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 (°C), black globe temperature (°C), 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 (°C), initial and final mean skin temperatures (°C), oxygen consumption (L.min⁻¹) and respiratory exchange ratio (RER = VCO₂/VO₂).

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 (°C), 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)

\[
T_r (\text{°C}) = ((1 + (0.222 \times (v_a^{0.5}))) \times (T_g - T_{db})) + T_{db}
\]

where \(v_a\) = air velocity (m.s \(^{-1}\)), \(T_g\) = black globe temperature (°C) and \(T_{db}\) = dry bulb temperature (°C).

**Calculation of convective heat transfer coefficient, h\(_c\)**

(from Kerslake, 1972)

\[
h_c (\text{W.m}^{-2}.\text{K}^{-1}) = 8.3 \times (v_a^{0.6})
\]

where \(v_a\) = air velocity (m.s \(^{-1}\)).

**Calculation of radiative heat transfer coefficient, h\(_r\)**

(from Parsons, 1993)

\[
h_r (\text{W.m}^{-2}.\text{K}^{-1}) = 4.\text{E.} \sigma \cdot A_r A_d \cdot ((273.2 + ((T_{cl} + T_{r})/2))^4)
\]

where \(E\) = emissivity of the skin surface (0.98: Gonzalez, 1995, p.299), \(\sigma\) = Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{W.m}^{-2}.\text{K}^{-4}), A_r A_d = \text{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} = \text{mean surface temperature of the body (°C), and T}_{r} = \text{mean radiant temperature (°C).}
Calculation of combined heat transfer coefficient, \( h \)
(from Parsons, 1993)

\[ h = h_c + h_r \]

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)

\[ h_e = 16.5 \times h_c \]

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)

\[ f_{cl} = 1 + (0.31 \times \frac{I_{cl}}{0.155}) \]

where \( I_{cl} \) = intrinsic clothing insulation (m\(^2\).°C.W\(^{-1}\)).

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

\[ I_{cle} = I_{cl} - \left( \frac{f_{cl} - 1}{0.155 \times f_{cl} \times h} \right) \]

where \( I_{cl} \) = intrinsic clothing insulation (m\(^2\).°C.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)

\[ f_{pcl} = \frac{1}{1 + (0.344 \times h_c \times I_{cle})} \]

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)

\[ R_c = \frac{T_{sk} - T_{db}}{h_c} \]

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)

\[ R_e = \frac{(P_s - P_a)}{h_e} \]

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, \( A_D \)

\[ A_D = 0.00718 \times \text{wt}^{0.425} \times \text{H}^{0.725} \]

where \( \text{wt} \) = body mass (kg) and \( \text{H} \) = height (cm).

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

\[ T_b = 0.33 \times T_{sk} + 0.67 \times T_c \]

where \( T_{sk} \) = skin temperature (°C) and \( T_c \) = body core temperature (°C).
Calculation of saturated water vapor pressure at the skin surface, $P_s$ (from Fanger, 1970)

$$P_s \text{(mmHg)} = 1.92 \times T_{sk} - 25.3 \text{ (for } 27^\circ\text{C} < T_{sk} < 37 \, ^\circ\text{C)}.$$ where $T_{sk} = \text{skin temperature (} ^\circ\text{C)}$.

Partitional Calorimetry Equations

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

$$EE \text{ (J.L O}_2^{-1}) = (0.23 \times \text{RER} + 0.77) \times 21 \, 166$$ where $\text{RER} = \text{respiratory exchange ratio (ND)}$, 21 166 is the energy equivalent of oxygen (J.L O$_2^{-1}$).

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

$$M \text{ (W.m}^{-2}) = \frac{(EE \times VO_2 \times t)/(t \times 60)}{A_D}$$ where $EE = \text{energy equivalent (J.L O}_2^{-1})$, $VO_2 = \text{oxygen consumption (L.min}^{-1})$, $t = \text{exercise time (min)}$ and $A_D = \text{body surface area (m}^2\text{)}$.

Calculation of mechanical efficiency, $\eta$ (from Parsons, 1993)

$$\eta = \frac{W}{M}$$ where $W = \text{work rate (W.m}^{-2})$ and $M = \text{metabolic free energy production (W.m}^{-2})$.

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

$$H \text{ (W.m}^{-2}) = (M \times (1- \eta)) \times 1/A_D$$ where $M = \text{metabolic free production (W.m}^{-2})$, $\eta = \text{mechanical efficiency and } A_D = \text{body surface area (m}^2\text{)}$.

Calculation of body heat storage, $S$

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

Calculation of heat transfer via conduction, $K$

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

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

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

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

$$C \text{ (W.m}^{-2}) = (A_D \times f_{cl} \times h_c \times (T_s - T_{db}))/A_D$$ where $A_D = \text{body surface area (m}^2\text{)}$, $f_{cl} = \text{clothing area factor (ND)}$, $h_c = \text{convective heat transfer coefficient (W.m}^{-2}.K^{-1}\text{)}$, $T_s = \text{surface temperature of the body (} ^\circ\text{C)}$ and $T_{db} = \text{dry bulb temperature (} ^\circ\text{C)}$. 
Calculation of required evaporative heat loss, $E_{req}$ (from Gonzalez, 1995)

$E_{req} \left( \text{W.m}^{-2} \right) = H - K - R - C - S$

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)

$E_{max} \left( \text{W.m}^{-2} \right) = f_{pcl} \times h_{e} \times (P_{s} - P_{a})$

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 $P_{a} =$ 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)

$E_{d} \left( \text{W.m}^{-2} \right) = \left( \frac{\lambda \cdot m \cdot A_{D} \cdot (P_s - P_a)}{A_{D}} \right)$

where $\lambda =$ latent heat of evaporation of sweat (2430 J.g$^{-1}$), $m =$ permeance coefficient of the skin (1.694 x 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, $E_{sw}$

$E_{sw} \left( \text{W.m}^{-2} \right) = \frac{(((wt_{initial} - wt_{final})-(fluid/food intake+urine/faeces loss)-((0.019 \times VO_2 \times (44-P_a))) \times 2430)/(t \times 60 \times A_{D})}{t}$

where $wt =$ body mass (g), fluid/food intake and urine/faeces loss are in grams, the expression 0.019 x VO$_2$ x (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, $E_{sk}$

$E_{sk} \left( \text{W.m}^{-2} \right) = E_{d} + E_{sw}$

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)

$E_{res}+C_{res} \left( \text{W.m}^{-2} \right) = (0.0014 \times M \times (T_{ex}-T_{db}))+((0.0017 \times M \times (58.7-P_{a})))$

where $M =$ metabolic heat production (W.m$^{-2}$), $T_{ex} =$ expired air temperature (assumed to be 34$^\circ$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).

REFERENCES


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