

Chapter 5: The Human Thermal System¹

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¹Cooney, David O. 1976. Biomedical Engineering Principles: An Introduction to Fluid, Heat and Mass Transport Processes. New York: Marcel Dekker, Inc.

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Appendix 1. EXERCISES

1. Body temperature rise with no heat loss. We assume a body weight of 68 kg, heat capacity of 0.86 kcal/kg-°C and a basal heat production rate of 72 kcal/hr. We then find that

$$\frac{dT}{dt} = \frac{Q}{mC_p} = \frac{72}{(68)(.86)} \frac{^{\circ}\text{C}}{\text{hr}} = 1.2^{\circ}\text{C/hr}$$

2. Estimation of radiative heat loss from the body. We assume a surface temperature T_s of 33 °C (91.4 °F); surroundings at 29 °C (84.2 °F); $A_r = 1.4\text{m}^2$; $e_s = 0.97$; and $K_r = 7 \text{ kcal/hr-m}^2\text{-}^{\circ}\text{C}$. We determine that

$$Q_r = K_r A_r e_s (T_s - T_r) = (7)(1.4)(.97)(33-29) = 38 \text{ kcal/hr}$$

3. Prediction of forced convection heat losses from humans using literature correlations for cylinders. We consider the human body to be roughly cylindrical. The equivalent diameter of this cylinder can be computed for a man of 5'8" (1.73m) tall who has a total body surface area of 1.8 m²:

$$\text{Area} = \pi DL + 2 \frac{\pi D^2}{4} = 1.73\pi D + \frac{\pi D^2}{2} = 1.8 \text{ m}^2$$

Solving for D by trial and error gives D = 30.5 cm or 12". Assuming the ambient is air at 70 °F, for which P_r is 0.72, $\mu/\rho = 1.6 \times 10^{-5} \text{ m}^2/\text{sec}$, and $k = 2.2 \times 10^{-2} \text{ kcal/m-hr-}^{\circ}\text{C}$, we have from the long cylinder correlation

$$\frac{k_c (.305)}{(.022)} = \left[\frac{(.305)v}{1.6 \times 10^{-5}} \right]^{1/2} (.72)^{1/3}$$

where v is in meters per second. This yields

$$k_c = 5.4v^{1/2}$$

4. Heat loss via forced convection. For a velocity of a mph (0.447 m/sec), we compute the magnitude of convective heat losses from a nude person. For $v = 0.447$, the correlation $5.6v^{.67}$ yields $k_c = 3.27$ (note that this is larger than free convection coefficient of 2.3; hence, even had we not performed the preceding calculation, we would immediately realize that at this velocity forced convection controls). The corresponding heat loss, assuming $T_s = 33^{\circ}\text{C}$ and $T_a = 29^{\circ}\text{C}$, and using an effective heat loss area for convection of 80% of the total area, is

$$Q_c = 3.27(0.8)(1.8)(33-29) = 18.8 \text{ kcal/hr}$$

5. Heat loss via evaporation of sweat. The amount of cooling that can be achieved by evaporation of water from the skin can be estimated for some typical conditions. Let us assume air is moving at 1 mph (0.45 m/sec) and is at 70 °F with a relative humidity of 30%. Then, since the vapor pressure of water at 70 °F and 1

atm equals 18.8 mm Hg, $P_a = 0.3(18.8) = 5.65 \text{ mm Hg}$. The vapor pressure of water at the temperature of skin (say 33 °C) is about 38.8 mm Hg. Arbitrarily using $K_e = 12.7v^{.634}$ gives a K_e of 7.6 kcal/hr-m²-mm Hg. We next assume a fairly large wetted area, say 1.5 m², corresponding to conditions of moderately strenuous activity. Then,

$$Q_e = 7.6(1.5)(38.8 - 5.65) = 378 \text{ kcal/hr}$$

6. Heat loss via respiration. We will assume that 6 liters/min of bone-dry 20 °C air are inspired (e.g., 12 breaths per minute at 500 ml tidal volume per breath) and the air expired is saturated with water vapor and is at 37 °C. known physical properties are

$$C_{p,\text{air}} \text{ at } 20^{\circ}\text{C} = .25 \text{ cal/g-}^{\circ}\text{C}$$

$$\lambda_{\text{H}_2\text{O}} \text{ at } 37^{\circ}\text{C} = 577 \text{ cal/g}$$

$$\text{Vapor pressure of water at } 37^{\circ}\text{C} = 47 \text{ mm Hg}$$

Using the ideal gas law, the dry air flow in grams per minute can be determined as follows:

$$\begin{aligned} \dot{m}_a &= (6 \text{ liters/min})(\text{g-mol}/22.4 \text{ liters})(273 \text{ k}/293 \text{ k}) \\ &\quad (28.9 \text{ g/g-mol}) \\ &= 7.2 \text{ g/min dry air} \end{aligned}$$

The amount of water in the expired air is

$$\dot{m}_w = \left(\frac{7.2}{28.9} \right) \left(\frac{47}{760 - 47} \right) (18) = .295 \text{ g/min}$$

The sensible heat loss associated with raising the dry air from 20 °C to 37 °C is therefore

$$Q_{\text{sensible}} = 7.2(0.25)(37 - 20) = 30.4 \text{ cal/min}$$

While the latent heat loss derived from water evaporation is

$$Q_{\text{latent}} = 0.295(577) = 170 \text{ cal/min}$$

Appendix II. FIGURES

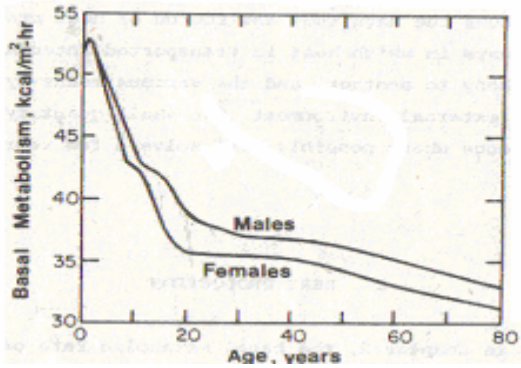


Figure 1. Normal basal metabolic rates at different ages for each sex.[3, 828].

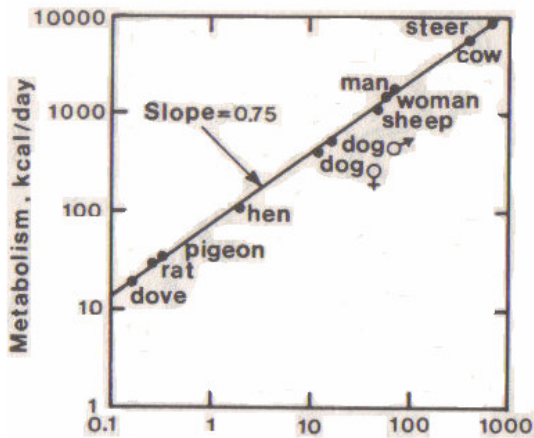


Figure 2. Logarithm of metabolism plotted against logarithm of weight. [7,1045].

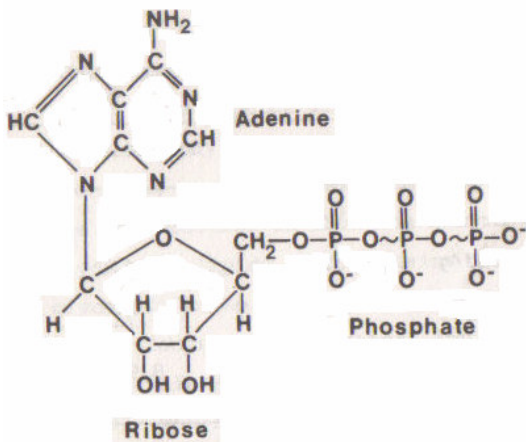


Figure 3. The structure of ATP.

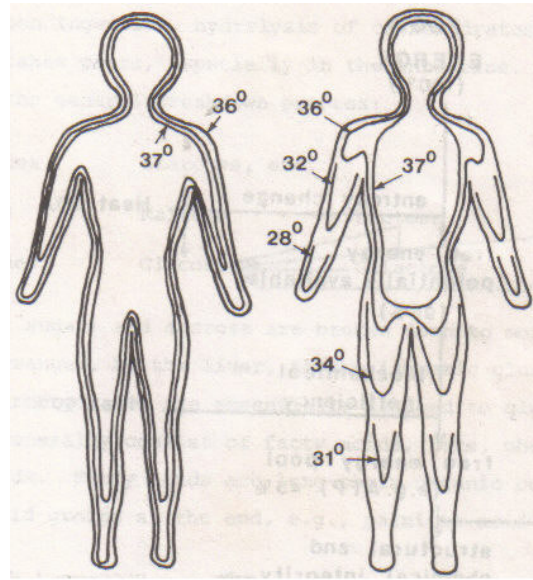


Figure 4. Isotherms (surfaces connecting points of equal temperature) in the body. Left, isotherms in a warm environment; right, in a cold environment. The innermost isotherm may be considered as the boundary of the body "core"; the core includes most of the body in hot environments. When heat must be conserved, the core contracts to the proportions indicated on the right. In severe cold exposure, the combined effect of vasoconstriction and counter-current heat exchange results in the pattern of isotherms shown in the limbs, the distal portions of which become part of the body "shell" and fall nearly to environmental temperatures [7,1057].

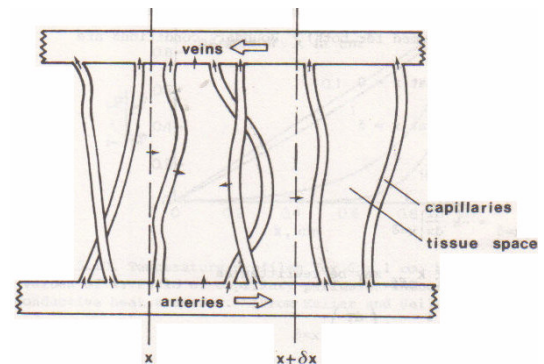


Figure 5. Schematic diagram of an element in subcutaneous region [4].

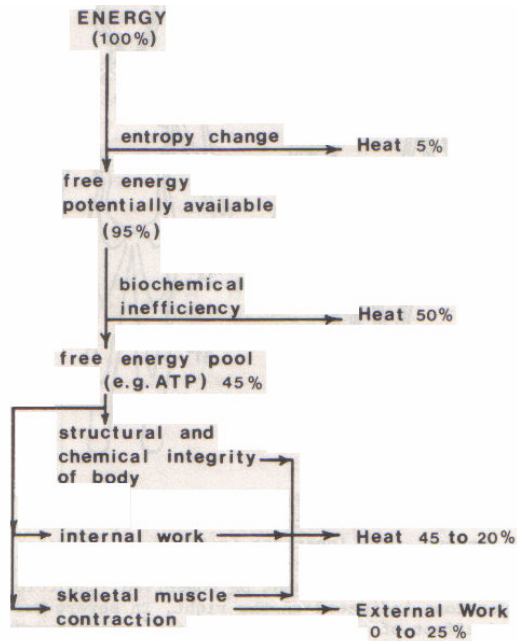


Figure 6. Summary of the distribution of ingested food energy within the body and its transfer to the environment [7,1034].

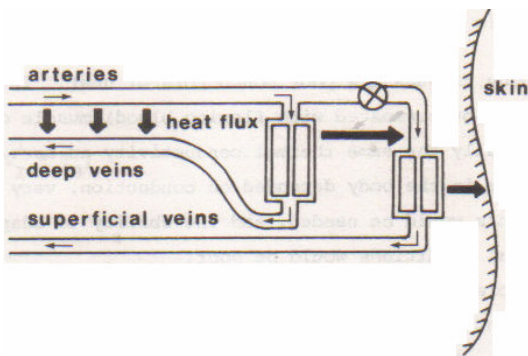


Figure 7. Countercurrent heat exchange in the extremities. When “valve” is open, blood flow is routed through superficial capillary bed, allowing efficient transfer of to body surface. Blood returning through superficial veins does not exchange significant amounts of heat with deep arterial blood. When “valve” is closed superficial blood flow is reduced, and most blood returns via deep veins [7,1057].

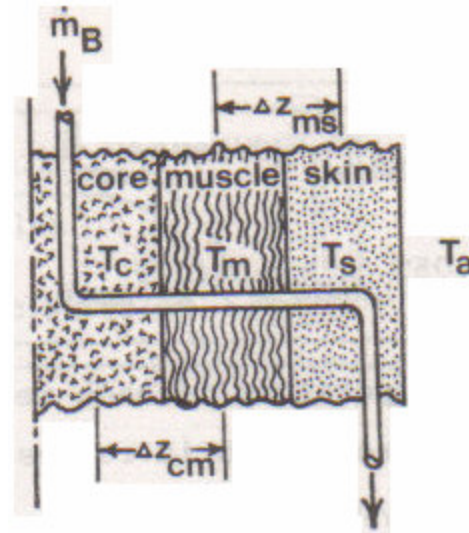


Figure 8. Model system for heat transfer between core and skin[8].

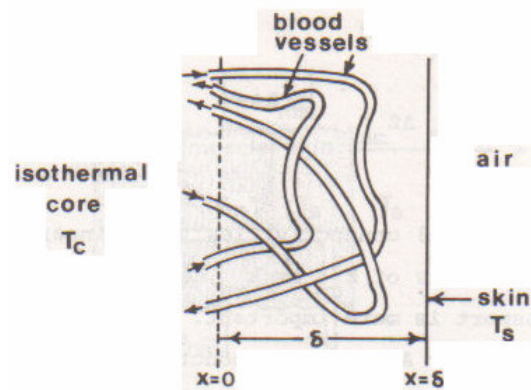


Figure 9. Schematic diagram of subcutaneous tissue region emphasizing its vascularization and temperature variation [4].

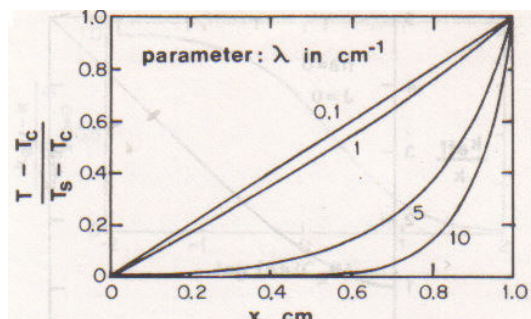


Figure 10. Temperature profiles for $\delta = 1$ cm, $h_a = 0$ and various values of λ , ratio of capillary-perfusion-induced heat transfer to conductive heat transfer [4].

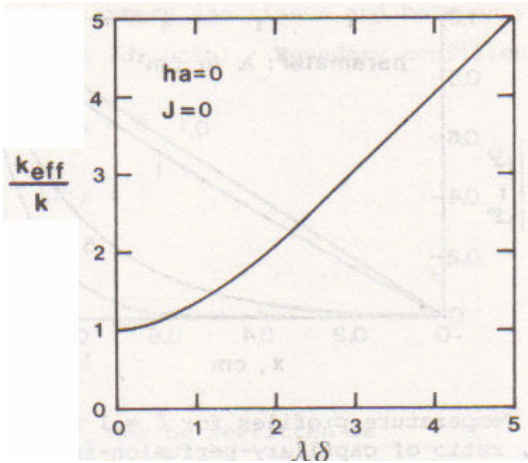


Figure 11. Illustration of dependence of effective thermal conductivity on dimensionless quantity $\lambda\delta$ in the limiting case where arterial-venous heat exchange is negligible [4].

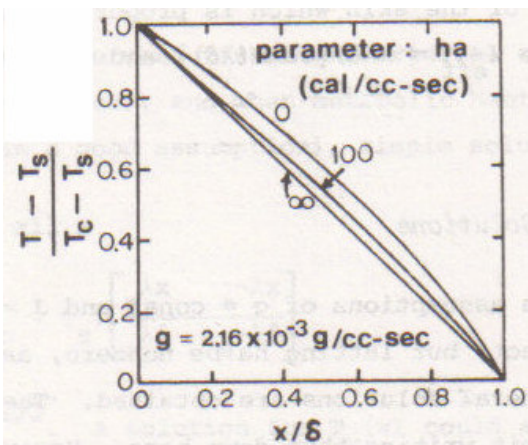


Figure 12. dimensionless temperature profiles illustrating the effect of various extents of arterial-venous heat exchange at a fixed capillary perfusion rate [4].

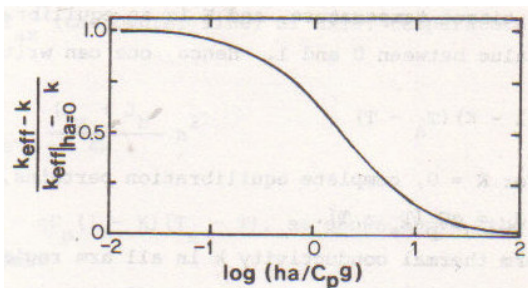


Figure 13. Illustration of dependence of effective thermal conductivity on ratio of arterial-venous heat exchange rate to rate of heat transfer due to capillary perfusion [4].

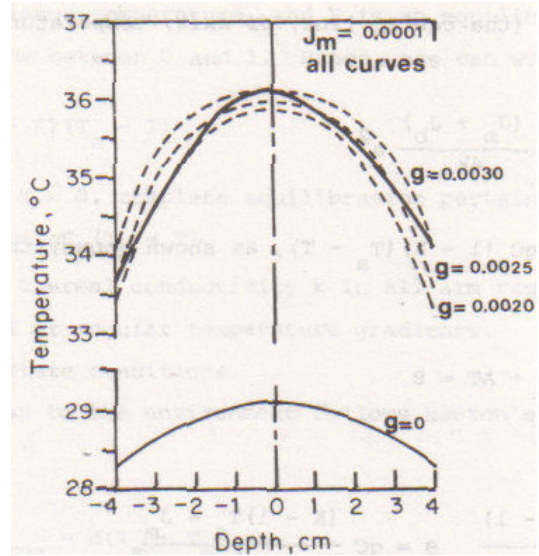


Figure 14. Radial temperature profiles in the human arm from Pennes' model and experimental data [6].

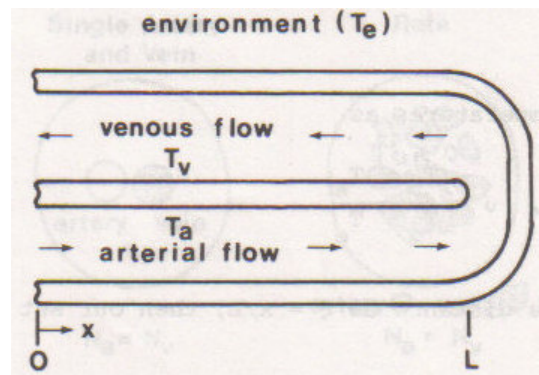


Figure 15. Analytical model for countercurrent heat exchange [5].

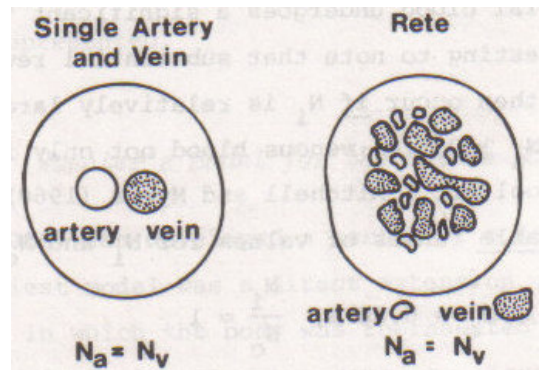


Figure 16. Anatomical models for countercurrent heat exchange [5].

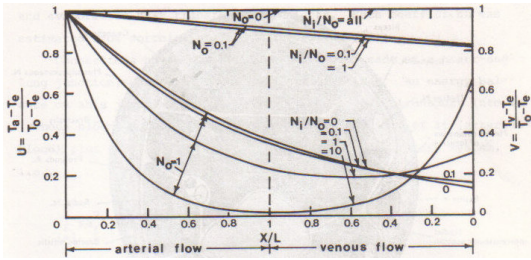


Figure 17. Axial temperature profiles in the arteries and veins of the human arm [5].

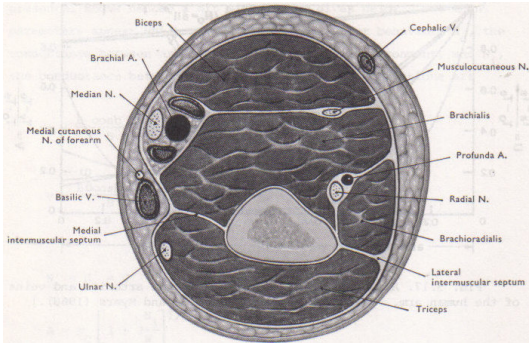


Figure 18. Section through the distal third of the right arm [10,65].

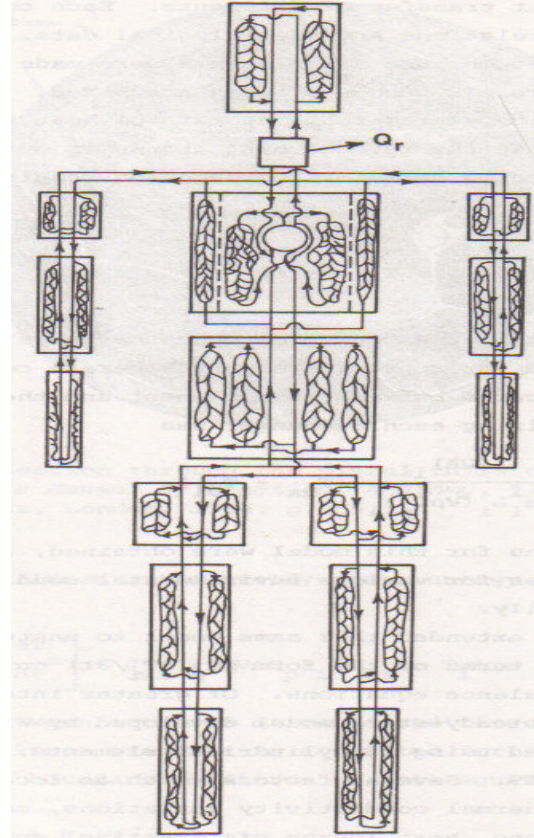


Figure 19. A schematic diagram showing the geometric arrangement of the elements and the circulatory system [9].

Appendix III. TABLES

Table 1. Balance of heat production and heat losses.

Production	Losses
Basal metabolism	Radiation
Voluntary muscular activity	Evaporation from skin
Involuntary muscular activity (shivering)	Evaporation from respiratory tract
Effects of hormones (thyroxin, adrenaline) on cellular metabolism	Sensible losses via respiration
Effects of temperature on metabolic rate	Convection Conduction

Table 2. Resistance and surface area factors for various clothing ensembles^a [Fanger 1968].

Clothing ensemble	I_{cl} (clo)	F_{cl}
Nude	0	1.0
Light working ensemble	0.6	1.1
U.S. Army fatigues, man's	0.7	1.1
Typical American business suit	0.7-1.0	1.1-1.15
Light outdoor sportswear	0.9	1.15
Heavy traditional European Business suit	1.2	1.15-1.20
U.S. Army standard cold-wet uniform	1.5-2.0	1.3-1.4
Heavy wool pile ensemble (polar weather suit)	3.4	1.3-1.5

Table 3. Radiation heat transfer coefficients for nude humans.

K'_r (kcal/m ² -hr-°C)	Authors	Conditions
4.50-4.77	Colin et al. (1970)	Range of postures
4.7	Cited by Sibbons (1970)	
4.5	Gagge et al. (1964)	Seated posture

Table 4. Data for different common activities^a [Fanger 1968].

Type of activity	Metabolic rate per unit body surface area (kcal/m ² hr)	Estimated mechanical efficiency	Estimated relative velocity in still air (m/sec)
Seated, quiet	50	0	0
Seated, drafting	60	0	0-0.1
Seated, typing	70	0	0-0.1
Standing at attention	65	0	0
Standing, washing dishes	80	0-0.05	0-0.2
Shoemaker	100	0-0.10	0-0.2
Sweeping a bare floor (38 strokes/min)	100	0-0.05	0.2-0.5
Seated, heavy leg and arm movements (metalworker)	110	0-0.15	0.1-0.3
Walking about, moderate lifting or pushing (carpenter, metalworker)	140	0-0.10	0-0.9
Pick and shovel, stonemason work	220	0-0.20	0-0.9
Walking on the level with the velocity (mph):			
2.0	100	0	0.9
2.5	120	0	1.1
3.0	130	0	1.3
3.5	160	0	1.6
4.0	190	0	1.8
5.0	290	0	2.2

Table 5. Metabolism of specific compounds

	Glucose	Triolein	Hydroxylysine
Liters O ₂ used/g	0.75	2.03	0.90
Liters CO ₂ produced/g	0.75	1.44	0.69
Respiratory quotient	1.00	0.71	0.77
Kcal/g	3.74	8.93	5.25

Table 6. Coefficients for free convection heat transfer from nude person to air.

Coefficient ^a	Authors	Conditions
2.12	Buettner (1934)	
2.3	Colin and Houdas (1967)	Standing
1.95	Colin and Houdas (1967)	Seated
3.0	Winslow et al. (1939)	
$2.05\Delta T^{0.25}$	Nielsen and Pedersen (1952)	Seated or standing

^a $\Delta T = T_s - T_a$, in degrees centigrade. Units of coefficient K_c are kcal/m²-hr-°C.

Table 7. Coefficients for forced convection heat transfer from nude persons to air.

Coefficient ^a	Authors	Conditions
$5.6v^{0.67}$	Colin and Houdas (1967)	Standing, cross flow
$3.66v^{0.643}$	Tamari and Leonard (1972)	Standing, cross flow
$7.5v^{0.5}$	Nelson et al. (1947)	Standing, cross flow
$6.4v^{0.67}$	Colin and Houdas (1967)	Seated, vertical flow
$7.5v^{0.67}$	Colin and Houdas (1967)	Reclining, parallel flow
$10.4v^{0.5}$	Winslow et al. (1939)	Reclining, parallel flow
$2.54v^{0.72}$	Tamari and Leonard (1972)	Standing, parallel flow
$6.3v^{0.5}$	Buettner (1934)	Reclining, parallel flow

^a v is approach velocity in meters per second. Coefficient K_c in kcal/m²-hr-°C

Table 8. Metabolism of different classes of foods.

	Carbohydrate	Lipid	Protein
Liters O ₂ used/g	0.81	1.96	0.94
Liters CO ₂ produced/g	0.81	1.39	0.75
Respiratory quotient	1.00	0.71	0.80
Kcal/g	4.1	9.3	5.4

Table 9. free and forced convection heat transfer correlations^a.

Forced convection	Free convection
<u>Sphere</u> $Nu = 2 + 0.6 Re^{1/2} Pr^{1/3}$	<u>Sphere</u> $Nu = 2 + 0.56 (Gr Pr)^{1/4}$
<u>Long cylinder</u> $Nu \approx 0.6 Re^{1/2} Pr^{1/3}$ For $10 < Re < 10^5$	<u>Long horizontal cylinder</u> $Nu = 0.525 (Gr Pr)^{1/4}$
	<u>Vertical cylinder or thin plate</u> $Nu = 0.59 (Gr Pr)^{1/4}$ The above are generally limited to Gr Pr greater than 10^4 and less than 10^9

^a $Gr = (D^3 \rho^2 g \beta \Delta T / \mu^2)$, where β is the coefficient of volume expansion of the fluid, $-(1/\rho)(d\rho/dT)_p$, and ΔT is the surface temperature minus the temperature of the fluid far from the surface. $Nu = K_c D/k$, $Re = Dv/\mu$, $Pr = C_p \mu / k$.

Table 10. Convective heat transfer coefficient in water^a [Colin 1970].

Authors	Experimental conditions	Transfer coefficient (kcal/m ² -hr-°C)
Lefevre (1929)	Stirred water at 5 °C	57.6 54 54 54 57.6
	12 °C	
	18 °C	
	24 °C	
	30 °C	
Goldman et al. (1966)	Still water Stirred water	39.63 50.45
Boutelier et al. (unpublished data)	Still water Water agitated by shivering	37.6 52.2

^a from Colin et al. (1970)

Table 11. Coefficients for forced convection evaporation heat transfer from nude persons in air^{a, b} [Colin and Houdas ,1967].

Coefficient	Authors	Conditions
$12.70v^{0.634}$	Clifford et al. (1959)	$v > 0.58$ m/sec, standing, cross flow
$9.66v^{0.25}$	Clifford et al. (1959)	$v < 0.51$ m/sec
$10.17v^{0.37}$	Nelson et al. (1947)	$0.15 < v < 3.05$ m/sec
$18.4v^{0.37}$	Machle and Hatch (1947)	
$11.6v^{0.4}$	Wyndham and Atkins (1960)	
$19.1v^{0.66}$	Fourt and Powell ^c	
$13.2v^{0.6}$	Fourt and Powell ^c	

a for free convection, Clifford et al. (1959) give a coefficient $K_e = 3.37(T_s - T_a)^{0.258}$, for $1 < \Delta T < 20$ °C.

b Rapp (1970) discusses how theoretical analyses indicates that K_e / K_c should equal approximately 2.2.

c based on studies with simple geometric models, as cited by Colin and Houdas (1967).

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