular protective garment ensembles so as not to compromise the regional skin temperatures. Therefore, knowledge of regional skin temperature in the presence of peripheral vasoconstriction and as a function of mean skin temperature is most desirable in predicting minimum regional supplementary energy requirements.

The concept of mean skin temperature is predicated on the following: 1) the true mean temperature is the mean of an infinite number of body temperature points, and the weighted mean of some finite number of points provides a good estimate of the true value; and 2) local areas of the body may be assumed to be nearly homogeneous with respect to temperature. The

TABLE 1
KERSLAKE'S CURVE-FITTING COEFFICIENTS A(i)*

i	Region of Skin	A(i)	Equivalent Regional Indexes of Fig. 1
1	Head	0.27	1
2	Trunk	0.27	2,3,4,5
3	Lower arm	−0.365	6
4	Hand	−0.73	7
5	Thigh	0.00	8,10
6	Calf	−0.365	9,11
7	Foot	−0.73	12
8	Upper arm	0.00	6

*A(i), distribution fraction for region i. Data adapted from Kerslake (4).

sum of mean weighted temperatures from the regions is then assumed to be characteristic of the mean surface temperature of the human body. The weighting factors utilized with various regions of the human body surface are normally equivalent to the percentage of the total surface area represented by the respective region (7). Teichner (7) compared various methods cited in the literature for calculating mean skin temperature. He found that a 6- or 7-point weighted system and an unweighted 10-point mean could be used to estimate the mean skin temperature of human beings as well as could more sophisticated schemes. Teichner concluded that no more than 6 values are required to provide a good estimate of mean skin temperature and that little is gained when more than 6 are utilized. The statistical reliability of an estimate of true mean temperature is improved, however, when additional points are considered.

DEVELOPMENT OF EQUATIONS

Experimental data obtained from five nearly nude, resting divers exposed to a 20°C helium-oxygen gas mixture at a pressure equivalent to 200 msw (656 fsw) were used to develop Kerslake-type algebraic equations to predict 12 regional skin temperatures rather than Kerslake's 8. These data were collected in an experimental dive conducted by the Navy Experimental Diving Unit to study respiratory heat loss under controlled hyperbaric conditions. The details of these physiological investigations, including a description of the instrumentation system and its calibration, are cited in Ref. 8. Hody's (9) and Kuehn and Zumrick's (10) 12-point mean skin temperature scheme, Eq. *2*, was used in developing the predictive regional temperature equations because much of the experimental data available for analysis had been recorded in the Hody format. Figure 1 shows the locations of these 12 sites; Table 2 defines indexes, nomenclature, abbreviations, and surface area fractions for each of the regions (11).

$$\overline{T}_{sk} = 0.070\,T_1 + 0.085\,T_2 + 0.085\,T_3 + 0.090\,T_4 + 0.090\,T_5 + 0.140\,T_6 + 0.050\,T_7 + 0.095\,T_8 + 0.065\,T_9 + 0.095\,T_{10} + 0.065\,T_{11} + 0.070\,T_{12} \quad (2)$$

where T_1 is temperature of the head; T_2, chest; T_3, abdomen; T_4, upper back; T_5, lower back; T_6, arm; T_7, wrist; T_8, front of thigh; T_9, front of calf; T_{10}, rear of thigh; T_{11}, rear of calf; and T_{12}, foot (Fig. 1 and Table 2).

Figures 2, 3, and 4 graph the representative regional and Hody mean skin temperatures of Piantadosi and Thalmann's (8) 200-m hyperbaric experiment when the ambient temperature was held at 20°C. Temperature profiles were obtained by averaging, for each recorded minute of time, the data from five experimental subjects. Each regional plot is identified with the corresponding numeral cited in Fig. 1 and Table 2. Each experimental curve was analyzed by the method of least squares (12), after incongruous data points were eliminated, to obtain a linear regression equation for the time span from 35 min to 90 min. This was selected as a representative quasi–steady-state time period. Subsequently, the representative linear regression representations of the experimental data were used to facilitate the numerical development of regional predictive equations.

Our first task was to evaluate the suitability of Kerslake's equation for predicting regional skin temperatures under hyperbaric conditions. To obtain equivalent values of experimental temperature for the 8-region Kerslake model, regional values at the 84th min of Figs. 2, 3, and 4 were weight averaged, using the surface area factors (Table 2) for the Hody equivalent regions defined in Table 1. Table 3 points out the very good comparison between the respective regional weight-averaged experimental temperatures and predicted temperatures when the

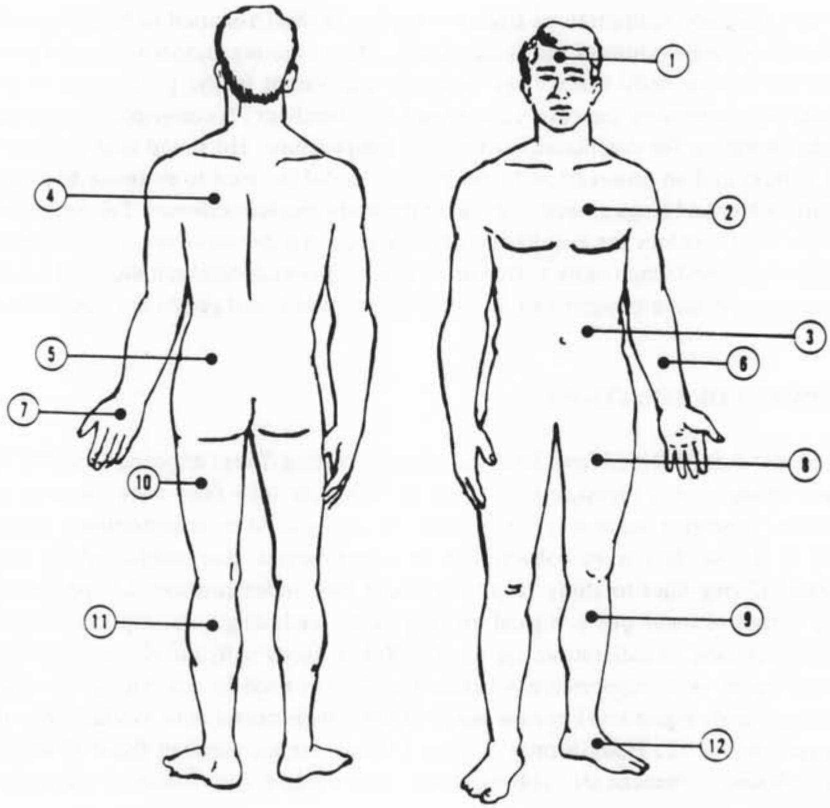

Fig. 1. Hody's 12 regions, adapted from Ref. 13.

TABLE 2
INDEXES, NOMENCLATURE, ABBREVIATIONS, AND SURFACE-AREA FRACTIONS FOR HODY'S 12-REGION MAP*

Regional Index	Region of Skin	Abbreviation	Surface Area Fraction
1	Head	HEAD	0.070
2	Chest	CHST	0.085
3	Abdomen	ABD	0.085
4	Upper back	UBAC	0.090
5	Lower back	LBAC	0.090
6	Arm	ARM	0.140
7	Wrist	WRST	0.050
8	Front thigh	F-TH	0.095
9	Front calf	FCLF	0.065
10	Rear thigh	R-TH	0.095
11	Rear calf	RCLF	0.065
12	Foot	FOOT	0.070

*Data adapted from Zumrick (11).

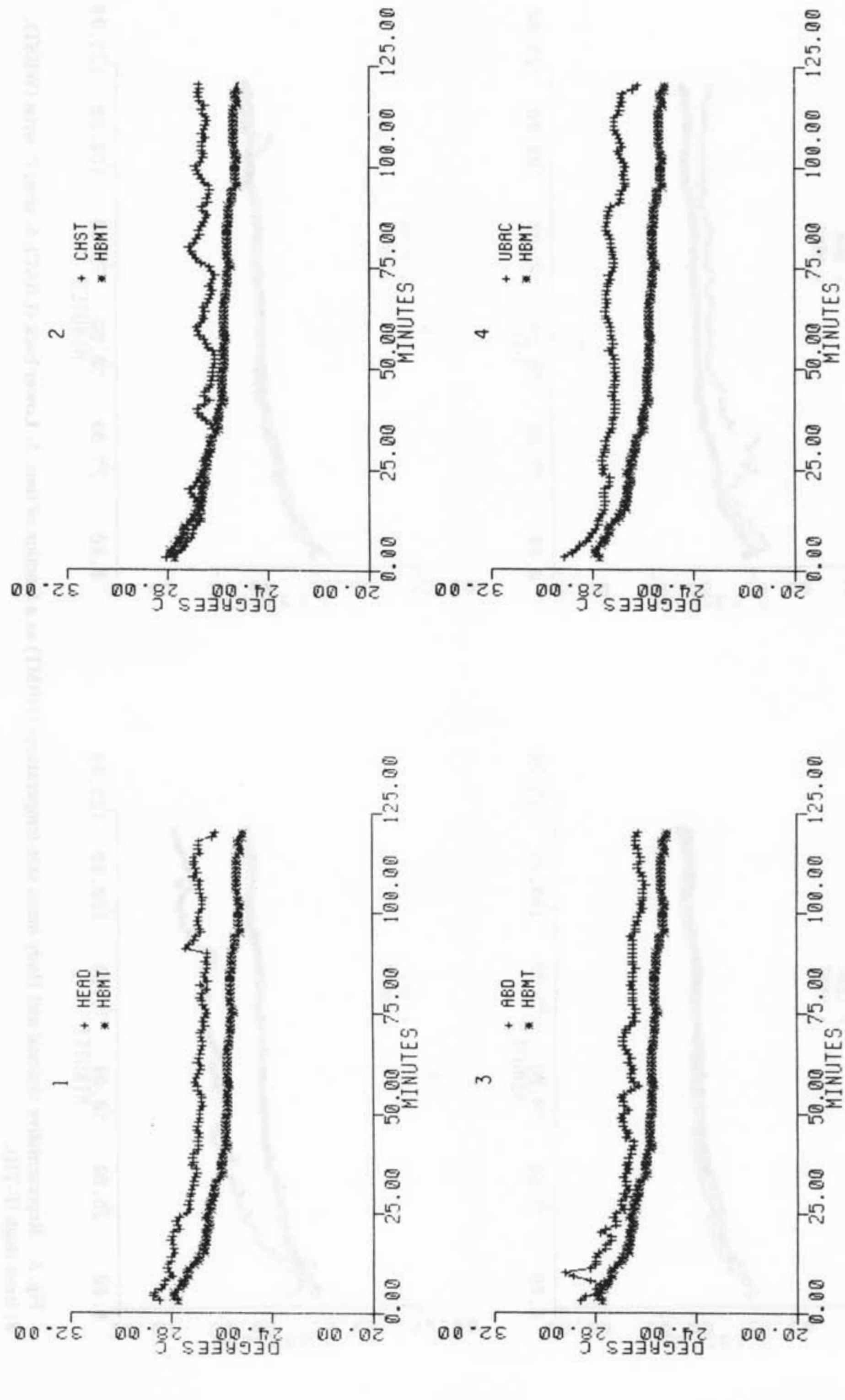

Fig. 2. Representative regional and Hody mean skin temperature (HBMT) as a function of time *1*: Head; 2: chest (CHST); *3*: abdomen (ABD); *4*; upper back (UBAC).

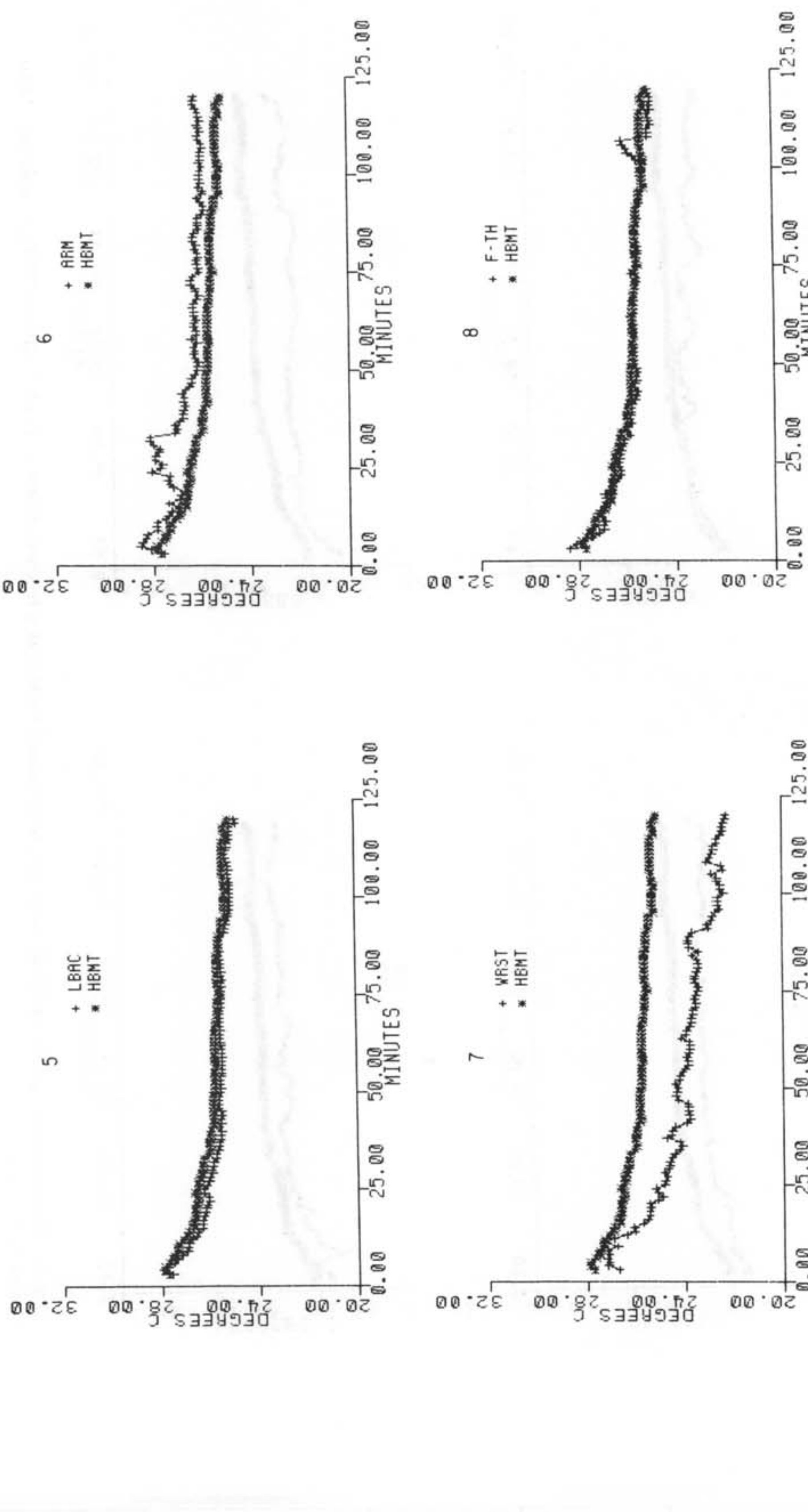

Fig. 3. Representative regional and Hody mean skin temperatures (HBMT) as a function of time. *5*: Lower back (LBAC); *6*: arm; *7*: wrist (WRST); *8*: front thigh (F-TH).

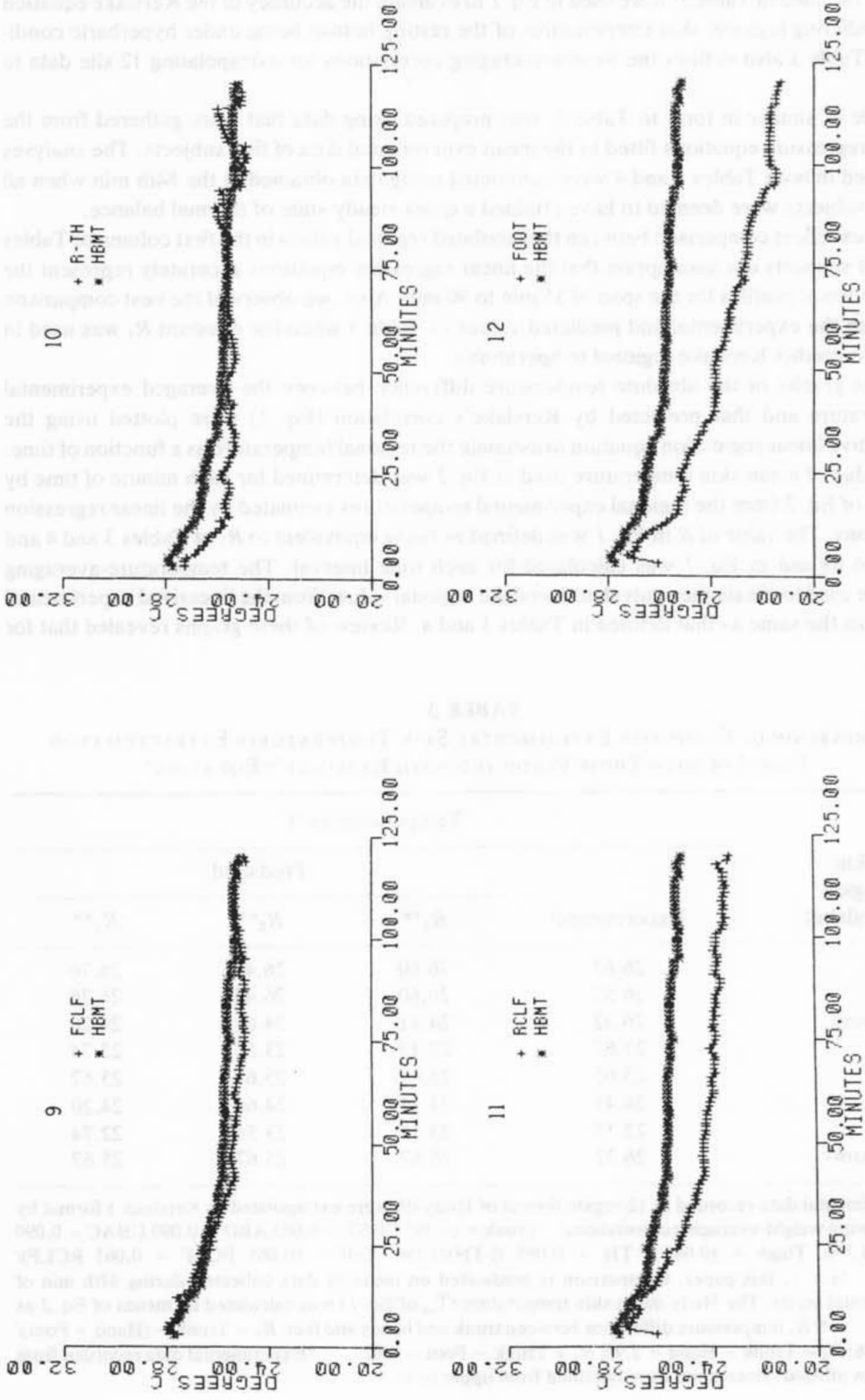

Fig 4. Representative regional and Hody mean skin temperatures (HBMT) as a function of time 9: Front calf (FCLF); *10*: rear thigh (R-TH); *11*: rear calf (RCLF); *12*: foot.

experimental Hody mean skin temperature is used as the argument in Eq. *1*. Three separate R-values (defined in Table 3) were used in Eq. *1* to evaluate the accuracy of the Kerslake equation for predicting regional skin temperatures of the resting human being under hyperbaric conditions. Table 3 also defines the weight-averaging correlations for extrapolating 12 site data to 8 sites.

Table 4, similar in form to Table 3, was prepared using data that were gathered from the linear regression equations fitted to the mean experimental data of five subjects. The analyses reflected in both Tables 3 and 4 were conducted using data obtained at the 84th min when all of the subjects were deemed to have attained a quasi-steady state of thermal balance.

The excellent comparison between the tabulated regional values in the first column of Tables 3 and 4 supports our assumption that the linear regression equations accurately represent the experimental profiles for the span of 35 min to 90 min. Also, we observed the best comparison between the experimental and predicted values of Table 3 when the constant R_1 was used in Eq. *1* to predict Kerslake regional temperatures.

Eight graphs of the absolute temperature difference between the averaged experimental temperature and that predicted by Kerslake's correlation (Eq. *1*) were plotted using the respective linear regression equation to estimate the regional temperature as a function of time. The value of mean skin temperature used in Eq. *1* was determined for each minute of time by means of Eq. *2* from the regional experimental temperatures estimated by the linear regression equations. The value of R in Eq. *1* was defined as being equivalent to R_1 of Tables 3 and 4 and prior to its use in Eq. *1* was calculated for each time interval. The temperature-averaging scheme used to obtain the equivalent Kerslake regional values from the linearized experimental data was the same as that defined in Tables 3 and 4. Review of these graphs revealed that for

TABLE 3

COMPARISON OF COMPOSITE EXPERIMENTAL SKIN TEMPERATURES EXTRACTED FROM FIGS. 2–4 WITH THOSE PREDICTED WITH KERSLAKE'S EQUATION*

Skin Region (Kerslake)	Temperature in °C			
		Predicted		
	Experimental	R_1**	R_2**	R_3**
Head	26.67	26.60	26.45	26.76
Trunk	26.57	26.60	26.45	26.76
Lower arm	26.32	24.41	24.61	24.20
Hand	23.67	23.15	23.56	22.74
Thigh	25.65	25.67	25.67	25.67
Calf	24.43	24.41	24.61	24.20
Foot	22.55	23.15	23.56	22.74
Upper arm†	26.32	25.67	25.67	25.67

Experimental data recorded in 12-region format of Hody (9) were extrapolated to Kerslake's format by the following weight-averaging correlations: Trunk = (0.085 CHST + 0.085 ABD + 0.090 UBAC + 0.090 LBAC)/0.350. Thigh = (0.095 F-TH + 0.095 R-TH)/0.190. Calf = (0.065 FCLF + 0.065 RCLF)/0.130. *Eq. *1*, this paper. Comparison is predicated on mean of data collected during 84th min of experimental series. The Hody mean skin temperature ($\overline{T}_{sk}$ of Eq. *1*) was calculated by means of Eq. *2* as 25.67°C. **R, temperature difference between trunk and hands and feet: R_1 = Trunk − (Hand + Foot)/2.0 = 3.46; R_2 = Trunk − Hand = 2.90; R_3 = Trunk − Foot = 4.02. †Experimental data recorded from lower arm utilized, since none were obtained from upper arm.

TABLE 4

COMPARISON OF COMPOSITE EXPERIMENTAL SKIN TEMPERATURES ESTIMATED BY MEANS OF LINEAR REGRESSION EQUATIONS DERIVED FROM FIGS. 2–4 WITH THOSE PREDICTED WITH KERSLAKE'S EQUATION*

Skin Region (Kerslake)	Temperature °C			
		Predicted		
	Experimental	R_1**	R_2**	R_3**
Head	26.65	26.53	26.39	26.68
Trunk	26.51	26.53	26.39	26.68
Lower arm	26.10	24.32	24.51	24.12
Hand	23.55	23.04	23.43	22.66
Thigh	25.65	25.59	25.59	25.59
Calf	24.37	24.32	24.51	24.12
Foot	22.49	23.04	23.43	22.66
Upper arm†	26.10	25.59	25.59	25.59

Experimental values estimated from Hody's 12-region format were extrapolated to Kerslake's format by the following weight-averaging correlations: Trunk = (0.085 CHST + 0.085 ABD + 0.090 UBAC + 0.090 LBAC)/0.350. Thigh = (0.095 F-TH + 0.095 R-TH)/0.190. Calf = (0.065 FCLF + 0.065 RCLF)/0.130. *Eq. *1*, this paper. Comparison is developed for the 84th min of the experimental series. The Hody mean skin temperature ($\overline{T}_{sk}$ of Eq. *1*) was calculated by means of Eq. *2* as 25.59°C. **R, temperature difference between trunk and hands and feet: R_1 = Trunk − (Hand + Foot)/2.0 = 3.49; R_2 = Trunk − Hand = 2.96; R_3 = Trunk − Foot = 4.02. †Linearized experimental data of lower arm used, since no experimental data were obtained from upper arm.

the entire period of analysis (35–90 min) the experimental temperature of the trunk, thigh, and calf agreed within ± 0.5°C of that predicted by Eq. *1*. The same conclusion was attained for the head and hand for 90% of the time span, and for 70% of the period for the foot. The predicted upper and lower arm values were compared to the linearized experimental data of the arm. (See Fig. 1 and Table 2 for measurement sites.) The absolute temperature difference between the predicted value of the upper arm and the experimental value varied between 0.5°C and 0.8°C throughout the time span; for the lower arm the absolute temperature difference observed was considerably larger, i.e., greater than 1.50°C throughout the entire time band studied. We do not understand the exact cause of this poor comparison between the predicted and linearized experimental skin temperatures of the upper and lower arm when such a good correspondence was observed for the other body regions. We suspect that the lack of similar regions for comparison of temperatures may have contributed to the noted incongruity. Regardless of the result of the arm comparison, the good agreement noted for the principal regions confirms the hypothesis of extrapolating Kerslake's predictive equation to the 12-segment map of Hody.

To adapt the Kerslake algebraic model to the Hody 12-region map it was necessary to compute curve-fitting coefficients [A(i)] from a transposition of Eq. *1*:

$$A(i) = [T(i) - \overline{T}_{sk}]/R_1 \qquad (3)$$

Into Eq. *3* we substituted values of T(i), $\overline{T}_{sk}$, and R_1 all of which had been evaluated at the midpoint of the selected time span of 35 min to 90 min. We then solved for the respective values of A(i); these are enumerated in Table 5.

TABLE 5

KERSLAKE'S A(i) DETERMINED FOR HODY'S 12 REGIONS OF SKIN

i	Skin Region (Hody)	A(i)*
1	Head	0.36
2	Chest	0.27
3	Abdomen	0.30
4	Upper back	0.52
5	Lower back	−0.08
6	Arm	0.22
7	Wrist	−0.64
8	Front thigh	−0.04
9	Front calf	−0.16
10	Rear thigh	−0.06
11	Rear calf	−0.55
12	Foot	−0.86

Time, 63 min; $R_1 = 2.95$. *A(i), distribution fraction for region i.

Although the numerical analysis was based on data obtained from a shivering diver at $\overline{T}_{sk}$ of approximately 26°C, we propose that the modified Kerslake correlation, Eq. *4*, may be used with the tabulated values (Table 5) to estimate the 12 regional surface temperatures that would be experienced by a vasoconstricted but nonshivering diver having a mean skin temperature between 31°C and 32°C.

$$T(i) = \overline{T}_{sk} + A(i)\,R_1 \qquad (4)$$

where T(i) = predicted temperature at region i; $\overline{T}_{sk}$ = Hody mean skin temperature; A(i) = distribution fraction for region i (Table 5); and $R_1 = 2.95$.

The application of Eq. *4* to the Hody mean skin temperature range of 31°C–32°C is by extrapolation. Ideally, this proposed application should be tested experimentally under physiological conditions analagous to those for which it is intended. Realistically, such experimental data are not currently available.

AUTHENTICATION OF THE MODEL

Skin temperature data were obtained from immersed subjects during several evaluations of a diver's passive thermal protection garment when the mean skin temperature approached that observed during the respiratory heat loss studies (13), and both shivering and pronounced vasoconstriction were observed. We assumed that if our predicted regional temperatures compared favorably with these experimental temperature records, then we could presume a reasonably accurate extrapolation to the more conservative temperature range of 31°C–32°C.

The modified Kerslake correlation was derived using the skin temperature data of five seated, resting subjects participating in studies conducted in a 20°C, 200-m hyperbaric helium-oxygen environment (8) because these data correlated well when comparing one subject with another and because the data were free from regional anomalies. Visual inspection of graphs prepared from data recorded during three available immersed studies had exhibited aberrant temperatures associated with the head, hand, and foot for a number of the experimental subjects. The variation of individual data from the corporate mean is a very important consideration with respect to statistical inference when the number of subjects is small. For this reason, the most statistically accurate predictive regional temperature correlations would be obtained from the hyperbaric data, despite significant convective respiratory heat loss in addition to that attributed to surface convection and radiation. We ignored any effect that respiratory heat loss may have produced on the peripheral vasomotor state of the hyperbaric subjects because of the observation that the peripheral thermoreceptors play the major role in regulating metabolic heat production without apparent adjustment for cooling through the respiratory tract (8).

To examine the accuracy of the modified Kerslake correlation in representing the entire quasi-steady period of thermal equilibrium (35 min to 90 min) chosen from the hyperbaric records, we calculated the value of T(i) for each minute of time by means of Eq. *4* and the parameters of Table 5. The independent variable $\overline{T}_{sk}$ was computed by Eq. *2* using regional temperatures determined from the experimental linearized equations. Finally, each predicted regional temperature was compared to the equivalent linearized experimental value for the same instant of time, and an absolute temperature difference was obtained. These computations were conducted twice—once with R_1 of Eq. 4 equal to a constant as defined in Table 5, and then with R_1 computed at each instant of time. The results of these comparisons are summarized in Table 6. Tabulated for both the case of variable and constant, R_1 is the percentage of the total number of compared points that had an absolute difference of less than or equal to 0.50°C, and less than or equal to 0.25°C. For R_1 evaluated as a function of time, the predicted skin temperature for each region is always within 0.50°C of the linearized experimental value. When R_1 is constant, all regions except the foot compare within 0.50°C; however, the foot satisfies the 0.50°C criterion for 63% of the time considered.

TABLE 6
PERCENTAGE OF TOTAL NUMBER OF COMPARED POINTS OF MEASUREMENT OF SKIN TEMPERATURE FOR 35TH TO 90TH MIN AT TWO VALUES OF ABSOLUTE TEMPERATURE DIFFERENCE

Skin Region (Hody)	R_1 = constant		$R_1 = R_1$ (time)	
	≤ 0.25°C	≤ 0.50°C	≤ 0.25°C	≤ 0.50°C
Head	100	100	76.8	100
Chest	69.6	100	100	100
Abdomen	100	100	100	100
Upper back	80.4	100	100	100
Lower back	100	100	100	100
Arm	100	100	83.9	100
Wrist	100	100	100	100
Front thigh	100	100	100	100
Front calf	100	100	100	100
Rear thigh	69.6	100	62.5	100
Rear calf	91.1	100	100	100
Foot	30.4	63	100	100

N = 56. See text for explanation of computations.

Further authentication of the modified Kerslake correlation was conducted using the actual experimental data from which the correlation was derived (8), as well as three sets of experimental regional skin temperatures, which were collected from immersed divers, as described by Zumrick (11), during evaluations of the Naval Coastal Systems Center's diver thermal protection (DTP) garment (13). Two sets of DTP data were obtained from divers immersed in water equivalent to 3 msw and the third set from divers submerged to a depth equivalent to 21 msw. The number of experimental subjects in each of the four studies (described above and designated as RHL1, DTP1, DTP2, and DTP3) were 5, 4, 3, and 3, respectively.

The authentication process was conducted using a normalized temperature, defined in Eq. *5*, which permits comparison of experimental studies having different mean skin ($\overline{T}_{sk}$) and ambient ($\overline{T}_a$) temperatures.

$$\overline{T}(i) = \frac{\overline{T}(i) - \overline{T}_a}{\overline{\overline{T}}_{sk} - \overline{T}_a} \quad (5)$$

A composite regional temperature profile, prepared from each set of data, was analyzed for a period of 75 min. This period began at the 30th min of each experimental record, after the suggestion of Piantadosi et al. (13) that transitory effects of peripheral vasoconstriction were then complete. Each data record was analyzed at discrete time intervals, and a normalized temperature for each of Hody's 12 regions was calculated as a function of time using a value of $\overline{T}_{sk}$ calculated by means of Eq. *2* from the composite experimental data. Using the same value of $\overline{T}_{sk}$, regional predicted temperatures were calculated for the same minute of time by means of Eq. *4* and the parameters defined in Table 5. The resultant normalized predicted temperature was determined using Eq. *5*. Both the experimental and the predicted normalized temperatures were averaged over time and are tabulated in Tables 7, 8, 9, and 10 for each set

TABLE 7

MEAN TIME-AVERAGED, NORMALIZED SKIN TEMPERATURES FOR EACH OF HODY'S 12 REGIONS COMPUTED FROM COMPOSITE TEMPERATURE PROFILES OF EXPERIMENTAL RECORD RHL1* AND EQUIVALENT NORMALIZED SKIN TEMPERATURE ESTIMATED FROM EQS. *4* AND *5*

Skin Region (Hody)	Experimental		Predicted		% Difference
	Mean	SD**	Mean	SD**	
Head	1.208	4.24E−02	1.188	1.21E−02	−1.66
Chest	1.146	7.41E−02	1.141	9.03E−03	−0.44
Abdomen	1.160	3.63E−02	1.157	1.01E−02	−0.26
Upper back	1.268	4.89E−02	1.271	1.75E−02	0.24
Lower back	0.963	1.64E−02	0.958	2.59E−03	−0.52
Arm	1.121	4.16E−02	1.115	7.45E−03	−0.54
Hand	0.642	7.36E−02	0.666	2.15E−02	3.74
Front thigh	0.993	2.70E−02	0.979	1.43E−03	−1.41
Front calf	0.924	3.21E−02	0.916	5.37E−03	−0.87
Rear thigh	0.963	5.13E−02	0.969	2.04E−03	0.62
Rear calf	0.719	4.83E−02	0.713	1.84E−02	−0.83
Foot	0.526	1.31E−01	0.551	2.89E−02	4.75

Percentage of difference between respective regional experimental and predicted time-averaged, normalized temperatures computed by Eq. *6*. Time-averaged $\overline{T}_{sk}$ = 25.70°C, SD = 0.2464; Time-averaged $\overline{T}_a$ = 20.03°C, SD = 0.3162. *RHL1, composite of experimental data collected by Piantadosi and Thalman (8). **E, exponent notation follows ASTM notation; i.e., E−02 = 10^{-2}.

TABLE 8

MEAN TIME-AVERAGED, NORMALIZED SKIN TEMPERATURES FOR EACH OF HODY'S 12 REGIONS COMPUTED FROM COMPOSITE TEMPERATURE PROFILES OF EXPERIMENTAL RECORD DTP1* AND EQUIVALENT NORMALIZED SKIN TEMPERATURE ESTIMATED FROM EQS. *4* AND *5*

Skin Region (Hody)	Experimental		Predicted		
	Mean	SD**	Mean	SD**	% Difference
Head	0.903	6.53E−02	1.045	1.61E−03	15.73
Chest	1.111	4.03E−02	1.034	1.03E−03	− 6.93
Abdomen	1.131	1.84E−02	1.037	1.24E−03	− 8.31
Upper back	1.155	4.28E−02	1.065	2.28E−03	− 7.79
Lower back	1.084	1.01E−02	0.990	6.18E−04	− 8.67
Arm	1.090	1.56E−02	1.027	1.03E−03	− 5.78
Hand	1.116	3.16E−02	0.920	2.86E−03	−17.56
Front thigh	0.712	8.51E−02	0.995	2.76E−04	39.75
Front calf	0.933	2.56E−02	0.980	5.52E−04	5.04
Rear thigh	0.877	2.28E−02	0.993	5.52E−04	13.23
Rear calf	0.938	1.47E−02	0.932	2.49E−03	− 0.64
Foot	0.907	3.25E−02	0.893	3.81E−03	− 1.54

Percentage of difference between respective regional experimental and predicted time-averaged, normalized skin temperatures computed by Eq. *6*. Time-averaged $\overline{T}_{sk}$ = 27.77°C, SD = 0.7740; Time averaged $\overline{T}_a$ = 4.04°C, SD = 0.1316. *DTP1, one of several studies evaluating diver thermal protection garment (13). **E, exponent notation follows ASTM notation; i.e., E−02 = 10^{-2}.

of data. The standard deviations determined when the 2 normalized temperatures were time averaged are also listed for each of the 12 regions. To quantify the accuracy of the predictive correlation with respect to the actual experimental data, the time-averaged predicted and experimental normalized temperatures were used to calculate a percentage of difference, taking the normalized experimental skin temperature as the computational base. The regional percentage of difference between the two cited normalized temperatures is also set out in Tables 7 through 10. A negative percentage of difference indicates that the normalized experimental temperature is greater than the predicted value as it is shown by Eq. *6*.

$$\% \text{ Diff} = \left[\frac{\overline{T}(i)_{predicted} - \overline{T}(i)_{exptl}}{\overline{T}(i)_{exptl}} \right] \cdot 100 \qquad (6)$$

Table 7 shows for experimental record RHL1 that the percentages of difference for all regions except the head, hand (WRST), and foot are less than 1%. This is expected, since the modified correlations of Kerslake were developed from this set of data. Table 8, based on experimental record DTP1, shows percentage of difference within 10% for all regions except the head (15.73%), hand (17.56%), front thigh (39.75%), and rear thigh (13.23%). The large error associated with the front thigh is probably an anomaly, since considerably better agreement is found for the front thigh in the other two submerged studies analyzed (Tables 9 and 10). Table 9, based on experimental series DTP2, shows percentages of difference for all regions of less than or equal to 15%.

During the 21-m submerged evaluation (DTP3) of the diver thermal protection garment (Table 10) insufficient data were recorded from the arm to permit a suitable comparative

TABLE 9

MEAN TIME-AVERAGED, NORMALIZED SKIN TEMPERATURES FOR EACH OF HODY'S 12 REGIONS COMPUTED FROM COMPOSITE SKIN TEMPERATURE PROFILES OF EXPERIMENTAL RECORD DTP2* AND EQUIVALENT NORMALIZED SKIN TEMPERATURE ESTIMATED FROM EQS. *4* AND *5*

Skin Region (Hody)	Experimental		Predicted		
	Mean	SD**	Mean	SD**	% Difference
Head	0.980	3.87E−02	1.045	2.26E−03	6.63
Chest	0.937	1.15E−02	1.033	1.68E−03	10.25
Abdomen	0.977	9.36E−03	1.037	1.77E−03	6.14
Upper back	1.194	3.21E−02	1.065	3.29E−03	−10.80
Lower back	1.102	1.62E−02	0.990	4.78E−04	−10.16
Arm	1.103	1.73E−02	1.027	1.30E−03	− 6.89
Hand	0.985	6.16E−02	0.921	4.02E−03	− 6.50
Front thigh	0.868	1.15E−02	0.995	3.91E−04	14.63
Front calf	1.018	2.04E−02	0.980	8.29E−04	− 3.73
Rear thigh	0.863	1.42E−02	0.993	3.91E−04	15.06
Rear calf	0.905	2.37E−02	0.932	3.43E−03	2.98
Foot	0.983	7.71E−03	0.893	5.39E−03	− 9.16

Percentage of difference between respective regional experimental and predicted time-averaged, normalized skin temperatures computed by Eq. *6*. Time-averaged $\overline{T}_{sk}$ = 28.58°C, SD = 1.2526; Time-averaged $\overline{T}_{a}$ = 4.77°C, SD = 0.0500. *DTP2, one of several studies evaluating diver thermal protection garment (13). **E, exponent notation follows ASTM notation; i.e., E−02 = 10^{-2}.

analysis. The percentages of difference comparisons associated with the head (81.77%) and the foot (213.43%) were obviously anomalous when compared to the significantly better comparisons for the head and foot in Tables 8 and 9. Review of the recorded data revealed that erroneous data for the head and foot were collected for much of the 75-min period of interest.[1] Only those data points that could possibly be assumed representative of the experimental phenomenon were considered in the analysis reflected in Table 10. Unfortunately, the small number of usable data points heavily biased the analytical results obtained. Of all the sets of experimental data, that set recorded during the 21-m evaluations of the DTP garment was the least congruous.

In considering the results of our analyses it is noted that all of the experimental data within the selected time period (75 min to 105 min of each composite record) were used for the computation of the time-averaged, normalized temperatures. Visualization of the composite experimental records for the 12 regions reveals the presence of outlying data points, particularly for the head, hands, and feet. Piantadosi et al. (13) suggest that some of the anomalies observed resulted from artificially high heat flux readings due to influx of cold water around areas of inadequate sealing of the dry suit outergarment. Leaks occurred between the suit sleeve and glove, and air often collected in the garment hood, compromising the intended thermal insulation in this region and precipitating leakage around the hood-face seal.

CONCLUSIONS

We conclude that the modified Kerslake equation, Eq. *4* and Table 5, can be used for predicting regional skin temperatures as a function of mean skin temperature in the range of

TABLE 10

MEAN TIME-AVERAGED, NORMALIZED SKIN TEMPERATURES FOR EACH OF HODY'S 12 REGIONS COMPUTED FROM COMPOSITE SKIN TEMPERATURE PROFILES OF EXPERIMENTAL RECORD DTP3* AND EQUIVALENT NORMALIZED SKIN TEMPERATURE ESTIMATED FROM EQS. *4* AND *5*

Skin Region (Hody)	Experimental Mean	Experimental SD**	Predicted Mean	Predicted SD**	% Difference
Head	0.576	5.90E−02	1.047	8.50E−04	81.77
Chest	1.133	1.83E−02	1.036	7.18E−04	− 8.56
Abdomen	1.091	5.80E−02	1.039	7.87E−04	− 4.77
Upper back	1.273	4.46E−02	1.068	1.20E−03	−16.10
Lower back	1.154	2.84E−02	0.989	3.21E−04	−14.30
Arm†					
Hand	0.966	4.08E−02	0.916	1.73E−03	− 5.18
Front thigh	0.958	3.04E−02	0.995	7.87E−04	3.86
Front calf	1.155	3.25E−02	0.979	5.56E−04	−15.24
Rear thigh	0.845	5.30E−02	0.992	3.21E−04	17.40
Rear calf	0.930	5.45E−02	0.928	1.40E−03	− 0.22
Foot	0.283	1.86E−02	0.887	2.20E−03	213.43

Percentage of difference between respective regional experimental and predicted time-averaged, normalized skin temperatures computed by Eq. *6*. Time-averaged $\overline{T}_{sk}$ = 26.64°C, SD = 0.6198; Time-averaged $\overline{T}_a$ = 4.25°C, SD = 0.3600. *DTP3, one of several studies evaluating diver thermal protection garment. **E, exponent notation follows ASTM notation: i.e., E−02 = 10^{-2}. †Insufficient data recorded from arm to permit comparative analysis.

26°C–28°C. Extrapolation of $\overline{T}_{sk}$ above this envelope is probably reasonable, but it is dependent on levels of vasoconstriction and shivering, two variables over which we had no control during data acquisition or numerical analysis. Ideally, actual experimental data will confirm the utility of the extrapolation to other $\overline{T}_{sk}$. Furthermore, it is apparent from the tabulated comparisons of time-averaged, normalized predicted and experimental skin temperatures that the modified Kerslake correlation should approximate the principal region skin temperatures within a 15% error.

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[1]The 75-min period of time, beginning at the 30th and ending at the 105th min of each experimental record, was chosen to establish a representative common period of exposure among the 4 experimental records considered.

Johnson CE, Collins JD, Piantadosi CA. Equations pour prédire les températures cutanées régionales à partir de la température moyenne de la peau chez le plongeur. Undersea Biomed Res 1982; 9(2):59–74.—Une série d'équations algébriques linéaires ont été dérivées de celles de Kerslake (Flying Personnel Research Committee Memo 213, R.A.F. Institute of Aviation Medicine, 1964) pour prédire les températures régionales de la peau chez le plongeur quasi-euthermique en état de vasoconstriction prononcée. Les équations ont été développées par l'analyse numérique de douze températures cutanées enregistrées chez cinq sujets au repos, exposés en caisson à un environnement hyperbare à 20°C, 95% d'hélium, 5% d'oxygène, comprimé à l'équivalent de 200 mètres (656 pieds). La variable indépendante de la corrélation fondamentale est une température cutanée moyenne arbitrairement définie. Ces équations empiriques étaient développées en vue d'aider un ingénieur à estimer les besoins de chauffage suppémentaire par région, pour un plongeur revêtu d'un habit de protection thermique de composition connue. Les équations développées étaient validées en comparant la température régionale normalisée qui était prédite et sa valeur respective, obtenue expérimentalement à partir de plusieurs ensembles de données physiologiques recueillies au cours des essais de l'équipement de protection thermique de plongée (DTP) du "Naval Coastal System Center." Les résultats de ces comparaisons de températures non-dimensionnées indiquaient que les corrélations obtenues permettaient de prédire de façon précise les températures de la peau des principales régions en fonction de la température cutanée moyenne avec une erreur nominale de pas plus de 15%.

température cutanée | température cutanée moyenne
équations de prédiction | température cutanée dans un environnement hyperbare
modélisation des déperditions caloriques du plongeur

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