

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 2007	3. REPORT TYPE AND DATES COVERED Conference Paper-Sports Med	
4. TITLE AND SUBTITLE Thermoregulatory Function During the Marathon			5. FUNDING NUMBERS	
6. AUTHOR(S) R.W. Kenefick, S.N. Cheuvront, M.N. Sawka				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Thermal and Mountain Medicine Division U.S. Army Research Institute of Environmental Medicine Natick, MA 01760-5007			8. PERFORMING ORGANIZATION REPORT NUMBER M06-43	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Same as #7 above			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Marathon races are performed over a broad range of environmental conditions. Hyperthermia is a primary challenge for runners in temperate and warm weather, but hypothermia can be a concern during cool-wet or cold conditions. Body temperature during the marathon is a balance between metabolic heat production and exchange with the environment described by the heat balance equation. During exercise, core temperature is proportional to the metabolic rate and largely independent of a wide range of environmental conditions. In temperate or cool conditions, a large skin-to-ambient temperature gradient facilitates radiant and convective heat loss, and reduces skin blood flow requirements, which may explain the tolerance for high core temperature observed during marathons in cool conditions. However, in warmer environments, skin temperatures and sweating rates increase. In addition, greater skin blood flow is required for heat loss, magnifying thermoregulatory and circulatory strain. The combined challenge of exercise and environment associated with marathon running can substantially challenge the human thermoregulatory system.				
14. SUBJECT TERMS heat balance; thermoregulatory control; core temperature; heat loss			15. NUMBER OF PAGES 4	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unclassified	

Thermoregulatory Function During the Marathon

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Abstract

Marathon races are performed over a broad range of environmental conditions. Hyperthermia is a primary challenge for runners in temperate and warm weather, but hypothermia can be a concern during cool-wet or cold conditions. Body temperature during the marathon is a balance between metabolic heat production and exchange with the environment described by the heat balance equation. During exercise, core temperature is proportional to the metabolic rate and largely independent of a wide range of environmental conditions. In temperate or cool conditions, a large skin-to-ambient temperature gradient facilitates radiant and convective heat loss, and reduces skin blood flow requirements, which may explain the tolerance for high core temperature observed during marathons in cool conditions. However, in warmer environments, skin temperatures and sweating rates increase. In addition, greater skin blood flow is required for heat loss, magnifying thermoregulatory and circulatory strain. The combined challenge of exercise and environment associated with marathon running can substantially challenge the human thermoregulatory system.

Marathon races are performed over a broad range of environmental conditions (temperature, humidity, sun, wind, rain), which can act in concert with metabolic rate (exercise intensity) and race duration (exposure time) to accentuate either heat gain or heat loss, causing body temperature to rise or fall, respectively. If body temperatures rise or fall outside of a narrow range, both the athlete's performance and possibly health could be compromised. The primary thermoregulatory problem for runners competing in temperate and warm weather is hyperthermia. However, hypothermia can be a problem during cool-wet and cold weather marathons.^[1]

Most marathons are not held in extremely hot or cold weather conditions. However, temperature ranges, precipitation and wind can vary widely within a race day or from year to year. For example,

between the years of 1984 and 1995, air temperatures on race day of the New York City Marathon ranged from 1°C to 29°C, despite a consistent annual race day. Furthermore, air temperature changes of up to 17°C have been reported from the start to the finish of a race on the same day.^[1] Therefore, the unpredictability of weather conditions may make it difficult for runners to adequately prepare themselves.

Optimal thermoregulatory responses are observed in runners who are heat acclimatised and well hydrated. An overview of these responses and factors can be found elsewhere.^[2] The purpose of this review is to outline thermoregulatory control, heat balance and physiological challenges associated with minimising body temperature perturbations during marathon competition. Of specific focus will

be the mechanisms used to minimise hyperthermia during marathon races.

1. Heat Balance

Body temperature changes during a marathon race reflect a balance between metabolic heat (energy) production and exchange with the environment. The heat balance equation (equation 1) describes the relationship between heat production and loss to the environment:

$$S = M \pm W \pm (R+C) - E \quad (\text{Eq. 1})$$

where, S is the rate of body heat storage, M is the rate of metabolic energy (heat) production, W represents mechanical work (either concentric [positive] or eccentric [negative] exercise), $R+C$ is the rate of radiant and convective energy exchanges, respectively, and E indicates rate of evaporative loss. The sum of these (heat storage) represents heat gain if positive or heat loss if negative. Body temperature increases when S is positive, decreases when S is negative and remains constant when S equals zero.

2. Thermoregulatory Control

Regulation of body temperature is achieved through two collaborative processes: (i) behavioural

temperature regulation; and (ii) physiological temperature regulation. Behavioral temperature regulation operates through conscious behaviour, which may be ignored by highly motivated athletes. Physiological temperature regulation includes: (a) heat flow via the blood from the core to the skin (for $R+C$ heat loss); (b) sweating (for evaporative heat loss); and (c) metabolic heat production (e.g. shivering or altering running pace).

Figure 1^[2] schematically depicts the function of the human thermoregulatory system. When thermal balance is upset, body temperatures in the core or skin (or both) will change. Those temperature changes will be detected by the thermal receptors. Both peripheral (skin) and core (brain, spinal column) thermal receptors provide afferent signals into the hypothalamic thermoregulatory centers, where this information is integrated, compared with a reference or 'set-point temperature' and a 'thermal command signal' is generated for heat loss/gain responses.

In response to input from the thermal receptors, the thermoregulatory controller in the central nervous system will call for responses that alter heat loss and/or production. Unless the thermal stress exceeds the capacity of the thermoregulatory system, these responses will continue until they are

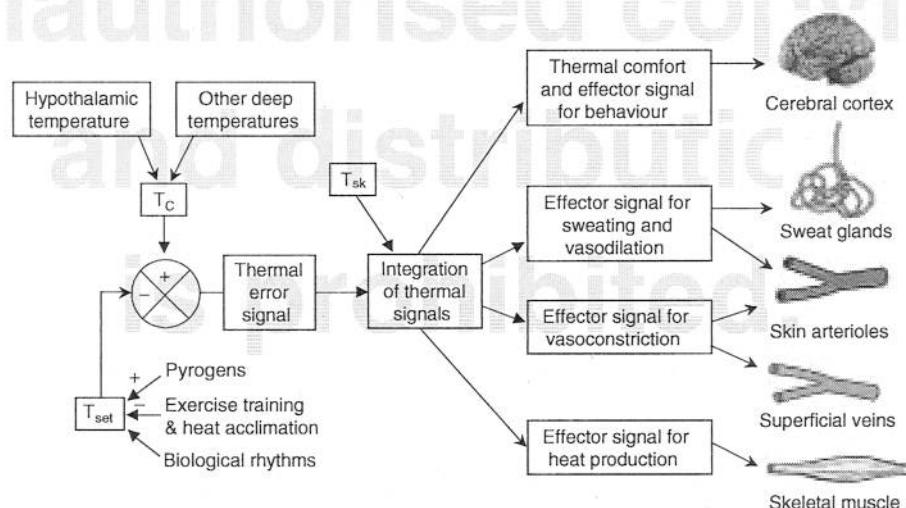


Fig. 1. Schematic of human thermoregulatory control.^[2] Reproduced with permission. T_c = core temperature; T_{set} = set temperature; T_{sk} = skin temperature.

Table I. Marathon runner's skin blood flow requirements for several core (T_c) and skin (T_{sk}) temperatures during heat stress^a

Heat production (watts/kcal/min)	T_c (°C)	T_{sk} (°C)	Core-to-skin gradient (°C)	Skin blood flow ^b (L/min)
540/7.7	38	30	8	1.1
540/7.7	38	34	4	2.2
540/7.7	38	36	2	4.4
540/7.7	39	36	3	3

a Calculations assume the metabolic energy to be dissipated is =540W (50% of 1080W), with 50% coming from evaporation. Calculations assume a constant sweat rate independent of skin temperature.

b Equation for skin blood flow: $Q_s = 1/C \times h/(T_c - T_{sk})$.

C = specific heat of blood = 0.87 kcal/°C/L; h = heat production; Q_s = skin blood flow.

sufficient to restore heat balance and prevent further change in body temperatures. In addition, non-thermal signals from baroreceptors, osmoreceptors and metaboreceptors can modify the heat loss/gain responses.^[2]

3. Core Temperature Response

The specific heat of body tissue (amount of energy required for 1kg of tissue to increase temperature by 1°C) approximates 3.5 kJ/°C/kg, given a 60kg runner this would equate to 210kJ of stored heat for each 1°C increase in body temperature. In the absence of heat loss, core temperature would increase to within dangerous levels before reaching the 5km mark in a marathon. Metabolic heat production increases immediately at the onset of exercise, so that during the early stages of exercise, the rate of heat production exceeds the rate of heat dissipation, resulting in the storage of the undissipated heat, causing core temperature to rise. As core temperature increases, heat-dissipating reflexes are prompted and the rate of heat storage decreases, thus core temperature climbs more slowly. Eventually, as exercise continues, heat dissipation increases sufficiently to balance heat production and a steady state in core can be achieved if the environment allows adequate heat loss.

During exercise, the magnitude of core temperature elevation is proportional to metabolic rate and largely independent of the environmental condition over a wide range ('prescriptive zone').^[3] Competitive marathoners (60kg) will often run at metabolic rates of >1350W (2-hour 10-minute pace). As a result, runners commonly finish races with core

temperatures ranging from 38.5°C to 39.5°C, but can have core temperatures of >40°C during or after a race.^[1,4,5] The ability to tolerate high core temperatures is likely somewhat dependent upon the athlete's skin temperature, as warmer skin (warmer environment) creates greater circulatory strain and lowers core temperature tolerance.^[2] In addition, there are likely undefined genetic and training/acclimatisation factors that can influence tolerance for high core temperatures.^[2]

4. Heat Loss Requirements During the Marathon

The 'prescriptive zone' progressively narrows as metabolic rate increases.^[3] In temperate or cool environments, a large skin-to-ambient temperature gradient facilitates dry (R+C) heat loss. The amount of heat produced by competitive runners during a 42km race is difficult to determine as the actual mechanical efficiency of running is difficult to calculate given that physical work cannot be calculated when running on flat terrain. However, for the sake of example, if we assume at maximal mechanical efficiency ≈80% of the 1350W required for competitive runners to run 42km must be dissipated to avoid heat storage. Assuming 50% of 1080W of heat stored can be dissipated by evaporative sweating, 540W of heat must be dissipated by radiation and convection.

Skin blood flow requirements for dry heat exchange depend on skin (influenced by ambient temperature, humidity, air motion) and core temperatures.^[6,7] Using the assumptions described earlier, table I provides calculations for minimal skin blood

flow requirements at several core temperature and skin temperature combinations. It is clear from table I that as skin temperature increases, a greater skin blood flow is required to provide the same dry heat loss. In fact, skin temperature often rises because evaporative cooling is decreasing; therefore, the contribution of R+C may also be increasing. Interestingly, at a constant skin temperature of 36°C, it can be observed that an increase in core temperature from 38°C to 39°C actually reduces skin blood flow (table I). This is explained by blood flow limitations to the skin, active musculature and the quintessential need to maintain blood pressure.^[8,9] In a 20°C environment, with a 28°C skin temperature and a 39°C core temperature, skin blood flow would be 0.80 L/min. In a further example, if given a 10°C environment, a 25°C skin temperature and a 39°C core temperature, skin blood flow would be 0.63 L/min. The large core-to-skin gradients and relatively low skin blood flows in these examples, which can occur in cool weather, may explain the tolerance for high core temperatures observed during marathons in cool weather.^[4]

When ambient temperature equals or exceeds skin temperature, heat loss is totally dependent upon sweat evaporation. Sweating rates of 0.5–1.5 L/h are commonly observed among marathon runners.^[1] If sweat evaporation was 100% efficient (i.e. no drip-page), the conversion to vapour of sweat volumes in this range would liberate 340–1000 W of heat energy. Although competitive international marathons may be contested in warm or hot climates,^[10] most marathon races are held in cooler conditions^[1] and heat balance is achieved by a combination of dry and evaporative heat losses.

5. Conclusion

The combination of endogenous (exercise) and exogenous (environment) heat gains associated with marathon running can substantially challenge the human thermoregulatory system. Heat stress results in sweating and skin blood flow effector responses that allow thermoregulatory homeostasis. The po-

tential health and performance consequences associated with maintaining these responses (heat strain, dehydration) will be addressed by others papers in this symposium.

Acknowledgements

The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy or decision unless so designated by other official documentation. The authors have indicated that they have no affiliation or financial interest in any organisation(s) that may have a direct interest in the subject matter of this article.

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