Continuous Thermoregulatory Responses to Mass-Participation Distance Running in Heat

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ABSTRACT

BYRNE C., J. K. W. LEE, S. A. N. CHEW, C. L. LIM, and E. Y. M. TAN. Continuous Thermoregulatory Responses to Mass-Participation Distance Running in Heat. *Med. Sci. Sports Exerc.*, Vol. 38, No. 5, pp. 803–810, 2006. **Purpose:** To continuously measure core temperature (T_c) and heart rate (HR), and quantify fluid balance during a 21-km mass-participation road race in warm, humid environmental conditions. **Methods:** Eighteen heat-acclimatized male soldiers ingested a telemetric T_c sensor on the evening prior to the race and wore an ambulatory T_c data recorder and HR monitor during the race. Pre- to postrace changes in nude body mass quantified fluid balance. **Results:** Environmental wet bulb globe temperature averaged 26.5°C. All runners finished the race asymptomatic of heat illness in a mean ± SD (range) time of 118 ± 13 (105–146) min, corresponding to an average running speed of 10.8 ± 1.1 (8.6–12.0) $km \cdot h^{-1}$. All runners recorded peak T_c > 39°C; 56% (N = 10) > 40°C; and 11% (N = 2) > 41°C. Peak T_c was 40.1 ± 0.7 (39.3–41.7) °C at 86 ± 36 (13–130) min, with T_c 39.9 ± 0.8 (38.3–41.7) °C at race finish. The magnitude of T_c response was unrelated (P > 0.05) to running time or fluid balance (e.g., fluid intake, % dehydration). Cumulative heat strain index was 2790 ± 1112 (1046–5144) units at race finish. **Conclusion:** Ingestible telemetric temperature sensors demonstrated utility for continuous measurement of T_c during mass-participation running. Successful application of this technology has highlighted the magnitude and duration of T_c elevation that runners will voluntarily achieve during mass-participation distance races in heat and high humidity without medical consequence. **Key Words:** CORE TEMPERATURE, HYPERTHERMIA, HEAT ILLNESS, FLUID BALANCE, CUMULATIVE HEAT STRAIN INDEX

Exertional heat illnesses represent the greatest threat to the health and performance of distance runners in environmental conditions of heat and humidity (1,5,12). Distance running elevates T_c in proportion to relative exercise intensity (7), heat and humidity restrict dry and evaporative heat loss (15,22), and the interaction of these and predisposing factors, such as illness and lack of heat acclimatization, increase the risk of heat illness (1,19). Single postrace rectal temperature measurements have traditionally quantified T_c responses to outdoor distance running (7,17,21,25–27). Immediate postrace values in the range of 38.0–41.1°C have frequently been reported (3). Attempts at continuous measurement of T_c during distance running have been restricted to serial (e.g., 9- and 10-min intervals) rectal temperature measurements (4,16,18). To our knowledge, only one study has successfully recorded rectal temperature continuously (i.e., 1-min intervals) in four subjects during a 5-km run (11). Serial measurements from highly trained distance runners have revealed fluctuating steady-state T_c (4,16) as high as 41.6–41.9°C (16) and linearly increasing T_c to approximately 40°C at race finish (18). Although the magnitude of T_c elevation following outdoor distance running has been well quantified (3), the continuous temporal nature of T_c in a moderately sized sample of runners undertaking a mass-participation race has not previously been investigated.

The invasive and obtrusive nature of rectal thermometry, which requires a wire connection from the sensor (typically inserted 10–15 cm beyond the anal sphincter) to the data recording device (24), represents a significant practical difficulty for the continuous measurement of T_c during outdoor running. An alternative method of thermometry suitable for ambulatory applications is the ingestible telemetric temperature sensor, which offers a wireless and valid measure of T_c during steady-state, increasing, and decreasing T_c conditions (24). The primary aim of this study was to continuously measure T_c using ingestible telemetric

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temperature sensor technology in a sample of runners competing in a 21-km mass-participation running event in environmental conditions of heat and humidity representing a high risk of heat illness (1). Furthermore, we aimed to quantify the physiological strain experienced by runners as evidenced by T_c and HR responses. In this regard, we applied the cumulative heat strain index (CHSI), which combines the thermoregulatory load, described by the hyperthermic area (i.e., T_c integral), and the circulatory load, described by heart beat accumulation (9). Finally, we investigated the relationship between thermoregulatory responses and fluid balance.

METHODS

Subjects. Twenty-three male volunteers provided written informed consent to participate in this institute ethics committee–approved study after reading a document describing the nature, benefits, and risks of the study. Core temperature data for 18 subjects are presented due to excretion of the temperature sensor before the race in one subject and incomplete recordings of T_c in four subjects. Corresponding HR data were gained for 15 of these 18 subjects due to incomplete HR recordings in three subjects. Table 1 provides the physical characteristics of the 18 subjects. Volunteers were soldiers in the Singapore Armed Forces participating in the 2003 Singapore Army Half-Marathon as part of their training. They were considered fully heat-acclimatized due to their upbringing, completion of basic military training, and continued active military training in Singapore's tropical environment. Although volunteers were trained for endurance during military activity, they were not distance running athletes, with specific training for distance running occurring on 2.4 ± 0.8 occasions per week, resulting in an accumulated weekly distance of 21 ± 16 km.

Ingestible telemetric temperature sensor system. On the evening prior to the race (approximately 8–10 h before race start), volunteers, in the presence of a researcher, ingested a telemetric temperature sensor (CORTEMP™ COR-100 Wireless Ingestible Temperature Sensor, HQ Inc, Palmetto, FL). The sensors are 20 mm long, 10 mm in diameter, and contain a temperature-sensitive quartz crystal oscillator that vibrates at a frequency relative to its surrounding temperature. Temperature signals are transmitted by radio waves to an external temperature-recording device (CORTEMP™ CT2000 Miniaturized Ambulatory Recorder, HQ Inc, Palmetto, FL). The sensors are energized by an internal silver-oxide battery, have a protective silicone coating, and are passed through the gastrointestinal tract in approximately 8–92 h. Sensors were calibrated on the day of swallowing to ± 0.1°C using a heated water bath at known water temperatures of 35 and 43 (± 0.1) °C.

Experimental procedures. All measurements took place on the day of the 2003 Singapore Army Half-Marathon. Subjects reported at 0430 h. They were immediately asked to produce a urine sample for the analysis of urine specific gravity using a digital refractometer (UG-1, Atago, Tokyo, Japan). Nude body mass was measured to the nearest 0.1 kg using a digital scale (Seca 881, Seca Vogel & Halke GmbH & Co, Hamburg, Germany). Subjects were fitted with a chest band and wrist-watch HR monitor (Polar Vantage, Polar Electro Oy, Kempele, Finland) and dressed in running singlet, shorts, socks, and shoes. A telemetric check was performed to ensure the temperature sensor was residing within the volunteer and transmitting a signal. Finally, the ambulatory T_c data-recording device was placed in a sealed waterproof bag, fitted into a padded pouch, and worn on a lightweight harness around the waist with the data recorder positioned in the lumbar region. The total weight of the data-recording device and harness was 301 g.

Following preparation, volunteers consumed water *ad libitum* in a prescribed 1.5-L water bottle until race start. All fluid intake and urine output was measured before the race. During the race, fluid stations positioned 1.5–2.0 km

TABLE 1. Physical characteristics, race performance, average running speed, and average metabolic heat production of the 18 runners.

Runner	Height (m)	Mass (kg)	BMI (units)	A_D (m^2)	A_D:mass ($cm^2 \cdot kg^{-1}$)	Finish Time (min)	Running Speed ($km \cdot h^{-1}$)	Heat Production (W)
1	1.67	50.2	18.0	1.55	309	105	12.0	669
2	1.66	56.3	20.4	1.62	288	106	11.9	744
3	1.70	60.7	21.0	1.70	281	107	11.8	794
4	1.78	56.8	17.9	1.71	301	108	11.7	736
5	1.73	57.5	19.2	1.69	293	108	11.7	745
6	1.84	76.1	22.5	1.99	261	111	11.4	960
7	1.75	61.0	19.9	1.74	286	111	11.4	769
8	1.74	54.3	17.9	1.65	304	111	11.4	685
9	1.80	67.3	20.8	1.86	276	111	11.4	849
10	1.76	70.2	22.7	1.86	265	112	11.3	878
11	1.67	51.2	18.4	1.56	305	115	11.0	623
12	1.79	63.2	19.7	1.80	285	117	10.8	756
13	1.63	66.9	25.2	1.72	257	122	10.3	768
14	1.80	59.2	18.3	1.76	297	124	10.2	668
15	1.66	56.9	20.6	1.63	286	130	9.7	613
16	1.71	57.7	19.7	1.67	290	137	9.2	590
17	1.61	53.6	20.7	1.55	290	146	8.6	514
18	1.73	64.7	21.6	1.77	274	146	8.6	620
Mean ± SD	1.72 ± 0.06	60.2 ± 6.8	20.3 ± 1.9	1.71 ± 0.12	286 ± 15	118 ± 13	10.8 ± 1.1	721 ± 111

BMI, body mass index; A_D, body surface area, Dubois (14).

apart provided water and carbohydrate–electrolyte fluid (Gatorade) in standard volume cups. Fluid intake during the race was estimated by asking volunteers to completely finish any drinks taken and to note and recall the total number of drinks consumed. Immediately following the race, volunteers towelled dry, and nude body mass was recorded. The change in body mass, corrected for fluid intake and urine loss, but not accounting for metabolic fuel oxidation, metabolic water gain, or respiratory water losses, was used as an estimate of sweat loss. Dry bulb, wet bulb, and globe temperatures; and the wet bulb globe temperature index (WBGT = 0.1 ($T_{dry\ bulb}$) + 0.7 ($T_{wet\ bulb}$) + 0.2 (T_{globe})) were measured at minute intervals throughout the race using a portable climate monitoring device (Questemp°15 Area Heat Stress Monitor, Quest Technologies, WI) positioned at the start/finish area. Ambient water vapor pressure and relative humidity were calculated from the relationship between dry bulb and wet bulb temperature using a simplified psychrometric chart (15). Wind velocity was not measured, although conditions could be described as calm.

Core temperature and HR data were recorded at 15-s intervals. Data were downloaded and plotted at minute intervals against time allowing determination of peak, final (i.e., at race finish), and mean (HR only) values. Maximum T_c elevation (i.e., Δ peak T_c) was calculated as peak T_c – preexercise T_c. Core temperature elevation at race finish (i.e., Δ final T_c) was calculated as final T_c – preexercise T_c. Core temperature rate of rise during the initial 30 min of running (i.e., $rate_{30}$ in degrees Celsius per hour) was quantified as the slope of a linear regression line (i.e., regression coefficient as degrees Celsius per minute × 60 min) fitted to the T_c data from 0 to 30 min when T_c was increasing linearly. Average rate of metabolic heat production for the whole race was estimated based on the assumption that heat liberation during running approximates 4 $kJ \cdot kg^{-1}$ body $mass \cdot km^{-1}$ (8,22), and thus the rate of heat production is equal to the product of the runner's body mass (kg), the running speed ($m \cdot s^{-1}$), and the approximately 4 J produced per kilogram of body mass per meter run (8,22). Preexercise body mass and average speed for 21 km were used in the computation. Split times during the race were not recorded, and therefore our measure of average heat production is not sensitive to the changes in running speed/heat production that would have occurred during the race. The cumulative heat strain index, which is a combination of circulatory and thermoregulatory loads, and is a function of the excess heart beat count over the initial state and the integral of T_c, was calculated at minute intervals as follows (9):

$$\mathrm{CHSI} = [\sum_{0}^{t} hb - f_c0 \cdot t] \cdot 10^{-3} \cdot [\int_0^t T_c \cdot dt - T_c0 \cdot t] (\mathrm{units})$$

where Σhb = accumulation of heart beats over the period of running (t, min); f_{c0} = initial heart rate (taken as 70 bpm); $f_{c0} \cdot t$ = heart beat count over time at the level of the initial state; circulatory strain is gained by subtracting $f_{c0} \cdot t$ from Σhb; and thermoregulatory strain is calculated as the integral of core temperature ($\int T_c$). Finally, the two components are complementary rather than additive.

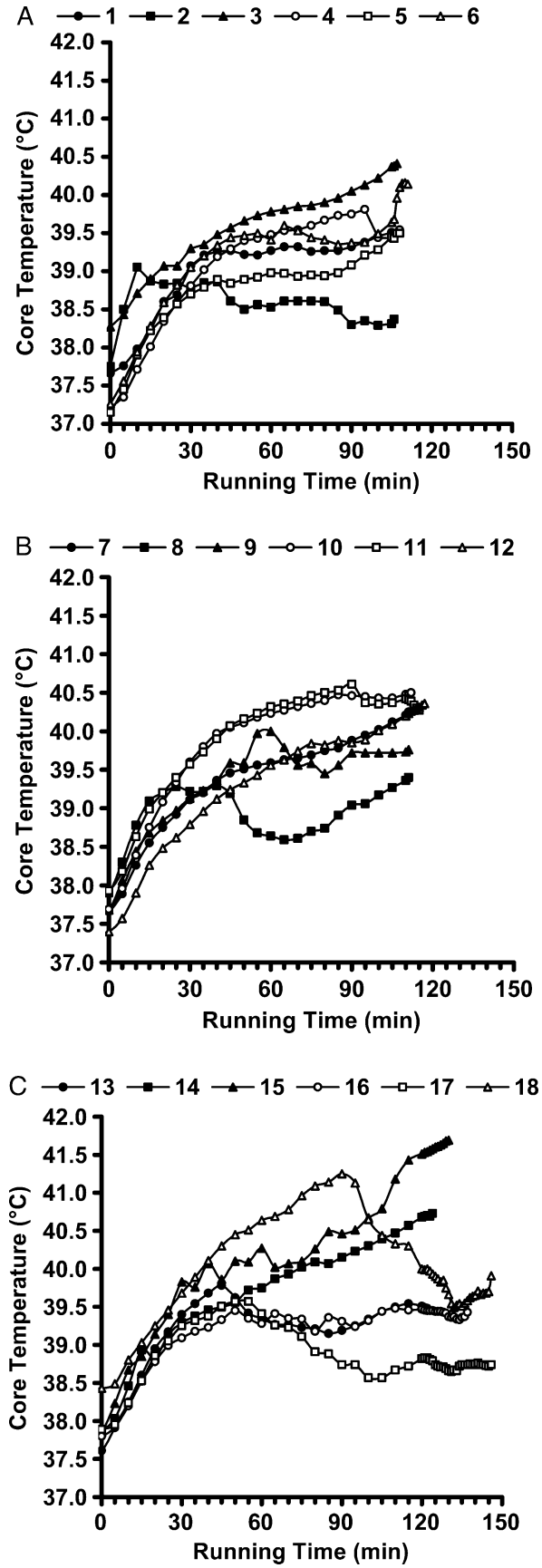

FIGURE 1—Individual core temperature responses of 18 runners during the half-marathon, presented in order of finishing time: (A) 105–111 min, *N* = 6; (B) 111–117 min, *N* = 6; (C) 122–146 min, *N* = 6. The legend indicates runner number, presented in Tables 1, 2, and 3.

TABLE 2. Thermoregulatory and cardiovascular responses of the 18 runners to the half-marathon.

Runner	Pre T_c (°C)	Peak T_c (°C)	Δpeak T_c (°C)	Final T_c (°C)	Δ Final T_c (°C)	$Rate_{30}$ (°C·h^{-1})	Time to Peak (min)	T_c Integral (°C·min)	Mean HR (bpm)	Peak HR (bpm)	Hb Count (beats)	CHSI (units)
1	37.6	39.5	1.9	39.5	1.9	2.9	104	147	174	181	10884	1600
2	37.8	39.3	1.5	38.3	0.5	1.3	13	86	181	188	11688	1005
3	38.3	40.4	2.1	40.4	2.1	2.2	107	134	177	197	11520	1544
4	37.2	39.8	2.6	39.4	2.2	3.5	89	201	169	181	10516	2114
5	37.1	39.5	2.4	39.5	2.4	3.2	107	178	—	—	—	—
6	37.2	40.2	3.0	40.2	3.0	3.8	110	214	178	189	11916	2550
7	37.7	40.3	2.6	40.2	2.5	3.0	111	183	174	183	11455	2096
8	37.9	39.4	1.5	39.4	1.5	2.9	25	114	183	191	12357	1409
9	37.7	40.0	2.3	39.7	2.0	2.8	53	186	173	185	11407	2122
10	37.7	40.5	2.8	40.5	2.8	4.0	112	240	188	196	13187	3165
11	37.9	40.6	2.7	40.3	2.4	3.5	90	231	184	192	13048	3014
12	37.4	40.4	3.0	40.3	2.9	3.1	118	220	181	188	13068	2875
13	37.6	39.8	2.2	39.5	1.9	3.8	45	195	—	—	—	—
14	37.9	40.7	2.8	40.7	2.8	3.0	124	221	194	203	15274	3376
15	37.8	41.7	3.9	41.7	3.9	3.6	130	301	187	201	15139	4557
16	37.8	39.5	1.7	39.4	1.6	3.0	52	186	176	183	14253	2651
17	37.9	39.6	1.7	38.7	0.8	3.1	53	147	—	—	—	—
18	38.4	41.3	2.9	39.7	1.3	2.8	107	249	182	196	16304	4060
Mean ± SD	37.7 ± 0.3	40.1 ± 0.7	2.4 ± 0.6	39.9 ± 0.8	2.1 ± 0.8	3.1 ± 0.6	86 ± 36	191 ± 52	180 ± 7	190 ± 7	12801 ± 1748	2543 ± 996

T_c, core temperature; Δ peak T_c, peak T_c – pre T_c; Δ final T_c, final T_c – pre T_c; $rate_{30}$, T_c rate of rise during initial 30 min of running; T_c integral, area under the T_c vs time curve; mean HR, average heart rate over 21 km; peak HR, maximum heart rate observed during running; Hb count, heart beat accumulation over 21 km; CHSI, cumulative heat strain index at race finish.

Race information. The Singapore Army Half-Marathon is an annual mass-participation 21-km road race. "Fun runs" over 5- and 10-km distances also take place at the same event. All volunteers ran in the 21-km competitive event starting at 0600 h. The event is organized primarily for servicemen and reservists in the Singapore Armed Forces, but it is also open to runners from the general public. Approximately 20,000 servicemen and 40,000 reservists and civilians participate in the various distance events.

Statistical analysis. Values are reported as means ± SD and range for the 18 runners. Statistical significance was accepted as $P \leq 0.05$. The change in T_c, HR, and CHSI responses over time (i.e., minutes 0, 30, 60, 90, and final) were analyzed with separate single-factor repeated-measures ANOVA. Significant main effects were analyzed with Tukey's *post hoc* test. Pearson's product–moment correlation coefficient (r) and the coefficient of determination (r^2) were used to examine the strength of the relationships between thermoregulatory responses and running time/average metabolic heat production, and thermoregulatory responses and fluid balance variables.

RESULTS

Environmental conditions. Wet bulb globe temperature (WBGT) at race start (0600 h) was 26.0°C, representing a high-risk (WBGT 23–28°C) of heat illness (1). At the time of the last finishing volunteers (0826 h), WBGT had increased to 29.2°C, representing a very high risk (WBGT > 28°C) of heat illness (1). Environmental conditions were characterized by high wet bulb temperature (25.9 ± 0.3; 25.6–27.3°C) in relation to dry bulb temperature (27.2 ± 1.0; 26.3–30.6°C) with corresponding high humidity (87 ± 5; 90–75%) and ambient water vapor pressure (3.3 ± 0.1; 3.2–3.7 kPa).

Magnitude of T_c responses. Mean T_c at 30 min (39.2 ± 0.3; 38.7–39.8°C), 60 min (39.6 ± 0.6; 38.5–40.6°C), 90 min (39.7 ± 0.7; 38.3–41.3°C), and final (39.9 ± 0.8; 38.3–41.7°C) were significantly higher ($P < 0.01$) than the 0-min value (37.7 ± 0.3; 37.1–38.4°C). Mean T_c at 60 min ($P < 0.05$), 90 min ($P < 0.05$), and final ($P < 0.01$) were significantly higher than the 30-min value. The entire sample of runners recorded peak T_c > 39°C; 56% ($N = 10$) recorded T_c > 40°C; and 11% ($N = 2$) recorded T_c > 41°C. For final T_c, 89% ($N = 16$) recorded T_c > 39°C; 44% ($N = 8$) recorded T_c > 40°C; and 6% ($N = 1$) recorded T_c > 41°C. Ten runners achieved their highest T_c during the race, whereas eight runners achieved their highest T_c at race finish. Figure 1 illustrates the individual T_c responses throughout the race, and Table 2 illustrates the magnitude, rate, and duration of the T_c responses. Core temperature rate of rise during the initial 30 min of running ($rate_{30}$) was positively associated with Δ peak T_c ($r^2 = 0.29$, $P < 0.05$), Δ final T_c ($r^2 = 0.38$, $P < 0.01$), T_c integral ($r^2 = 0.46$, $P < 0.01$), and CHSI at 60 min ($r^2 = 0.62$, $P < 0.01$), 90 min ($r^2 = 0.62$, $P < 0.01$), and final ($r^2 = 0.31$, $P < 0.05$).

Running time, heat production, morphology, and T_c responses. Table 1 illustrates individual and mean finishing time, average running speed for 21 km, average metabolic heat production for 21 km, and morphological characteristics. Neither finishing time nor heat production demonstrated a significant relationship ($P > 0.05$) with any T_c variable (e.g., peak T_c, final T_c, Δ peak T_c, T_c integral). Preexercise T_c demonstrated a slight positive relationship (approaching significance) with finish time ($r^2 = 0.22$, $P = 0.06$). Body morphology variables (i.e., height, mass, BMI, and A_D) failed to demonstrate any significant relationship ($P > 0.05$) with any T_c variable.

Heart rate responses. Heart rate at 30 min (182 ± 7; 166–193 bpm), 60 min (179 ± 9; 164–194 bpm), 90 min (181 ± 9; 164–200 bpm), and final (181 ± 13; 150–202 bpm) were significantly higher ($P < 0.01$) than the 0-min value (142 ± 20; 86–169 bpm) but did not differ ($P > 0.05$) at each time point during running. Peak HR was positively associated with peak T_c ($r^2 = 0.52$, $P < 0.01$), final T_c ($r^2 = 0.42$, $P < 0.01$), and Δ peak T_c ($r^2 = 0.26$, $P < 0.05$); with mean HR

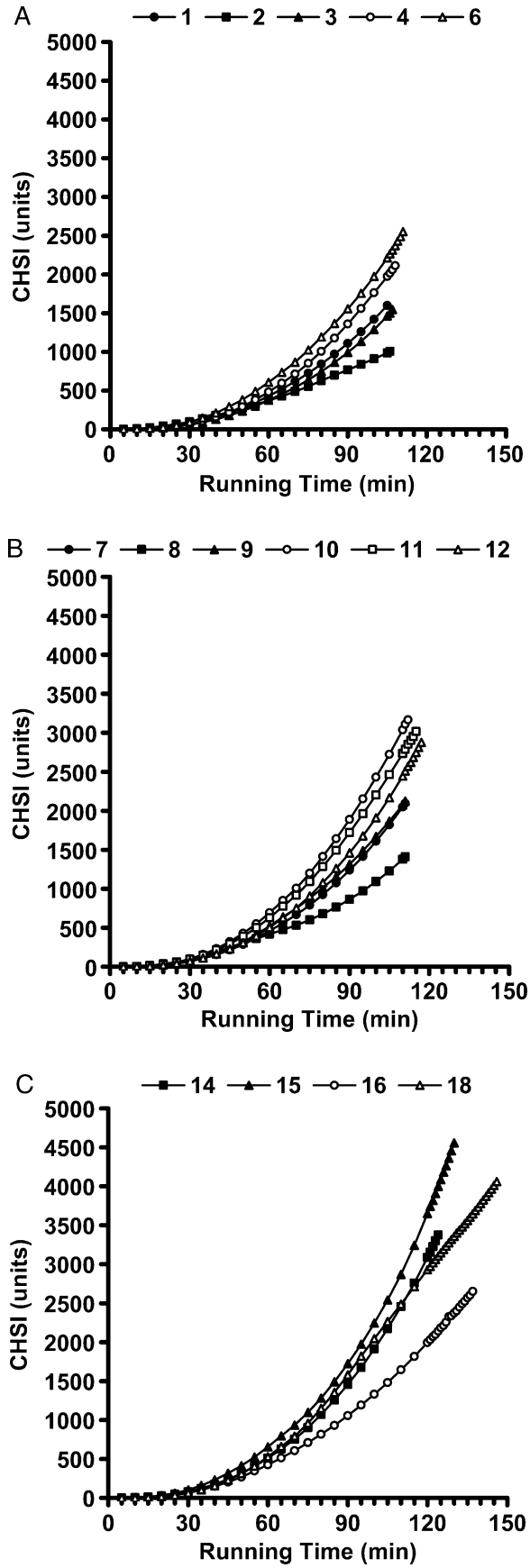

FIGURE 2—Cumulative heat strain index (CHSI) of 15 runners during the half-marathon, presented in order of finishing time: (A) 105–111 min, *N* = 5; (B) 111–117 min, *N* = 6; (C) 122–146 min, *N* = 4. The legend indicates runner number, presented in Tables 1, 2, and 3.

positively associated with peak T_c ($r^2 = 0.32$, $P < 0.05$) and final T_c ($r^2 = 0.27$, $P < 0.05$).

Cumulative heat strain index. Mean CHSI ($N = 15$) values increased significantly over time ($P < 0.001$) and were 80 ± 16 (58–103) units at 30 min, 507 ± 101 (373–691) units at 60 min, 1339 ± 332 (768–1889) units at 90 min, and 2541 ± 996 (1005–4557) units at race finish. Values were significantly different at each time point ($P < 0.001$). Figure 2 illustrates the individual CHSI responses throughout the race. Final CHSI was positively associated with CHSI at 60 min ($r^2 = 0.55$, $P < 0.01$) and 90 min ($r^2 = 0.67$, $P < 0.01$); finishing time ($r^2 = 0.58$, $P < 0.01$), peak T_c ($r^2 = 0.77$, $P < 0.001$), Δ peak T_c ($r^2 = 0.71$, $P < 0.001$), time to peak T_c ($r^2 = 0.40$, $P < 0.01$), post T_c ($r^2 = 0.50$, $P < 0.01$), and Δ post T_c ($r^2 = 0.36$, $P < 0.05$).

Fluid balance responses. Table 3 illustrates the individual and mean fluid balance responses to the half-marathon. Sweat rate was positively associated with body mass ($r^2 = 0.61$, $P < 0.01$), body surface area ($r^2 = 0.58$, $P < 0.01$), and average metabolic heat production ($r^2 = 0.40$, $P < 0.01$); and negatively associated with the surface area to body mass ratio ($r^2 = 0.46$, $P < 0.01$). Core temperature responses demonstrated no significant relationship ($P > 0.05$) with absolute change (kg) in body mass (peak T_c $r^2 = 0.01$; final T_c $r^2 = 0.02$; T_c integral $r^2 = 0.03$) and relative (% dehydration) change in body mass (peak T_c $r^2 = 0.00$; final T_c $r^2 = 0.00$; T_c integral $r^2 = 0.00$). Furthermore, no significant relationship was observed between any fluid balance variable and any core temperature or CHSI response.

DISCUSSION

The major finding of the present study is establishing the magnitude of T_c elevation that runners will voluntarily achieve during mass-participation distance races in heat and high humidity without medical consequence. Over half of our sample achieved temperatures greater than 40°C; two runners achieved T_c greater than 41°C, with the highest individual value being 41.7°C. This magnitude is greater than previous field-based observations on asymptomatic distance runners (3,7,17,21,25–27). Mean final T_c was 39.9 ± 0.8°C versus mean postrace rectal temperatures in previous studies of 38.7°C (17), 38.9°C (21), and 39.0°C (25). The highest individual response observed in the present study (i.e., 41.7°C) was also greater than the highest individual response observed in most (e.g., 40.3°C) (17), 40.5°C (21), 40.8°C (27), and 41.1°C (26,27), but not all, previous studies (e.g., 41.9°C) (16).

Metabolic rate ($\dot{V}O_2$) is an important determinant of T_c elevation during distance running (7,21). Noakes et al. (21) reported that absolute metabolic rate ($L \cdot min^{-1}$) in the last 6 km of a 42-km marathon was the most important predictor of postrace T_c, yet only accounted for 28% of the variation in postrace T_c. In laboratory and field measurements, Davies et al. (7) demonstrated that relative exercise intensity ($\%\dot{V}O_{2max}$) rather than absolute metabolic rate is

TABLE 3. Fluid balance responses of the 18 runners to the half-marathon.

Runner	Urine Specific Gravity	Estimated Fluid Intake (L)	Preexercise Intake (L)	Estimated Exercise Intake (L)	Estimated Rate of Intake ($L \cdot h^{-1}$)	Estimated Sweat Loss (L)	Estimated Sweat Rate ($L \cdot h^{-1}$)	Estimated Sweat Loss Replaced (%)	Mass Loss (kg)	Dehydration (%)
1	1.004	1.05	0.75	0.30	0.17	2.02	1.15	52	1.2	1.9
2	1.016	1.75	0.40	1.35	0.76	2.45	1.39	71	0.7	1.2
3	1.002	0.15	0.00	0.15	0.08	2.52	1.41	6	2.7	3.9
4	1.005	0.83	0.45	0.38	0.21	2.15	1.19	38	1.5	2.3
5	1.021	0.50	0.50	0.00	0.00	2.40	1.33	21	1.9	3.3
6	1.009	1.05	1.05	0.00	0.00	3.81	2.06	28	2.9	3.6
7	1.022	1.65	0.15	1.50	0.81	3.25	1.76	51	1.6	2.6
8	1.004	1.02	0.50	0.53	0.28	3.03	1.64	34	2.2	3.7
9	1.020	1.38	0.25	1.13	0.61	2.67	1.45	51	1.3	1.9
10	1.021	1.08	0.10	0.98	0.52	3.78	2.02	28	2.7	3.8
11	1.025	0.65	0.50	0.15	0.08	1.62	0.85	40	1.0	1.9
12	1.003	1.23	0.55	0.68	0.35	3.43	1.76	36	2.5	3.5
13	1.005	2.08	0.95	1.13	0.55	3.48	1.71	60	1.4	2.1
14	1.018	0.68	0.15	0.53	0.25	2.98	1.44	23	2.3	3.9
15	1.023	1.35	0.30	1.05	0.48	1.85	0.85	73	0.5	0.9
16	1.018	2.05	0.40	1.65	0.72	3.15	1.38	65	1.1	1.9
17	1.020	1.30	0.55	0.75	0.31	3.36	1.38	39	2.1	3.8
18	1.007	1.50	0.45	1.05	0.43	4.00	1.64	38	2.5	3.9
Mean ± SD	1.014 ± 0.008	1.18 ± 0.52	0.44 ± 0.28	0.74 ± 0.52	0.37 ± 0.26	2.89 ± 0.71	1.47 ± 0.34	42 ± 18	1.78 ± 0.74	2.8 ± 1.0

more closely related, in a curvilinear manner, to steady-state and postrace T_c. Furthermore, Davies (6) illustrated the complimentary influence of ambient temperature on the exercise intensity–T_c relationship. Dry bulb temperatures over the range 5–21°C influenced T_c during treadmill running at 85% $\dot{V}O_{2max}$ but not at 65% $\dot{V}O_{2max}$. At the higher intensity, T_c increased exponentially when ambient temperature exceeded 20°C (6). Due to the severity of the environmental conditions in the present study (i.e., 26.3–30.6°C dry bulb, 25.6–27.3°C wet bulb, and 90–75% relative humidity), which represent a greater restriction to dry and evaporative heat loss than many previous studies (3,17,21,25,27), we hypothesize that the exercise intensity–T_c relationship will have been exponential at intensities less than 85%$\dot{V}O_{2max}$. Thus, we hypothesize that at moderate relative exercise intensities our runners will have achieved comparatively higher T_c responses than previous studies due to the severity of the environmental conditions encountered. This could explain the magnitude of T_c responses at modest average running speeds (i.e., 8.6–12.0 $km \cdot h^{-1}$) in the current study, whereas previous studies (25,27) have only observed comparable temperatures (e.g., 40.2–41.1°C) in the fastest runners producing average running speeds of 15.2–16.0 $km \cdot h^{-1}$ and presumably high relative exercise intensities.

We further hypothesize that interindividual differences in relative exercise intensity and intraindividual variations in running pace during the race determined the magnitude and temporal nature of T_c responses in the present study, respectively (see Fig. 1). Due to the absence of split time and metabolic data, we are unable to confirm whether %$\dot{V}O_{2max}$ determined the magnitude of T_c elevation and whether variations in running pace were associated with the temporal variations in T_c illustrated in Figure 1. Nevertheless, our heart rate data provide indirect support linking variations in running pace to the temporal variations in T_c responses. For example, concomitant reductions in heart rate and T_c, indicating decreasing running pace and metabolic rate, were observed in runners 2, 8, 17, and 18. Conversely, concomitant increases in heart rate and T_c, indicating increasing running pace and metabolic rate, were observed in runners 3, 6, 8, 12, 14, and 15.

A more accurate description of the severity of the hyperthermic exposure is provided by the total thermal area, calculated from T_c elevation and the duration of T_c elevation (10,13), rather than the magnitude of T_c elevation alone. In this regard, we determined the area under the hyperthermic curve (i.e., T_c integral), but unfortunately comparable data for exercising humans are lacking in the scientific literature. In the study of Maron et al. (16), one highly trained marathon runner maintained T_c between 41.6 and 41.9°C for the final 44 min of a 163-min, 42-km marathon race. To our knowledge this is the highest recorded T_c in an asymptomatic distance runner. The corresponding T_c integral above 40°C was calculated as 102°C·min (10), which is approximately twofold higher than values calculated for the two runners in our study achieving $T_c > 41$°C (i.e., runner 15 = 47°C·min, and runner 18 = 53°C·min). In the present study, T_c integral was combined with heart beat accumulation to compute the cumulative heat strain index (CHSI) (see Fig. 2 and Table 2). The CHSI represents a novel approach for assessing the total physiological strain of subjects exposed to exercise-heat stress (9). A lack of comparative CHSI data for distance running prevents any meaningful comparisons of our data to previous studies (e.g., (9)). Further studies utilizing this index are required to place the current data in context. Our data indicate that T_c rate of rise during the first 30 min of running could explain 46% of the variation in T_c integral, 62% of the variation in CHSI at 60 and 90 min, and 31% of the variation in final CHSI. A high rate of rise in T_c is therefore associated with a greater hyperthermic exposure, suggesting that pacing in the early part of the race is an important strategy in the avoidance of exertional heat illnesses.

Laboratory studies of humans exercising at a fixed work rate in heat suggest that fatigue occurs and exercise is terminated when a critically high T_c, reported as approximately 40°C, is attained (23). Over half of our sample

(56% peak T_c > 40°C, 11% > 41°C) exceeded this value of T_c previously observed as limiting exercise performance in Scandinavian males (23). We do not believe the Singaporean sample/population is inherently different from other populations, whereby a tolerance to high T_c is afforded, since several other field-based studies have reported T_c > 40 and 41°C in asymptomatic distance runners (16,25–27). One of the main methodological differences between field-based race situations and the laboratory studies referred to above is that the former are self-paced and exercising subjects are free to increase or decrease their running pace and therefore regulate their heat production. In the latter, an inability to maintain the required work rate is classified as exhaustion and exercise is terminated (23). In the 10 runners achieving T_c > 40°C, our HR data do not support a reduction in running pace when a T_c of 40°C was achieved. Nevertheless, Table 2 indicates that 7 of the 10 runners displaying peak T_c > 40°C achieved their peak T_c at race finish, whereas only one of the eight runners displaying peak T_c < 40°C achieved their peak T_c at race finish. This may indicate that approximately half of the sample adopted a strategy to increase pace, heat production, and heat storage towards the end of the race, resulting in their highest T_c being achieved at race finish. Alternatively, it may suggest that time with T_c > 40°C is finite and a pacing strategy that results in T_c > 40°C is mainly adopted when race finish is anticipated. The latter explanation may suggest a role for T_c in regulating runners pacing strategy.

In agreement with previous studies (17,21), estimated fluid balance variables (e.g., fluid intake, % dehydration) demonstrated no significant relationship with the magnitude of T_c responses. Estimated sweat rates averaged 1.5 $L \cdot h^{-1}$, with combined prerace fluid intake and estimated race intake replacing less than half of total sweat losses (see Table 3). Of note, Table 3 illustrates that the two runners (i.e., 11 and 15) with the lowest estimated sweat rates (0.85 $L \cdot h^{-1}$) also had the highest preexercise urine specific gravity measurements (1.025 and 1.023, respectively). Table 2 illustrates that the runners peak T_c (i.e., 40.6 and 41.7°C, respectively) were among the highest of the sample. It is possible that the reduced sweat rate and elevated T_c in these runners was secondary to preexercise hypohydration and subsequent hyperosmolality, reduced blood volume, and reduced skin blood flow (2). The method of estimating fluid balance in the present study suffers from a lack of control in precisely quantifying fluid intake during running, since the method relies on runners accurately recalling the frequency of drinks consumed. We assumed all weight losses postexercise were due to sweat losses, which also adds an unknown error into the estimation because an unknown proportion of weight loss is accounted for by metabolic fuel oxidation and respiratory water losses (20). Furthermore, the unaccounted gain of metabolic water during the half-marathon will have resulted in an overestimation of dehydration (20).

CONCLUSIONS

This study represents the first report of continuous measurement of thermoregulatory data in a sample of runners competing in a mass-participation race in environmental conditions representing a high risk of heat illness. Ingestible telemetric temperature sensors demonstrated utility for continuous measurement of T_c during mass-participation running. Successful application of this technology has highlighted the magnitude and duration of T_c elevation that runners will voluntarily achieve during mass-participation distance races in heat and high humidity without medical consequence.

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