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A Spreadsheet for Partitional Calorimetry

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Partitional calorimetry is the measurement of heat storage in the body and the components of heat exchange (conductive, convective, radiative, and evaporative) between the body and the environment. We present here a spreadsheet using the principles of partitional calorimetry to estimate how a given environmental condition and/or clothing ensemble affects the ability of the body to gain or lose heat during prolonged exercise.

KEYWORDS: clothing, endurance, heat, temperature regulation

Metabolic heat generated during exercise is transferred to the environment from the skin surface via dry (conduction, convection and radiation) and evaporative heat transfer pathways. Parameters within the environment that influence heat exchange include the ambient temperature and water vapor pressure, radiant heat, air movement, and the properties of clothing (insulation and moisture transfer). Measurement of heat exchanged via dry and evaporative processes is useful to determine how workload, clothing and environmental conditions influence the degree of thermal strain during prolonged exercise. The procedure for calculating heat storage and heat lost or gained via dry and evaporative heat transfer pathways is termed partitional calorimetry.

The calculations in partitional calorimetry are necessarily complex. For the benefit of researchers and teachers interested in heat balance during exercise, we present here an Excel spreadsheet to perform the calculations. The spreadsheet automates the calculations with Visual Basic, using an approach similar to that of Egan (1999). A main menu, constructed from a userform, contains command buttons that guide the user to the relevant worksheets to input data and to receive calculated information. View the main menu at any time by typing Ctrl+Shift+R. Instructions are available via the main menu to guide you through the program.

Data required to run the program include:

- Subject and test parameters: observation time (min), height (cm), body mass (kg) and work rate (W).
- Environmental parameters: dry bulb temperature (^oC), black globe temperature (^oC), relative humidity (%), and air velocity ($m.s^{-1}$).
- Physiological parameters: initial and final body masses (g), fluid/food intake (g), urine/feces loss (g), dripped sweat (g), initial and final body core temperatures (^oC), initial and final mean skin temperatures (^oC), oxygen consumption ($L.min^{-1}$) and respiratory exchange ratio (RER = VCO_2/VO_2).

Userforms are provided in the environmental worksheet to calculate mean radiant temperature, the partial water vapor pressure in the ambient air, and the radiative heat transfer coefficient. The user inputs these values into the worksheet. For the intrinsic clothing insulation of garments worn, the user can either enter a measured value or estimate this value by selecting the checkboxes that correspond to the worn clothing items.

The data produce the following parameters:

- Environmental parameters: mean radiant temperature (^oC), partial water vapor pressure in ambient air (mmHg), the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$), the radiative heat transfer coefficient ($W.m^{-2}.K^{-1}$), evaporative heat transfer coefficient ($W.m^{-2}.kPa^{-1}$), and the combined heat transfer coefficient ($W.m^{-2}.K^{-1}$).
- Clothing parameters: Clothing area factor (ND), effective clothing insulation (clo unit), permeation efficiency factor of clothing (clo unit), intrinsic thermal resistance of clothing ($m^2.K.W^{-1}$), and the intrinsic evaporative resistance of clothing ($m^2.kPa.W^{-1}$).
- Physiological parameters: metabolic heat production ($W.m^{-2}$), internal heat production ($W.m^{-2}$), body heat storage ($W.m^{-2}$), heat loss or gain via conduction, convection, radiation and evaporation ($W.m^{-2}$), heat loss by skin diffusion ($W.m^{-2}$), skin wettedness and convective and evaporative heat exchange from the respiratory tract ($W.m^{-2}$).

The partitional calorimetry results appear in the worksheet *Program Outputs.* This worksheet is shown automatically after the program has performed the calculations. If the user is interested in other calculated variables (physiological, environmental and clothing), all the calculated variables are shown in the worksheet *Calculation.* Formulae that use fabric temperature in their calculations have the term *Tcl used* within the column. If mean skin temperature is used in a given formula instead of fabric temperature the term *Tsk used* is shown within the column.

Final points:

- The partitional calorimetry program is suitable for walking, running or cycling, and for air velocities to 4 $m.s^{-1}$.
- The program includes optional input of fabric temperature and intrinsic insulation of the clothing.
- See below for the formulae we have used to create the spreadsheet.
- Please contact us if you have suggestions to improve the program.

FORMULAE FOR PARTITIONAL CALORIMETRY CALCULATIONS

Environmental Variables

Calculation of mean radiant temperature, T_r (from Goldman, 1978)

T_r (^oC) = $((1+(0.222 \times (v_a^{0.5}))) \times (T_g - T_{db})) + T_{db}$
where v_a = air velocity ($m.s^{-1}$), T_g = black globe temperature (^oC) and T_{db} = dry bulb temperature (^oC).

Calculation of convective heat transfer coefficient, h_c (from Kerslake, 1972)

h_c ($W.m^{-2}.K^{-1}$) = $8.3 \times (v_a^{0.6})$
where v_a = air velocity ($m.s^{-1}$).

Calculation of radiative heat transfer coefficient, h_r (from Parsons, 1993)

h_r ($W.m^{-2}.K^{-1}$) = $4.E.\sigma.A_rA_d.((273.2 + ((T_{cl} + T_r)/2))^3)$
where E = emissivity of the skin surface (0.98: Gonzalez, 1995, p.299), σ = Stefan-Boltzmann constant (5.67×10^{-8} $W.m^{-2}.K^{-4}$), A_rA_d = ratio of the area of the body exposed to radiation versus the total body surface area (0.70 for seated postures, 0.73 for standing postures), T_{cl} = mean surface temperature of the body (^oC), and T_r = mean radiant temperature (^oC).

Calculation of combined heat transfer coefficient, h
(from Parsons, 1993)

$h\ (W.m^{-2}.K^{-1}) = h_c + h_r$
where h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$) and h_r is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$).

Calculation of evaporative heat transfer coefficient, h_e
(from Kerslake, 1972)

$h_e\ (W.m^{-2}.kPa^{-1}) = 16.5 \times h_c$
where h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$).

Clothing Variables

Calculation of the clothing area factor, f_{cl}
(adapted from Parsons, 1993)

$f_{cl} = 1 + (0.31 \times (I_{cl}/0.155))$
where I_{cl} = intrinsic clothing insulation ($m^2.^oC.W^{-1}$).

Calculation of effective clothing insulation, I_{cle}
(from McIntyre, 1980)

I_{cle} (clo units) = $I_{cl} - ((f_{cl}-1)/(0.155 \times f_{cl} \times h))$
where I_{cl} = intrinsic clothing insulation ($m^2.^oC.W^{-1}$), f_{cl} = clothing area factor (ND), h = combined heat transfer coefficient ($W.m^{-2}.K^{-1}$).

Calculation of the permeation efficiency factor of clothing, f_{pcl}
(adapted from Parsons, 1993)

$f_{pcl} = 1/(1+(0.344 \times h_c \times I_{cle}))$
where h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$) and I_{cle} is the effective clothing insulation (clo units).

Calculation of the intrinsic thermal resistance of clothing, R_c
(from Holmer, 1985)

$R_c\ (m^2.K.W^{-1}) = (T_{sk} - T_{db})/h_c$
where T_{sk} = mean skin temperature (K), T_{db} = dry bulb temperature (K) and h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$).

Calculation of the intrinsic evaporative resistance of clothing, R_e
(from Holmer, 1985)

$R_e\ (m^2.kPa.W^{-1}) = (P_s - P_a)/h_e$
where P_s = saturated water vapor pressure at the skin surface (kPa), P_a is the partial water vapor pressure (kPa) and h_e is the evaporative heat transfer coefficient ($W.m^{-2}.KPa^{-1}$).

Physiological Variables

Calculation of body surface area, A_D

$A_D\ (m^2) = 0.00718 \times wt^{0.425} \times H^{0.725}$
where wt = body mass (kg) and H = height (cm).

Calculation of mean body temperature, T_b
(from Kerslake, 1972)

$T_b\ (^oC) = (0.33 \times T_{sk} + 0.67 \times T_c)$
where T_{sk} = skin temperature (^oC) and T_c = body core temperature (^oC).

Calculation of saturated water vapor pressure at the skin surface, P_s (from Fanger, 1970)

P_s (mmHg) = 1.92 x T_{sk} -25.3 (for 27°C < T_{sk} < 37 °C).
where T_{sk} = skin temperature (°C).

Partitional Calorimetry Equations

Calculation of the energy equivalent of oxygen, EE (modified from Parsons, 1993)

EE ($J.L\ O_2^{-1}$) = (0.23 x RER + 0.77) x 21 166
where RER = respiratory exchange ratio (ND), 21 166 is the energy equivalent of oxygen ($J.L\ O_2^{-1}$).

Calculation of metabolic free energy production, M (modified from Parsons,1993)

M ($W.m^{-2}$) = (((EE x VO_2 x t)/(t x 60))/A_D)
where EE = energy equivalent ($J.L\ O_2^{-1}$), VO_2 = oxygen consumption ($L.min^{-1}$), t = exercise time (min) and A_D = body surface area (m^2).

Calculation of mechanical efficiency, η (from Parsons, 1993)

η = W/M
where W = work rate ($W.m^{-2}$) and M = metabolic free energy production ($W.m^{-2}$).

Calculation of internal heat production, H (from McIntyre, 1980)

H ($W.m^{-2}$) = (M x (1- η)) x 1/A_D
where M = metabolic free production ($W.m^{-2}$), η= mechanical efficiency and A_D is the body surface area (m^2).

Calculation of body heat storage, S

S ($W.m^{-2}$) = ((3474 x wt x (T_b final - T_b initial))/t)/A_D
where 3474= average specific heat of body tissue ($J.kg^{-1}.{}^oC^{-1}$), wt= body mass (kg), T_b = mean body temperature (°C), t = exercise time (s) and A_D = body surface area (m^2).

Calculation of heat transfer via conduction, K

K ($W.m^{-2}$) = A_D x ((T_{sk} - T_{cl})/R_c)
where A_D = body surface area (m^2), T_{sk} = mean skin temperature (K), T_{cl} = mean fabric temperature (K), and R_c = intrinsic thermal resistance of clothing ($m^2.K.W^{-1}$).

Calculation of heat transfer via radiation, R (adapted from McIntyre, 1980)

R ($W.m^{-2}$) = $E.\sigma.f_{cl}.f_{eff}.(T_s^4 - T_r^4)$
where E = emittance from the outer surface of a clothed body (0.97), σ = Stefan-Boltzmann constant (5.67 x 10^{-8} $W.m^{-2}.K^{-4}$), f_{cl} =clothing area factor (ND), f_{eff} = effective radiation area of a clothed body (0.71), and T_s = surface temperature of the body (°C) and T_r = mean radiant temperature (°C).

Calculation of heat transfer via convection, C (from Fanger, 1970)

C ($W.m^{-2}$) = (A_D x f_{cl} x h_c x (T_s - T_{db}))/ A_D
where A_D = body surface area (m^2), f_{cl} = clothing area factor (ND), h_c = convective heat transfer coefficient ($W.m^{-2}.K^{-1}$), T_s = surface temperature of the body (°C) and T_{db} = dry bulb temperature (°C).

Calculation of required evaporative heat loss, E_{req}
(from Gonzalez, 1995)

E_{req} ($W.m^{-2}$) = H - K - R - C -S
where H = internal heat production ($W.m^{-2}$), K = heat exchange via conduction ($W.m^{-2}$), R= heat exchange via radiation ($W.m^{-2}$), C = heat exchange via convection ($W.m^{-2}$), and S = body heat storage ($W.m^{-2}$).

Calculation of the maximal evaporative capacity of the environment, E_{max}
(from McIntyre, 1980)

E_{max} ($W.m^{-2}$) = $f_{pcl} \times h_e \times (P_s - P_a)$
where f_{pcl} = permeation efficiency factor of clothing, h_e = evaporative heat transfer coefficient ($W.m^{-2}.kPa^{-1}$), P_s = partial water vapor pressure at the skin surface (kPa), and Pa = partial water vapor pressure of ambient air (kPa).

Calculation of skin wettedness, w

$w = E_{req}/ E_{max}$
where E_{req} = required evaporative heat loss ($W.m^{-2}$) and E_{max}= maximal evaporative capacity of the environment ($W.m^{-2}$).

Calculation of evaporative heat transfer via skin diffusion, E_d
(modified from Fanger, 1970)

E_d ($W.m^{-2}$) = $(\lambda.m.A_D.(P_s - P_a))/A_D$
where λ = latent heat of evaporation of sweat (2430 $J.g^{-1}$), m = permeance coefficient of the skin (1.694×10^{-4} $g.s^{-1}.m^{-2}.mmHg^{-1}$), P_s = partial water vapor pressure at the skin surface (mmHg), P_a= partial water vapor pressure in ambient air (mmHg), and A_D = body surface area (m^2).

Calculation of heat transfer by sweat evaporation from the skin surface, E_{sw}

E_{sw} ($W.m^{-2}$) = $((((wt_{initial} - wt_{final})$-(fluid/food intake+urine/faeces loss)-$((0.019 \times VO_2$ $\times (44-P_a)) \times t)))\times 2430)/((t \times 60) \times A_D)$
where wt = body mass (g), fluid/food intake and urine/faeces loss are in grams, the expression $0.019 \times VO_2 \times (44-P_a)$ accounts for respiratory weight loss in $g.min^{-1}$ (Mitchell et al., 1972), VO_2= oxygen uptake in $L.min^{-1}$, t = observation time (min), and A_D = body surface area (m^2).

Calculation of heat transfer via evaporation from the skin surface, E_{sk}

E_{sk} ($W.m^{-2}$) = $E_d + E_{sw}$
where E_d = heat transfer by skin diffusion ($W.m^{-2}$) and E_{sw} = heat transfer from sweat evaporation from the skin surface ($W.m^{-2}$).

Calculation of heat transfer via the respiratory tract, $E_{res}+C_{res}$
(from McIntyre, 1980)

$E_{res}+C_{res}$ ($W.m^{-2}$) = $(0.0014 \times M \times (T_{ex}-T_{db}))+(0.0017 \times M \times (58.7-P_a))$
where M = metabolic heat production ($W.m^{-2}$), T_{ex}= expired air temperature (assumed to be 34°C if T_{ex} is not measured directly), T_{db} = dry bulb temperature (°C), and P_a= partial water vapor pressure of ambient air (mmHg).

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