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ANALYSIS OF ARTICULATED MANIKIN BASED CONVECTIVE HEAT TRANSFER DURING WALKING

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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Using the articulated manikin at U.S. Army Research Institute of Environmental Medicine (USARIEM) as a model, the effect of the walking motion on the local convective heat transfer at various body sites was studied. The forced convective heat transfer coefficient (h_c) was determined by the naphthalene sublimation technique. Circular naphthalene disks were affixed to various body segments of the articulated manikin. The manikin then simulated walking at five different gaits between 0 and 1.0 m/s (0 being stationary) under constant temperature and wind speed in an environmental chamber. The amount of naphthalene weight loss through sublimation was translated to h_c using the Chilton-Coburn j-factor analogy between heat and mass transfer. The results showed that the arm movement during walking, unexpectedly, diminished the local convective transfer coefficient. Increasing gait actually resulted in a decrease in h_c, as measured on the arms and legs. On the non-moving body trunk, no significant difference in h_c was observed with changing gait. When the manikin was held stationary and the chamber wind speed increased, a corresponding increase in h_c was observed. Thus, during walking, motion of the swinging

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Keywords; anatomical models; convection heat transfer; (KT)

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by

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ABSTRACT

Using the articulated manikin at U. S. Army Research Institute of Environmmental Medicine (USARIEM) as a model, the effect of the walking motion on the local convective heat transfer at various body sites was studied. The forced convective heat transfer coefficient (h_c) was determined by the naphthalene sublimation technique. Circular naphthalene disks were affixed to various body segments of the articulated manikin. The manikin then simulated walking at five different gaits between 0 and 1.0 m/s (0 being stationary) under constant temperature and wind speed in an environmental chamber. The amount of naphthalene weight loss through sublimation was translated to h_c using the Chilton-Colburn j-factor analogy between heat and mass transfer. The results showed that the arm movement during walking, unexpectedly, diminished the local convective transfer coefficient. Increasing gait actually resulted in a decrease in h_c, as measured on the arms and legs. On the nonmoving body trunk, no significant difference in h_c was observed with changing gait. When the manikin was held stationary and the chamber wind speed increased, a corresponding increase in h_c was observed. Thus, during walking, motion of the swinging limbs, the "pendulum" effect, tends to decrease the forced convective heat transfer as observed locally on the limbs. For the walking gaits applied in this study, a 5% -7% decrease in h_c was observed. This decrease in h_c apparently only occurs at moderate walking speeds (<0.7 m/s). For an overall average h_c over the surface area, the predictive equation formulated by Nishi and Gagge using naphthalene spheres, $8.6 \cdot u^{0.531}$, can be used reliably for ascertaining h_c in the articulated copper manikin.

INTRODUCTION

The effect of the swinging limbs during walking and running has been characterized as the "pendulum" effect [Clark et al. 1974] or, in connection with clothing insulation, the "pumping" effect [Vogt et al. 1983; Olesen et al. 1982]. Clark et al. studied evaporative and dry heat loss of an athlete running outdoors, and reported that the local convective heat transfer coefficient could be increased by at least a factor of two, as a result of the extra velocity of the limb relative to the body trunk. Vogt et al. [1983] studied the "pumping" effect on clothing insulation using human subjects. Olesen et al. [1982] performed similar studies using a movable thermal manikin. Complicated by the extra layer of clothing and the microclimates the layer created, the results varied. Vogt concluded that "pumping" effect may increase or decrease the resultant clothing insulation depending on the air temperature. Olesen's [1982] data showed negligible changes in thermal insulation values between sitting and bicycling; alternatively, Olesen and Madsen [1983] and Olesen and Nielsen [1984] reported a 30%-50% reduction in thermal insulation due to walking and wind effect.

This present report focuses on how the walking motion affects the convective heat transfer coefficient of forced flow. The effect of arm and leg swing on h_c was investigated using the USARIEM articulated manikin as a model. This manikin offers the advantage of exact and repeatable motion, and also avoids the problem of perspiration and thus eliminates any evaporative contribution usually involved in exercising human subjects. Convective coefficient, h_c, is determined using a modification of the naphthalene sublimation technique [Nishi and Gagge, 1970a] based on heat and mass transfer analogy, independent of energy and metabolism measurement.

METHOD AND THEORY

Heat-mass transfer analogy of a sublimation substance has been traditionally used to acurately predict the forced convective heat transfer coefficient [Sogin 1958; Neal 1974]. Naphalene very conveniently sublimates at room temperature and thus has been used by a number of investigators to experimentally determine h_c. Sparrow and Tien [1977, 1979] studied forced convection to a square plate at different yaw angles. Sogin [1958] applied jet stream normally to naphthalene disks. Nishi and Gagge [1970a] attached naphthalene balls to different body segments on human subjects.

In our study, circular naphthalene disks were attached to the surface of various body segments on the articulated manikin. The naphthalene disks were appropriately curved to conform to the corresponding body segment curvature. Airflow was directed normally at the disk surface. Since the naphthalene disk conforms to the body segment curvature and sits directly over the specific body site, the local h_c over the specific site is measured, rather than being simply an average h_c for the entire body segment.

Theory of Heat - Mass Transfer Relationship

Mass transfer of naphthalene sublimation h_m can be expressed as [Nishi and Gagge 1970a]

$$h_m = R \cdot T_a \cdot \dot{m} \;/\; (P_s - P_a) \qquad (1)$$

h_m = naphthalene mass transfer coefficient (m/s)
$\dot{m}$ = measured naphthalene sublimation loss per surface area ($kg \cdot m^{-2} \cdot s^{-1}$)
T_a = ambient temperature (°K)
P_s = naphthalene surface vapor pressure (mmHg)
P_a = naphthalene vapor pressure in air (assumed = 0)
R = naphthalene gas constant (0.487 $mmHg \cdot m^3 \cdot kg^{-1} \cdot K^{-1}$)

Assuming the heat of sublimation is negligible, P_s may be considered as equal to the saturated vapor pressure at T_a [Sherwood and Träss 1960],

$$\log_{10} P_s = 11.55 - 3765/T_a$$

or,

$$P_s = 10^{(11.55 - 3765/T_a)} \qquad (2)$$

P_s in mmHg, T_a in °K

The Chilton-Colburn analogy j-factor [ASHRAE Fundamentals 1985] can be described:

$$\text{for heat transfer} \quad j_h = \frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3}, \quad \text{with} \quad Pr = \frac{c_p \cdot \mu}{\kappa} \qquad (3)$$

$$\text{for mass transfer} \quad j_m = \frac{P_{AM} \cdot h_m}{u} (Sc)^{2/3}, \quad \text{with} \quad Sc = \frac{\mu}{\rho \cdot D_v} \qquad (4)$$

h_c = heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
h_m = mass transfer coefficient (m/s)
κ = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
c_p = specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
μ = viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
P_{AM} = logarithmic mean density factor of naphthalene in air (ND)
Pr = Prandtl's number (ND)
Sc = Schmidt's number (ND)
D_v = mass diffusivity (m^2/s)
ρ = density (kg/m^3)
u = air velocity (m)

The physical properties of naphthalene vapor transfer at 30°C (typical values):

κ = 0.02636 $W \cdot m^{-1} \cdot K^{-1}$
c_p = 1006 $J \cdot kg^{-1} \cdot K^{-1}$
μ = $1.869 \cdot 10^{-5}$ $kg \cdot m^{-1} \cdot s^{-1}$
D_v = $6.330 \cdot 10^{-6}$ m^2/s
ρ = 1.165 kg/m^3

$$Pr = \frac{c_p \cdot \mu}{\kappa} = 0.7133 \qquad Sc = \frac{\mu}{\rho \cdot D_v} = 2.534$$

P_{AM} = 0.319

Now, equating heat and mass transfer j-factors,

$$\frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} = \frac{P_{AM} \cdot h_m}{u} (Sc)^{2/3}$$

$$h_c = \rho \cdot c_p \left(\frac{Sc}{Pr}\right)^{2/3} \cdot P_{AM} \cdot h_m \tag{5}$$

h_c in $W/(m^2 \cdot K)$

A computer algorithm implementing Equations 1 through 5 is included as Appendix. The computer program computes h_c from the naphthalene weight loss.

Experiment

The USARIEM articulated manikin is capable of simulated walking up to 80 steps/minute. Five walking speeds were applied, 0 (standstill), 20, 40, 60, and 80 steps/min. Length of leg stride and arm swing are individually adjustable. For this study, they were set to give swing lengths of 13 cm (upper arm), 31 cm (lower arm), 16 cm (thigh), and 51 cm (calf). The five walking speeds gave gaits of 0, 0.22, 0.45, 0,67, and 0.89 m/s (Table 1a). The environmental chamber was set at an ambient temperature (T_a) of 30°C, with dew point at 5°C. The regional air velocity ranged between 0.4 and 0.7 m/s at different body segments of the manikin. The duration of each experiment was 55 minutes. The regional temperature and air velocity were measured at five sites: upper arm, lower arm, thigh, calf, and chest. Figure 1 gives a schematic representation of the locations of naphthalene disks. Omnidirectional thermal anemometers and thermistor temperature probes were placed approximately 2 cm above and 2 cm away from the naphthalene disk, in such a way as not to disturb the impinging airflow to the disk. The omnidirectional anemometers have a response time of two seconds. Airflow in the chamber was directed normally at the disks.

Scintillation grade naphthalene with a melting point of approximately 80°C was poured into casting disk cassettes, which were modified from aluminum camera lens covers. The casting quickly hardens at room temperature, after which a nonadhering cover plate is removed to reveal a smooth naphthalene surface. The cassettes were appropriately curved to conform to surface curvatures of the upper arm, lower arm, thigh, and calf of the manikin. Casting cassettes used for the chest were not curved. The curved disks expose an elliptic rather than circular surface. The elliptic surface area of each cassette disk was measured (Table 1b) and properly quantified (during evaluation of the $\dot{m}$ term in Equation 1). Immediately after casting, the disks were stored individually in airtight containers. All naphthalene disks were allowed to equilibrate in the chamber at 30°C for 24 hours before using. The disks were mounted into vinyl retainers which were in turn fastened to the manikin using Velcro straps. Disks were weighed immediately before and after an experiment on a balance sensitive to ±0.01 mg.

The logarithmic mean density factor of naphthalene in air, P_{AM} in equations 4 and 5, is a correction factor which results from difffusion of air toward the naphthalene surface due to an air partial pressure gradient [ASHRAE Fundamentals, 1985; Fobelets and Gagge, 1988]. It is well known for water vapor - air interface, P_{AM} is approximately equal to unity. For naphthalene - air interface, only one account is available: Nishi and Gagge [1970b] reported a value of 0.370. For our study, P_{AM} was determined employing a mass transfer experiment similar to that performed by Nishi and Gagge (1970a). A 1.21 m long magnesium bar was rotated at its center by a stepping electric motor at 10 constant speeds ranging from 3 to 30 rpm. Two flat naphthalene disks were attached to each end of the magnesium bar, in such a way that as the bar rotates the naphthalene disks faced normally into the air. The rotation resulted in translational speeds from 0.183 to 1.83 m/s for the disks. In Table 2, h_c was computed using equation 5, without the P_{AM} factor, and subsequently compared to data calculated using Nishi and Gagge's predictive equation: $h_c = 8.60 \cdot u^{0.531}$ (u =

speed in m/s). An average value of 0.319 was obtained for P_{AM} from our measurements at the 10 rotational speeds. This compares to the 0.370 value reported by Nishi and Gagge [1970b].

RESULTS

Table 3 shows the regional air velocity with the manikin assuming a stationary position. The uneven regional air velocity is an intrinsic property of the articulated manikin chamber [Chang and Gonzalez 1988]. This background level of regional wind speed was maintained throughout the experiment. Also shown is the local h_c at the specific sites, computed using Equations 1 - 5 (see also algorithm in Appendix). For each study run, h_c was averaged over the 55 minute experiment period. The results in Table 3 are the average of 15 runs.

Figure 2 gives the local h_c at the five naphthalene disk sites: upper arm, lower arm, calf, chest, and thigh. The five walking speeds were 0 (standstill), 20, 40, 60, and 80 steps/min. In Figure 2, the five rows of bar graphs represent h_c measurement at the five naphthalene disk sites, the columns represent the manikin walking speed. The five h_c bar graphs in Figure 2 are presented separately in Figure 3 through Figure 7, and will be discussed individually. A more detailed set of the information presented in Figure 2 is tabulated in Table 4, where h_c is shown with its corresponding dispersion range (standard deviation value). The entire naphthalene disk weight loss data sets are included as Tables 5a - 5e.

Analysis of variance (ANOVA) were performed on the h_c values at each disk site, to see if any significant difference exists. The f-values from the ANOVA tests are listed in Table 6a. A f-value > 2.50 indicates that the hc sequence does show a significant difference, with $p<0.05$. The Tukey test was then used to determine exactly where the differences occur, and the result is given in Table 6b. Tukey test was evaluated between the stationary position h_c and h_c at each of the other four walking gaits. The 0-20, 0-40, 0-60, and 0-80 columns give the test comparison between walking speeds of 0 and 20, 0 and 40, 0 and 60, and 0 and 80 steps/min, respectively. From the result of the Tukey test, in Table 3b, if the difference-between-means is greater than the critical-difference-value then the two h_c under comparison show a statistically significant difference ($p<0.05$).

To further ascertain that the decrement in h_c (at the sites shown in Figure 2) was indeed due to the walking motion and not artifact, another set of experiments were performed without the complication of limb movement. Figure 8 gives the data obtained when the manikin was held stationary, but with the chamber wind speed set at levels comparable to the walking gaits.

DISCUSSION

Rapp [1973] defined the free and mixed convection region as that when ambient air velocity is < 0.2 m/s. Hence, from Table 1, the experimental condition in our study was well into the forced convection region. The measured h_c should, therefore, be predominately h_c from forced airflow. The range of h_c, 5 - 8 $W/(m^2 \cdot K)$, in Table 3, is comparable to that reported by Nishi and Gagge [1970a].

Figure 2 and Table 4 give the regional h_c at the five naphthalene disk sites, upper arm, lower arm, calf, chest, and thigh, at the five walking speeds 0, 20, 40, 60, and 80 steps/min. The five h_c bar graphs in Figure 2 are separated into

Figures 3 to 7. In Figures 3 - 7, a schematic diagram of the manikin depicting the location of the disk is also included.

Looking at Figures 3 and 4, on the upper and lower arms, there is clearly a decreasing trend for h_c at these sites, as the manikin walking speed increased from 0 to 80 steps/min. Decrease in h_c was between 5% to 7%. The ANOVA f-value in Table 3a showed the decrement to be highly significant. In contrast, for the chest site in Figure 5, h_c stayed quite constant, and f-value showed no statistically significant difference between gaits. The motion of the arms quite unexpectedly caused a decrese in the forced convective heat transfer, evident, perhaps from localized eddy formation at these sites. Although the exact physical mechanism is not apparent, one rational explanation could be that the naphthalene disks experienced nonuniform airflow during the arm swing cycle. On the forward stroke of the arm swing, the naphthalene disks were moving in the opposite direction to the chamber airflow. The airflow that the disks encountered was enhanced (a vector sum). Conversely, on the backward stroke of the arm swing, the arm and chamber airflow were in the same direction. Airflow experienced by the disk was therefore diminished (a vector difference). Naphthalene sublimation rate, hence h_c, does not vary linearly with changing air velocity [Nishi and Gagge 1970a]. The effect of a vector sum (forward stroke) and a vector difference (backward stroke), not surprisingly, do not cancel each other. The calculated h_c thus is an algebraic sum of the two effects, averaged over the 55 minute study period. At present, we can only ascertain the average air velocity from the data. Our omnidirectional anemometers (response time = 2 second) do not have fast enough of a response time to distinctly measure the different air velocities that must exist on the forward and backward strokes. A protocol using faster response anemometer to study the air velocity variation during each arm swing is anticipated in the future.

On the calf, in Figure 6, a 7% decrease in h_c was also evident. Here, however, we found that h_c did not further decrease after a walking speed of 60 steps/min but, rather, showed an increase at 80 steps/min. It appears that at some threshold point the combined vector sum and vector difference yields a minimum average airflow over the disk, hence a minimum h_c. Beyond this point, as walking speed increases further, the resultant airflow vector commences to increase, thereby h_c increases after 60 steps/min. With the swing length at the calf site equal to 51 cm, the motion of the calf disk translated to an equivalent linear forward velocity of 0.5 - 0.7 m/s at 60 - 80 steps/min. Hence, the latter result suggests that at a moderate walking speed (<0.7 m/s) in the nonuniform chamber [Chang and Gonzalez, 1988], the motion of walking tends to decrease h_c. However, at higher speed, e.g. running, motion of the arms could well increase h_c as Clark's [1974] results suggest.

The thigh data in Figure 7 showed no particular pattern. One peculiarity about the thigh data is also evident in Nishi and Gagge's [1970a] results. Comparison of Nishi and Gagge 's Tables 3 and 4 showed that on the bicycle ergometer, increase in h_c paralleled the increase in air movement on the thigh. However, with free walking, h_c is ≈25% lower on the thigh than other sites, e.g. upper arm and legs, with similar air movement. Nevertheless, relative motion of the limbs may well be a factor. Only this time, there were two relative motions involved. It can be seen from the schematic representation of Figure 1 that the naphthalene disk on the thigh was at the same level as the hand. As the manikin walked, the hand swung in the opposite direction to the thigh. Movement of the hand could thus disturb the impinging airflow over the thigh disk. On a bicycle ergometer, presumablly the arms do not swing in opposite directions to modify airflow over the thighs. In our study, relative motion of the arm and leg could have generated a more complex airflow pattern over the thigh disk, the result of which simply cannot be visualized from only the averaged anemometer data.

Data in Figure 8 were obtained with the manikin held stationary and the chamber air speed set at levels comparable to the walking gaits. On a standstill manikin, h_c from all five naphthalene disks increased accordingly with increasing chamber air velocity. The observation that it was the walking motion that decreased the effective local h_c, is further reinforced.

CONCLUSION

This study looked at the effect of walking on the convective heat transfer coefficient of forced airflow. It was found that slow walking in the manikin, or the motion of the swing limbs during slow walking, by peculiarities of wind flow over these sites, decreased the forced h_c as measured on the arms and legs. For the walking gaits applied in this study, a 5% - 7% decrease in h_c was observed at these sites. This amount of decrease in h_c, displayed in Figure 2 and tabulated in Table 4, is suggested to represent, quantitatively, the "pendulum" effect of air velocity on the convective heat exchange as measured with naphthalene disks. The decrease in h_c apparently only occurred at moderate walking speeds (<0.7 m/s). As the walking speed increased beyond this threshold point, and indeed during running, the motion of the arms and legs increases the convective heat transfer coefficients at these sites in a conventional manner.

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Table 1a articulated manikin walking gaits

	0	20	40	60	80 (steps/min)
gaits (m/s)	0	0.22	0.45	0.67	0.89

Table 1b Naphthalene disk surface areas and articulated manikin arm swing and leg stride lengths

site	disk surface area (cm^2)	manikin limb swing length (cm)
Upper Arm	19.23	13
Lower Arm	19.32	31
Calf	19.32	51
Chest	18.09	—
Thigh	18.85	16

Table 2 Determination of P_{AM} from the rotating arm mass transfer experiment radius = 58.1 cm (from center of bar to center of mounted disk) h_c is in $W \cdot m^{-2} \cdot K^{-1}$

rpm	m/s	(1) from Eqn. 5 h_c / P_{AM}	(2) from Nishi & Gagge $h_c = 8.6 \cdot u^{0.531}$	ratio (2)/(1)
3	0.183	13.76	3.46	0.251
6	0.365	17.64	5.07	0.287
9	0.548	20.16	6.26	0.311
12	0.730	22.75	7.28	0.320
15	0.913	24.89	8.18	0.329
18	1.10	27.02	9.09	0.336
21	1.28	29.01	9.59	0.331
24	1.46	30.83	10.51	0.341
27	1.64	32.79	11.18	0.341
30	1.83	34.48	11.85	0.344

Table 3

Regional air velocity and local h_c on a stationary articulated manikin

naphthalene disk site	regional air velocity (m/s)	local h_c W/($m^2 \cdot K$)
Upper Arm	0.61 ± 0.02	7.49 ± 0.133
Lower Arm	0.71 ± 0.01	7.23 ± 0.122
Calf	0.69 ± 0.02	7.78 ± 0.165
Chest	0.49 ± 0.01	5.30 ± 0.120
Thigh	0.42 ± 0.01	6.01 ± 0.110

Table 4

Local h_c at walking speeds of 0, 20, 40, 60, and 80 steps/min.

	h_c ± standard deviation W/(m^2•K)				
	0	20	40	60	80
Upper Arm	7.49±0.133	7.35±0.142	7.27±0.048	7.18±0.057	7.15±0.065
Lower Arm	7.23±0.122	7.13±0.112	7.03±0.082	6.86±0.059	6.73±0.087
Calf	7.78±0.165	7.69±0.139	7.48±0.097	7.24±0.058	7.67±0.079
Chest	5.30±0.120	5.38±0.117	5.35±0.073	5.34±0.066	5.31±0.090
Thigh	6.01±0.110	6.26±0.125	6.17±0.097	6.18±0.063	6.25±0.086

Table 5a Upper Arm disk site naphthalene weight loss data, at walking speeds of 0, 20, 40, 60, and 80 steps/min. Weight loss is in 10^{-8} kg. Temperature in °C is shown in parenthesis [ ].

Upper Arm naphthalene weight loss (10^{-8} kg) and [temperature] (°C)

0	20	40	60	80
4828 [29.9]	5092 [29.9]	4774 [29.8]	4680 [29.8]	4701 [30.0]
4891 [29.9]	4467 [29.5]	4600 [29.5]	4779 [30.0]	4725 [30.0]
4865 [29.9]	4881 [30.0]	4867 [30.0]	4797 [30.0]	4760 [30.0]
5070 [29.8]	4934 [30.0]	4927 [30.1]	4776 [29.8]	4813 [30.1]
4835 [29.8]	4978 [30.1]	4864 [30.1]	4845 [30.2]	4787 [29.9]
4946 [30.0]	4876 [30.0]	4906 [30.1]	4808 [30.2]	4793 [30.1]
5146 [30.1]	4937 [30.0]	4916 [30.1]	4858 [30.0]	4848 [30.1]
5066 [30.1]	4887 [29.8]	4982 [30.2]	4889 [30.2]	4741 [30.0]
4968 [30.1]	4932 [30.0]	4859 [30.0]	4826 [30.1]	4779 [30.0]
5125 [30.0]	4982 [30.1]	4933 [30.1]	4909 [30.3]	4771 [30.1]
5019 [30.2]	4886 [30.0]	4816 [29.9]	4884 [30.1]	4919 [30.1]
4985 [29.9]	4993 [30.1]	4897 [30.1]	4746 [29.9]	4749 [29.9]
5072 [29.9]	4988 [30.2]	4931 [30.2]	4888 [30.2]	4901 [30.2]
4978 [30.0]	4803 [30.0]	4805 [30.0]	4756 [30.0]	4754 [30.0]
4960 [30.0]	4841 [30.0]	4731 [29.9]	4785 [29.9]	4777 [30.0]

Table 5b Lower Arm disk site naphthalene weight loss data, at walking speeds of 0, 20, 40, 60, and 80 steps/min. Weight loss is in 10^{-8} kg. Temperature in °C is shown in parenthesis [ ].

Lower Arm naphthalene weight loss (10^{-8} kg) and [temperature] (°C)

0	20	40	60	80
4559 [29.8]	4896 [29.8]	4629 [29.7]	4481 [29.7]	4405 [30.0]
4745 [29.8]	4471 [29.5]	4420 [29.5]	4580 [29.9]	4483 [29.9]
4688 [29.8]	4773 [30.0]	4776 [30.0]	4583 [29.9]	4483 [29.9]
4805 [29.7]	4726 [30.0]	4721 [30.1]	4461 [29.8]	4469 [30.0]
4705 [29.8]	4789 [30.1]	4704 [30.0]	4662 [30.1]	4501 [29.8]
4781 [30.0]	4746 [30.0]	4752 [30.0]	4617 [30.1]	4504 [30.0]
4908 [30.0]	4786 [30.0]	4777 [30.0]	4632 [30.0]	4536 [30.0]
4883 [30.0]	4742 [29.7]	4844 [30.2]	4695 [30.1]	4452 [29.9]
4859 [30.0]	4783 [30.0]	4713 [30.0]	4597 [30.0]	4476 [30.0]
4932 [30.0]	4818 [30.0]	4789 [30.1]	4642 [30.2]	4451 [30.1]
4873 [30.2]	4740 [30.0]	4628 [29.8]	4670 [30.0]	4635 [30.0]
4870 [29.8]	4853 [30.0]	4763 [30.0]	4526 [29.8]	4475 [29.8]
4896 [29.9]	4814 [30.1]	4749 [30.1]	4630 [30.1]	4600 [30.1]
4809 [29.9]	4671 [29.9]	4675 [30.0]	4487 [29.9]	4488 [30.0]
4797 [29.9]	4657 [29.9]	4535 [29.9]	4517 [29.9]	4461 [29.9]

Table 5c Calf disk site naphthalene weight loss data, at walking speeds of 0, 20, 40, 60, and 80 steps/min. Weight loss is in 10^{-8} kg. Temperature in °C is shown in parenthesis [ ].

Calf naphthalene weight loss (10^{-8} kg) and [temperature] (°C)

0	20	40	60	80
5033 [29.9]	5260 [29.9]	4939 [29.8]	4688 [29.7]	5001 [29.9]
5027 [29.9]	4764 [29.5]	4677 [29.5]	4818 [30.0]	5073 [29.9]
5001 [29.9]	5072 [30.0]	5008 [30.0]	4851 [30.0]	5069 [29.9]
5256 [29.8]	5205 [30.0]	5096 [30.1]	4751 [29.8]	5139 [30.0]
5008 [29.8]	5161 [30.1]	4993 [30.1]	4882 [30.1]	5077 [29.9]
5175 [30.0]	5114 [29.9]	5079 [30.1]	4879 [30.1]	5134 [30.0]
5339 [30.0]	5182 [30.0]	5072 [30.0]	4943 [30.0]	5204 [30.0]
5270 [30.1]	5128 [29.8]	5170 [30.2]	4966 [30.1]	5107 [29.9]
5282 [30.1]	5197 [30.0]	5088 [30.0]	4849 [30.1]	5143 [30.0]
5345 [30.0]	5217 [30.1]	5096 [30.1]	4982 [30.3]	5127 [30.1]
5220 [30.2]	5109 [30.0]	4943 [29.9]	4957 [30.1]	5307 [30.1]
5242 [29.8]	5293 [30.0]	5108 [30.0]	4798 [29.9]	5153 [29.9]
5332 [29.9]	5299 [30.1]	5131 [30.2]	4969 [30.2]	5298 [30.2]
5173 [29.9]	5002 [30.0]	4963 [30.0]	4843 [30.0]	5088 [30.0]
5188 [30.0]	5073 [30.0]	4841 [29.9]	4807 [29.9]	5125 [30.0]

Table 5d Chest disk site naphthalene weight loss data, at walking speeds of 0, 20, 40, 60, and 80 steps/min. Weight loss is in 10^{-8} kg. Temperature in °C is shown in parenthesis [ ].

Chest naphthalene weight loss (10^{-8} kg) and [temperature] (°C)

0	20	40	60	80
3228 [29.9]	3539 [30.0]	3336 [29.8]	3316 [29.8]	3356 [30.1]
3186 [29.9]	3141 [29.6]	3163 [29.6]	3326 [30.0]	3364 [30.0]
3285 [29.9]	3389 [30.1]	3423 [30.1]	3383 [30.0]	3361 [30.0]
3443 [29.8]	3439 [30.1]	3479 [30.2]	3347 [29.8]	3431 [30.1]
3251 [29.8]	3420 [30.1]	3342 [30.1]	3383 [30.2]	3328 [30.0]
3302 [30.1]	3406 [30.0]	3411 [30.1]	3378 [30.2]	3387 [30.1]
3388 [30.1]	3403 [30.1]	3389 [30.1]	3412 [30.1]	3378 [30.2]
3343 [30.1]	3323 [29.8]	3462 [30.2]	3428 [30.2]	3324 [30.0]
3325 [30.1]	3397 [30.1]	3365 [30.1]	3345 [30.2]	3322 [30.1]
3478 [30.1]	3503 [30.1]	3461 [30.2]	3502 [30.3]	3392 [30.2]
3378 [30.3]	3366 [30.1]	3326 [29.9]	3446 [30.2]	3457 [30.2]
3370 [29.9]	3368 [30.1]	3429 [30.1]	3330 [29.9]	3282 [30.0]
3385 [30.0]	3504 [30.2]	3430 [30.2]	3462 [30.2]	3520 [30.2]
3250 [30.0]	3235 [30.0]	3317 [30.0]	3274 [30.0]	3294 [30.1]
3318 [30.0]	3325 [30.0]	3230 [29.9]	3333 [30.0]	3220 [30.0]

Table 5e Thigh disk site naphthalene weight loss data, at walking speeds of 0, 20, 40, 60, and 80 steps/min. Weight loss is in 10^{-8} kg. Temperature in °C is shown in parenthesis [ ].

Thigh naphthalene weight loss (10^{-8} kg) and [temperature] (°C)

0	20	40	60	80
3855 [29.9]	4245 [29.9]	4038 [29.8]	3953 [29.7]	4011 [30.0]
3810 [29.9]	3800 [29.6]	3822 [29.6]	4015 [30.0]	4030 [30.0]
3844 [29.9]	4086 [30.0]	4077 [30.0]	4044 [30.0]	4034 [30.0]
3985 [29.8]	4137 [30.0]	4124 [30.1]	4002 [29.9]	4106 [30.1]
3819 [29.8]	4140 [30.1]	4015 [30.1]	4053 [30.2]	4078 [29.9]
3894 [30.1]	4079 [30.0]	4091 [30.1]	4072 [30.2]	4111 [30.0]
4058 [30.1]	4143 [30.0]	4115 [30.0]	4115 [30.0]	4161 [30.1]
3975 [30.1]	4076 [29.8]	3989 [30.2]	4117 [30.2]	4031 [30.0]
3934 [30.1]	4133 [30.1]	4030 [30.0]	4058 [30.1]	4082 [30.0]
4021 [30.0]	4117 [30.1]	4108 [30.1]	4141 [30.3]	4080 [30.1]
3947 [30.3]	4086 [30.0]	4021 [29.9]	4128 [30.1]	4233 [30.1]
3954 [29.9]	4033 [30.1]	4159 [30.1]	4018 [29.9]	4111 [29.9]
4016 [30.0]	4219 [30.2]	4132 [30.2]	4201 [30.2]	4271 [30.2]
3888 [30.1]	4002 [30.1]	3981 [30.0]	4031 [30.1]	4097 [30.1]
3937 [30.0]	4043 [30.0]	3941 [30.0]	4067 [30.0]	4094 [30.0]

Table 6a f-value from Analysis of Variance (ANOVA test)
A $f > 2.50$ indicates that significant difference exists ($p<0.05$).

	Upper Arm	Lower Arm	Calf	Chest	Thigh
f	26.66	64.06	48.68	1.35	14.83

Table 6b Tukey test results (for $p<0.05$).
Difference is statistically significant when the difference-between-means is greater than the Critical-Difference-Value.

	difference between means				Critical Difference Value
	0 - 20	0 - 40	0 - 60	0 - 80	
Upper Arm	0.134	0.218	0.302	0.334	0.098
Lower Arm	0.098	0.199	0.372	0.503	0.095
Calf	0.087	0.297	0.535	0.108	0.115
Chest	0.074	0.047	0.042	0.009	0.096
Thigh	0.251	0.166	0.177	0.245	0.098

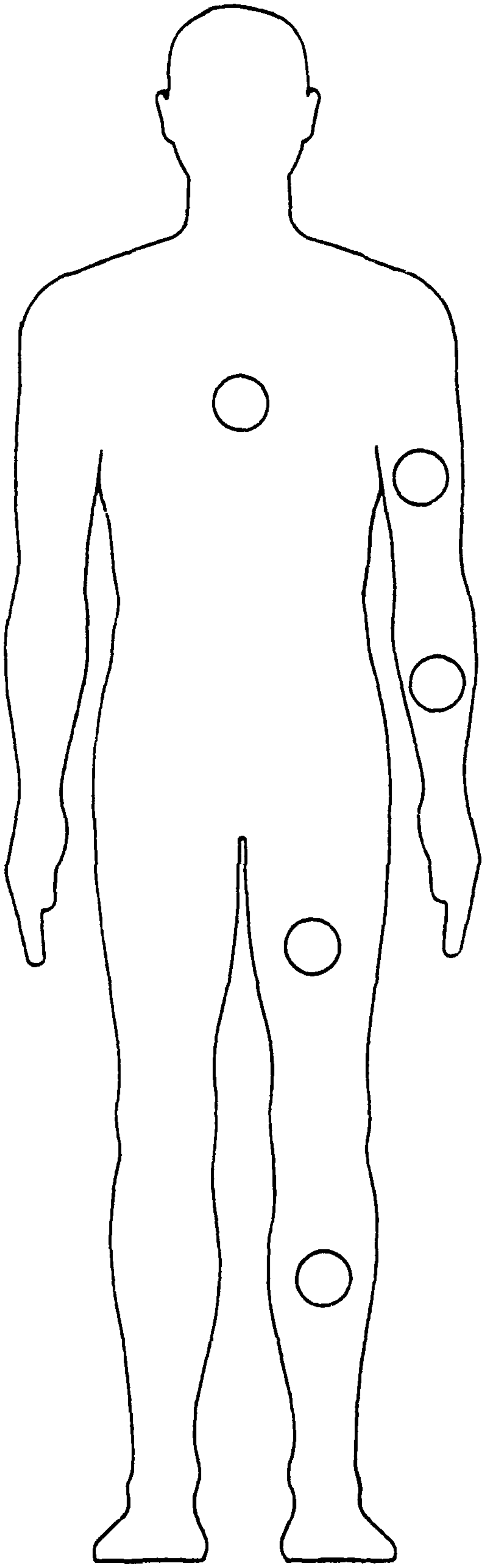


Figure 1 Schematic diagram showing locations of the naphthalene disk on the manikin

Figure 2 Convective Heat Transfer Coefficient h_c

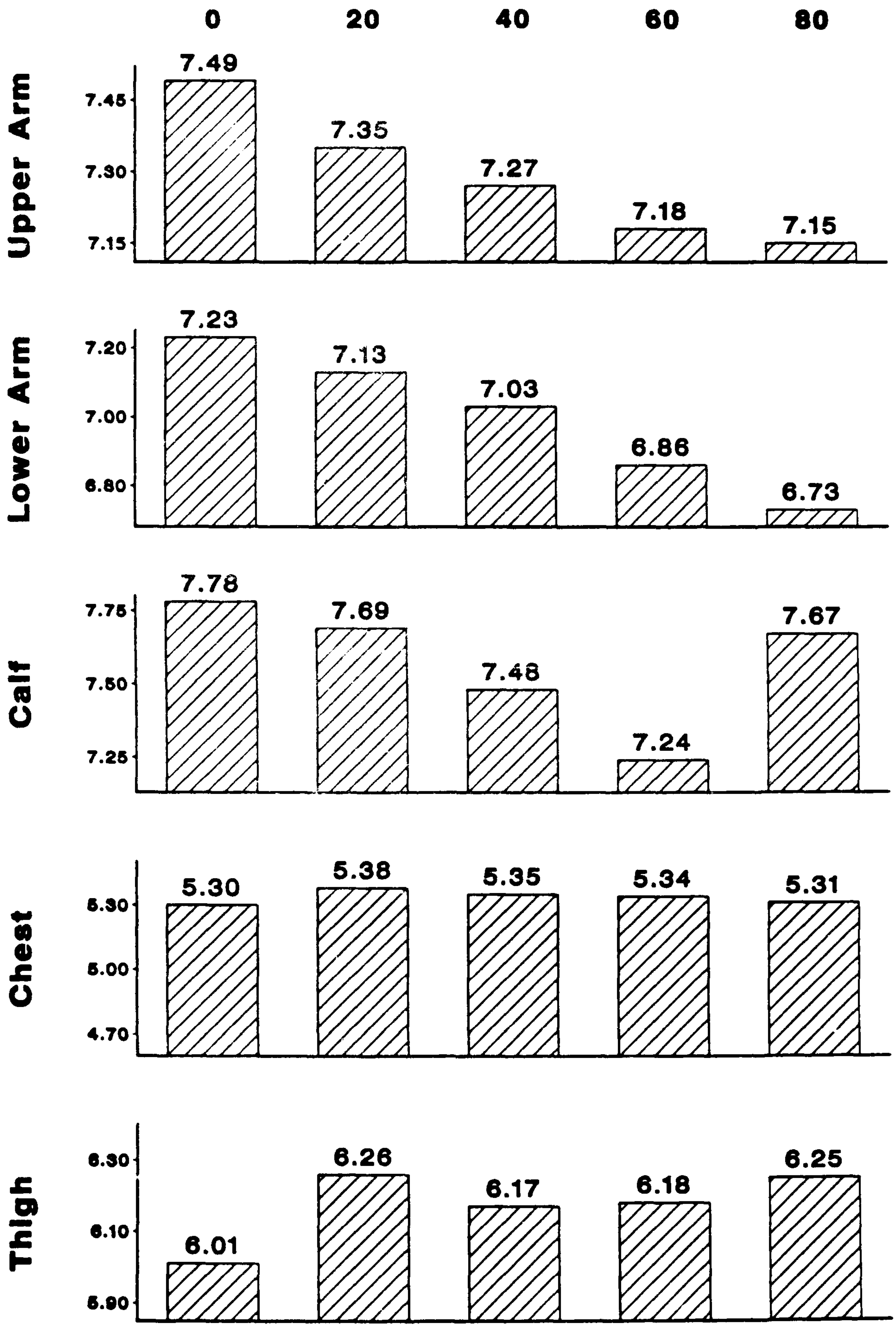
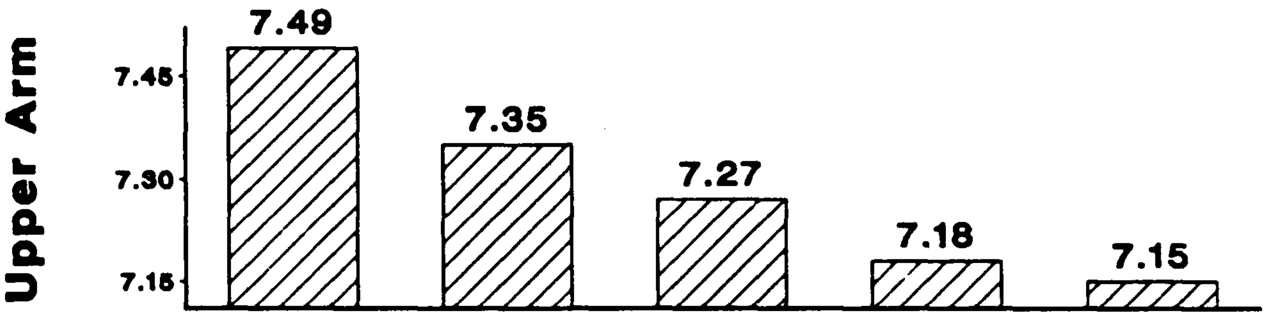


Figure 3 Upper arm h_c



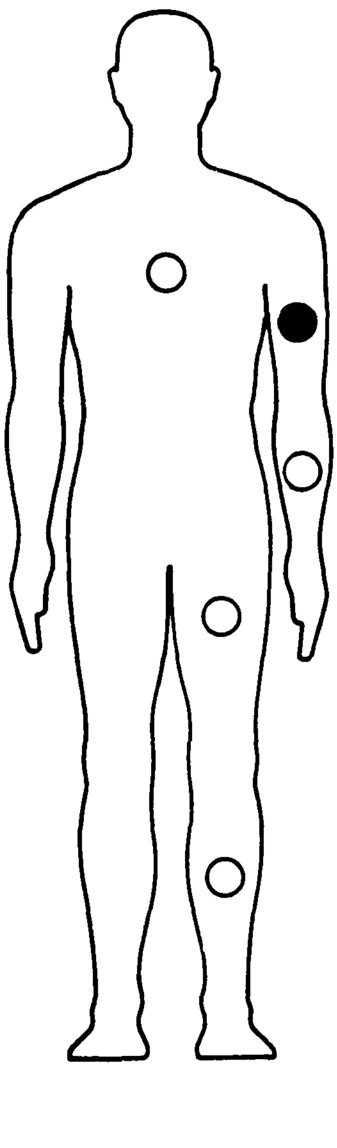


Figure 4 Lower arm h_c

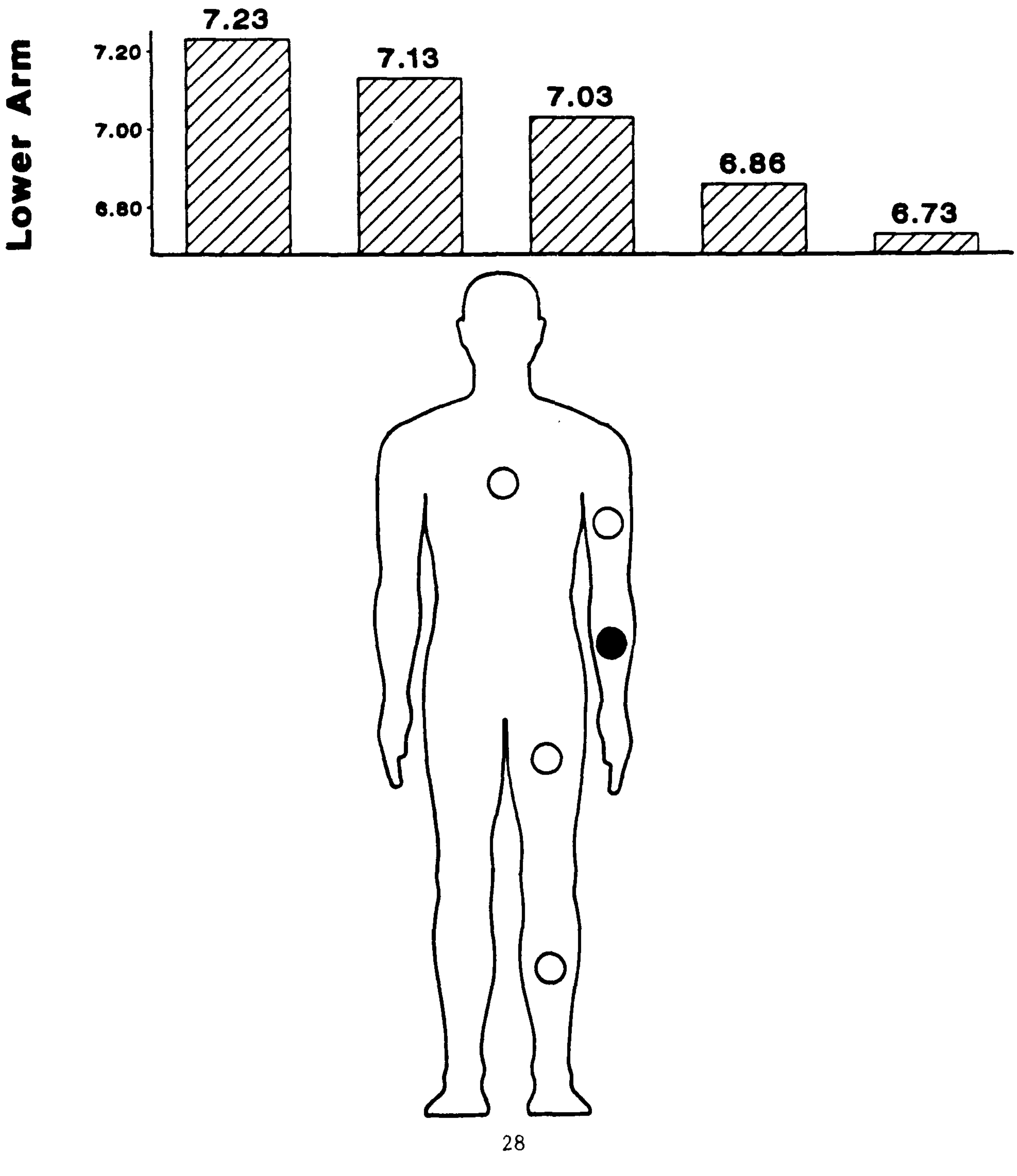


Figure 5 Calf h_c

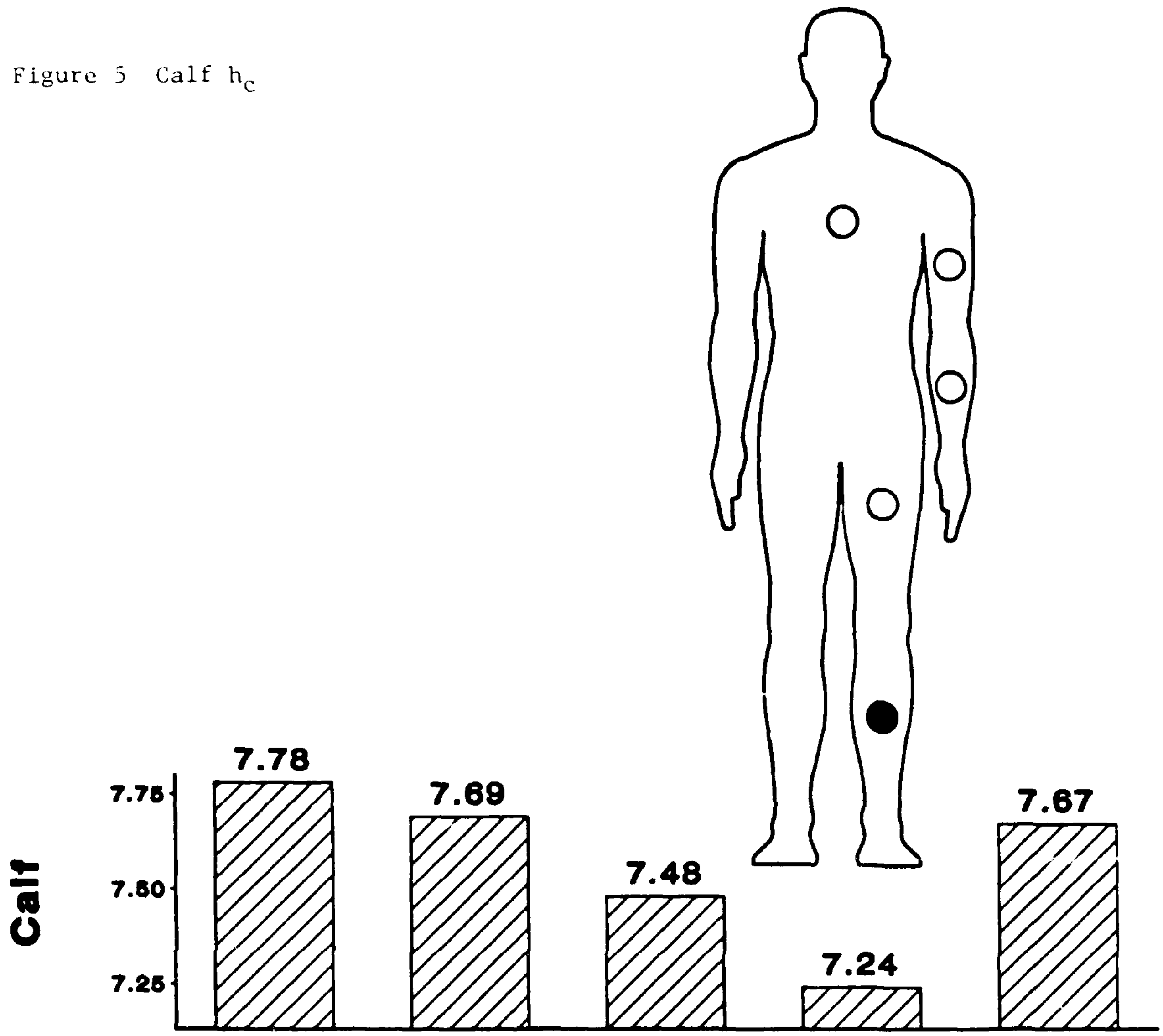
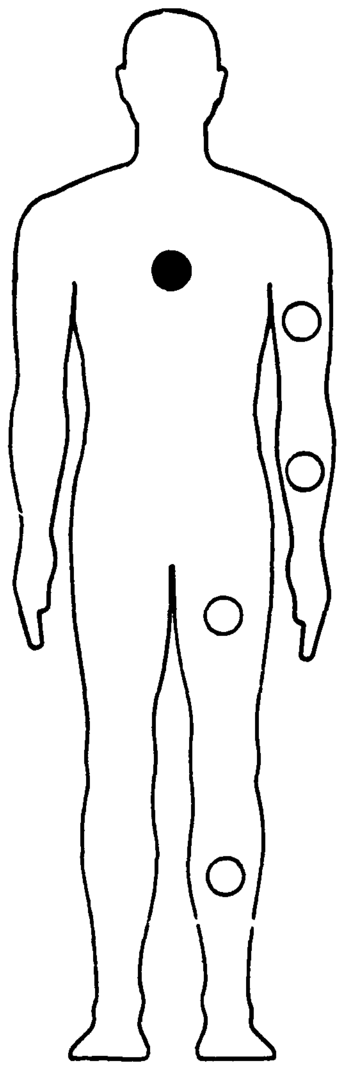


Figure 6 Chest h_c



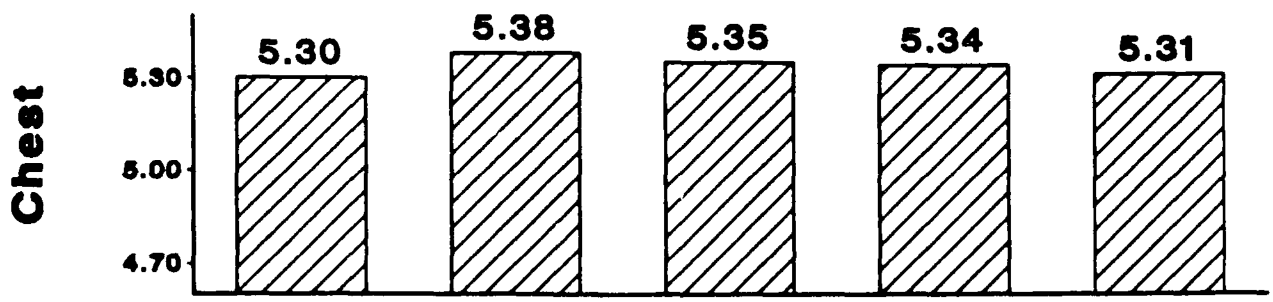


Figure 7 Thigh h_c

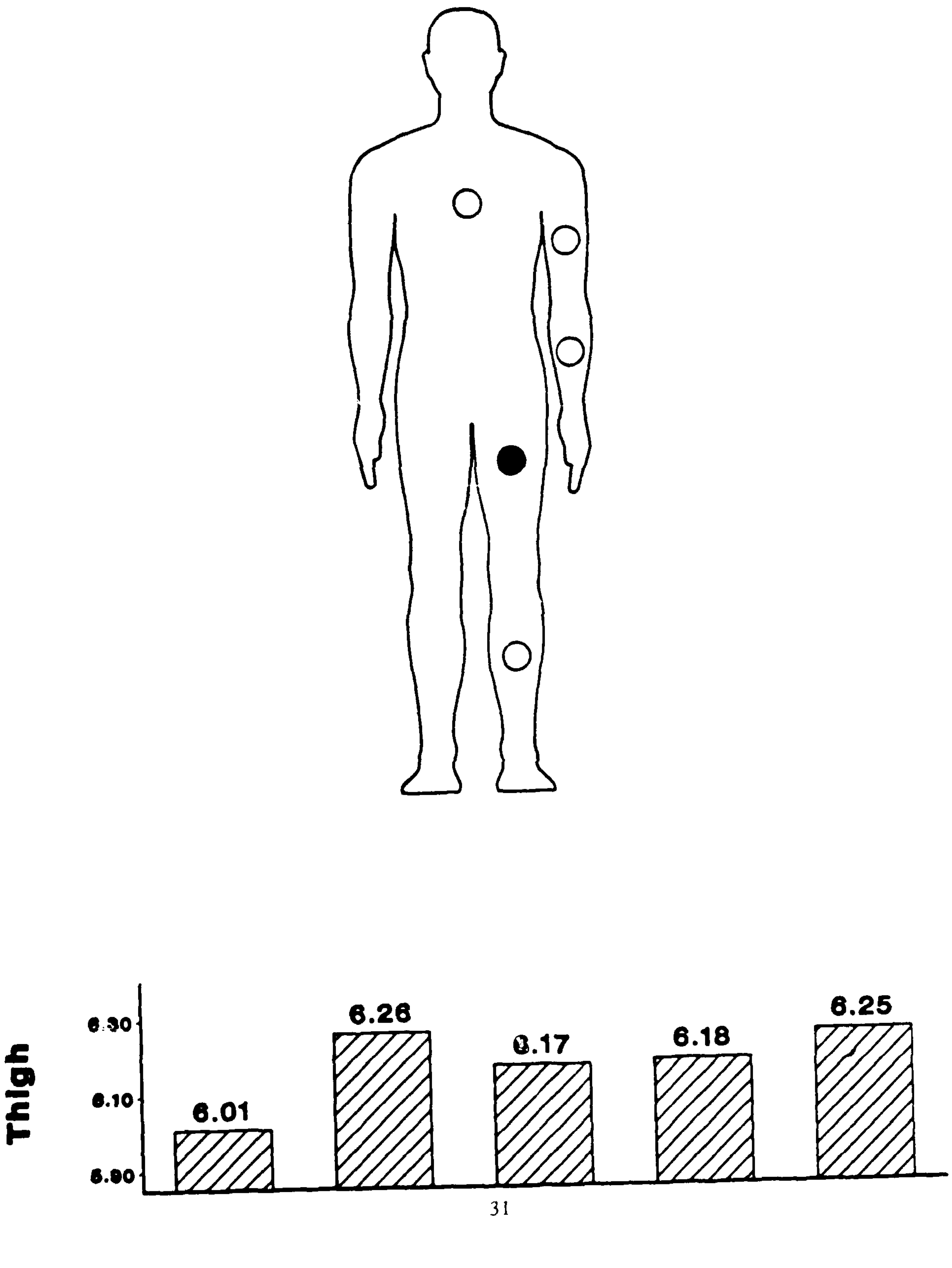
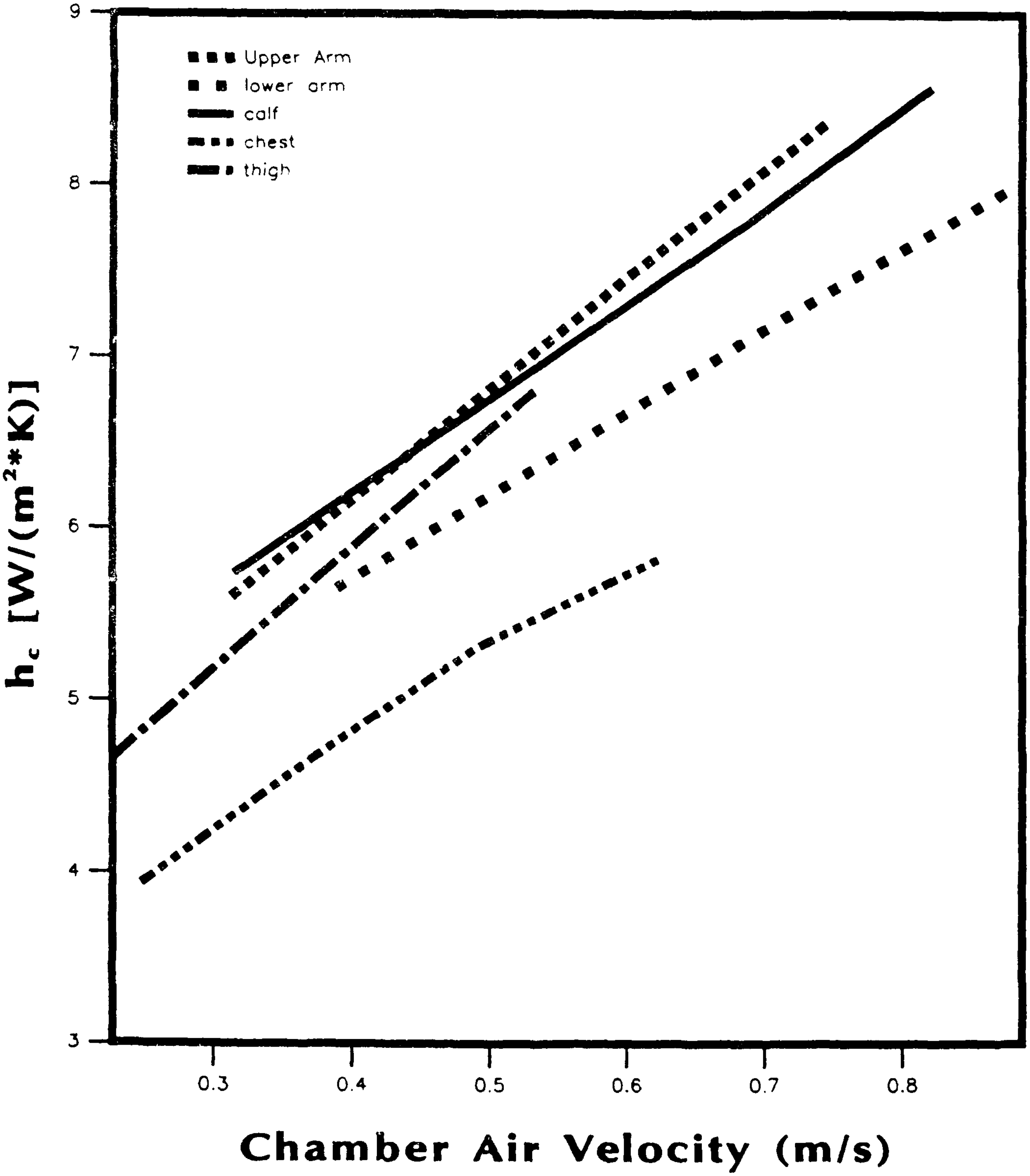


Figure 8 h_c **with stationary manikin at increasing chamber air velocity**



APPENDIX
Algorithm Implementing the Heat - Mass Transfer Relationship

```
' This program asks for naphthalene weight loss (in grams), and
' returns the computed convective heat transfer coefficient hc,
' and mass transfer coefficient hm, as the result.
' This program was written in QuickBASIC compiler (version 4.0).
' To convert to interpretive BASIC or BASICA is a simple process:
' add line numbers, and note the line number of the label 'Naph'.
' Substitute in this line number wherever the label 'Naph'
' appears.  The last step is to delete the label 'Naph:'.
'
CLS '                                                 clear screen
'                               disk surface area data (in cm^2)
DATA 19.32,19.32,19.32,19.32,19.32,19.23,19.23,19.00,18.85,18.85
DATA 18.09,18.09,18.09,18.09,19.32,19.23,18.85,18.09,18.09
'
DIM A(20)
FOR J = 1 TO 19: READ A(J): NEXT ' read in disk surface area data
'
k = .02636 '                   k=thermal conductivity
rho = 1.165 '                  rho=density
Cp = 1006 '                    Cp=specific heat
Alpha = k / (rho * Cp) '       Alpha=thermal diffusivity
Dv = 6.33E-06  '               Dv=Mass diffusivity
time = 55 * 60 '               time = 55 min (in sec.)
R = .487 '                     R=naphthalene gas constant
PAM = .319 '                   PAM=logarithmic mean density factor
'
Naph:
PRINT " "  '                                      skip a line
INPUT "Enter cassette number (1-19), 0 to quit "; n
IF n = 0 THEN END
IF n > 19 THEN
BEEP
PRINT "Cassette number must be between 1 - 19";
GOTO Naph
END IF
INPUT "Enter naphthalene weight loss (in grams)"; wt
INPUT "Enter temperature in deg. C "; temp
'
wt = wt * .001 '                    change weight from g to kg
temp = temp + 273.15 '              change temperature to deg. K
A = A(n) * .0001 '                  change area from cm^2 to m^2
'
Pns = 10 ^ (11.55 - 3765 / temp) '       Pns=naph. vapor pressure
m = wt / (time * A)  '              m=sublimation rate=kg/(m^2*sec)
Hm = R * temp * m / Pns '                Hm=mass transfer coeff.
Hc = Hm * PAM * rho * Cp * (Alpha / Dv) ^ (2 / 3)
'
PRINT SPC(49); "W/(m^2*K)       m/sec"
PRINT SPC(46); "Hc = "; : PRINT USING "##.##"; Hc;
PRINT "      Hm = "; : PRINT USING "##.###^^^^"; Hm
'
GOTO Naph
```

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