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ARTICLE

Do older adults experience greater thermal strain during heat waves?

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Abstract: Heat waves are the cause of many preventable deaths around the world, especially among older adults and in countries with more temperate climates. In the present study, we examined the effects of age on whole-body heat loss and heat storage during passive exposure to environmental conditions representative of the upper temperature extremes experienced in Canada. Direct and indirect calorimetry measured whole-body evaporative heat loss and dry heat exchange, as well as the change in body heat content. Twelve younger (21 ± 3 years) and 12 older (65 ± 5 years) adults with similar body weight (younger: 72.0 ± 4.4 kg; older: 80.1 ± 4.2 kg) and body surface area (younger: 1.8 ± 0.1 m^2; older: 2.0 ± 0.1 m^2) rested for 2 h in a hot–dry [36.5 °C, 20% relative humidity (RH)] or hot–humid (36.5 °C, 60% RH) environment. In both conditions, evaporative heat loss was not significantly different between groups (dry: $p = 0.758$; humid: $p = 0.814$). However, the rate of dry heat gain was significantly greater (by approx. 10 W) for older adults relative to younger adults during the hot–dry ($p = 0.032$) and hot–humid exposure ($p = 0.019$). Consequently, the cumulative change in body heat content after 2 h of rest was significantly greater in older adults in the hot–dry (older: 212 ± 25 kJ; younger: 131 ± 27 kJ, $p = 0.018$) as well as the hot–humid condition (older: 426 ± 37 kJ; younger: 317 ± 45 kJ, $p = 0.037$). These findings demonstrate that older individuals store more heat during short exposures to dry and humid heat, suggesting that they may experience increased levels of thermal strain in such conditions than people of younger age.

Key words: aging, passive heat stress, calorimetry, heat waves.

Résumé : Les vagues de chaleur entraînent dans le monde entier de nombreux décès évitables, particulièrement chez les personnes âgées et dans les pays au climat plus tempéré. Dans cette étude, on examine les effets de l'âge sur la perte et le stockage de chaleur corporelle au cours d'une exposition passive à des conditions environnementales semblables aux températures extrêmes supérieures observées au Canada. On mesure par calorimétrie directe et indirecte la perte globale de chaleur corporelle par évaporation et d'échange de chaleur sèche ainsi que la variation du contenu corporel de chaleur. Douze adultes jeunes (21 ± 3 ans) et 12 adultes âgés (65 ± 5 ans) de masse corporelle (jeunes: 72,0 ± 4,4 kg; âgés: 80,1 ± 4,2 kg) et de surface corporelle (jeunes: 1,8 ± 0,1 m^2; âgés: 2,0 ± 0,1 m^2) similaires se reposent durant 2 h dans un environnement chaud et sec [36,5 °C, 20 % humidité relative (RH)] ou chaud et humide (36,5 °C, 60 % RH). Dans les deux conditions, on n'observe pas de différences significatives de perte de chaleur par évaporation dans les deux groupes (sec: p = 0,758; humide: p = 0,814). Toutefois, on observe un gain de chaleur sèche significativement plus grand (~10 W) chez les personnes âgées comparativement aux jeunes dans un environnement chaud et sec (p = 0,032) et chaud et humide (p = 0,019). Par conséquent, l'augmentation du contenu corporel de chaleur après 2 h de repos est significativement plus grande chez les adultes âgés dans un environnement chaud et sec (âgés: 212 ± 25 kJ; jeunes: 131 ± 27 kJ, p = 0,018) et dans un environnement chaud et humide (âgés: 426 ± 37 kJ; jeunes: 317 ± 45 kJ, p = 0,037). Ces observations révèlent que, comparativement à de jeunes personnes, les personnes âgées emmagasinent plus de chaleur au cours d'une brève exposition dans un environnement chaud (sec et humide) et peuvent vivre un plus grand stress thermique dans de telles conditions. [Traduit par la Rédaction]

Mots-clés : vieillissement, stress thermique passif, calorimétrie, vagues de chaleur.

Introduction

Changes in climate towards more frequent and extreme heat events, which are longer in duration, have posed a significant health risk around the world. In Europe, 70 000 people died during the 2003 heat wave as a result of prolonged exposure to extreme heat. Countries with generally mild summertime temperatures were especially affected (Fouillet et al. 2006; Poumadere et al. 2005; Rey et al. 2007; Robine et al. 2008). In France for example, approximately 15 000 deaths were attributed to the exceptional heat wave where temperatures exceeded 40 °C on 7 consecutive days (Fouillet et al. 2006; Poumadere et al. 2005; Rey et al. 2007). More recently, an estimated 55 000 people died in Russia during the summer 2010 heat wave (Osborn 2010), including approximately 11 000 deaths in Moscow (Barriopedro et al. 2011). In Canada, summers are

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generally mild, with mid-summertime temperatures averaging approximately 25 °C in many parts of the country (Government of Canada 2013*a*). Canadian summers also tend to be humid with relative humidity typically ranging between 50% and 70% (Government of Canada 2013*a*). The temperate weather in addition to the large fluctuations in temperature throughout the year can make it difficult for individuals to become heat acclimatized. Therefore it is possible that people residing in these climates may be more susceptible to heat-related illness during periods of above-normal temperatures as a result of low levels of heat adaptation compared with people living in warmer places year round.

The number of days with temperatures ≥30 °C and humidity index values exceeding 40 °C is expected to increase in Canada (Maxwell et al. 2006). Such extremes can have a considerable impact on the health of many people (Bustinza et al. 2013; Pengelly et al. 2007; Water, Air and Climate Bureau 2011), and older adults may be especially vulnerable to heat-related illness in these conditions (Frumkin et al. 2012; Kenny et al. 2010; Minson et al. 1998). A number of studies have demonstrated important age-related differences in local heat loss responses (e.g., sweat rate) and (or) core temperature during passive heat exposure of 60 to 240 min in duration (Crowe and Moore 1974; Dufour and Candas 2007; Fennell and Moore 1973; Miescher and Fortney 1989; Sagawa et al. 1988). In some cases, significant impairments in local heat loss or core temperature responses were evident after just 30 min of resting in the heat (Dufour and Candas 2007; Miescher and Fortney 1989). However, whether these differences in local indices of heat strain are meaningful from a whole-body perspective is currently unclear. Moreover, thermoregulatory responses as a function of age were observed under ambient air temperatures ranging between 40 and 45 °C. During extreme heat events, temperatures rarely rise above approximately 36–37 °C in Canada. For example, the hottest day of the year in Toronto, one of the largest Canadian metropolitan cities, was 36.7 °C during the 2012 North American heat wave (Government of Canada 2013*b*). This is considerably lower than temperatures recorded in southern parts of the United States where daily temperatures were as high as 42.8–45.0 °C during this particular heat wave (Burt 2012). Nevertheless, humidity index readings, which indicate the approximate temperature when heat and humidity are considered, have been recorded upwards of 45 °C during extreme heat events in Canada (Government of Canada 2013*a*).

In the present study, we used conditions representative of the upper temperature extremes in Canada to assess the potential public health risk to older adults living in mild climates during heat waves. We examined whole-body heat loss and changes in body heat content in younger (21 ± 3 years) and older adults (65 ± 5 years) during 2 h of passive exposure to a hot–dry condition (temperature: 36.5 °C; relative humidity: 20%; equivalent humidity index: 38 °C) and a hot–humid condition (temperature: 36.5 °C, relative humidity: 60%, equivalent humidity index: 51 °C). It was hypothesized that whole-body heat loss would be reduced in older adults compared with their younger counterparts thereby leading to a greater change in body heat content over 2 h of exposure in both heat stress conditions.

Materials and methods

Ethical approval

The experimental protocol was approved by the University of Ottawa Health Sciences and Science Research Ethics Board and The Health Canada and Public Health Agency of Canada Research Ethics Board in accordance with the Declaration of Helsinki. Volunteers provided written informed consent before participating in the study.

Participants

Twelve younger (21 ± 3 years, 4 females and 8 males) and 12 older (65 ± 5 years, 3 females and 9 males) adults who were not overly physically active (i.e., no more than 3 days per week of continuous exercise of ≤20 min in duration) participated in the study. Participants were nonsmokers and were free of known respiratory or cardiovascular disease. Younger and older participants had similar height (younger: 1.7 ± 0.1 m; older: 1.8 ± 0.1 m), weight (younger: 72.0 ± 4.4 kg; older: 80.1 ± 4.2 kg), body surface area (younger: 1.8 ± 0.1 m^2; older: 2.0 ± 0.1 m^2), and body mass index (younger: 24.7 ± 1.2 $kg \cdot m^{-2}$; older: 25.8 ± 1.1 $kg \cdot m^{-2}$).

Experimental design

Participants volunteered for 1 preliminary session and 2 experimental test sessions. During the preliminary session, measurements of height and body mass were obtained. Body surface area was subsequently calculated from the measurements of height and body mass (Du Bois and Du Bois 1989). We also inquired about physical activity patterns using a quantitative (3 month) and 7 day physical activity recall questionnaire proposed by Kohl et al. (1988).

The experimental sessions involved 2 tests that were performed on separate days with a minimum of 72 h between sessions. Participants were instructed to consume a light meal before their arrival and to avoid major thermal stimuli on their way to the laboratory. Participants were also asked to refrain from engaging in strenuous physical activity and consuming alcohol for 24 h as well as caffeine for up to 12 h before the testing sessions. To ensure euhydration, participants were instructed to drink 250 mL of water before bed, in the morning, and within 2 h of the experimental trial. No fluid was ingested for the duration of the experimental protocol. There were no differences between groups in hydration status, according to urine-specific gravity measurements, at the start of the hot–dry (younger: 1.017 ± 0.002; older: 1.012 ± 0.002) and hot–humid sessions (younger: 1.018 ± 0.003; older: 1.012 ± 0.002). The experimental sessions were performed in a whole-body direct air calorimeter, without prior laboratory acclimation sessions. Each session involved 120 min of passive heat exposure. During 1 experimental session, participants were seated in a whole-body calorimeter (a device for making very accurate measurements of the amount of heat emitted by the human body) regulated to 36.5 °C and 20% relative humidity (RH), whereas during the other session the environmental conditions were set to 36.5 °C and 60% RH. The order of the sessions was random; an equal amount of participants performed the hot–dry session first followed by the hot–humid session and vice versa. Participants wore a light pair of athletic shorts and sandals during the sessions, and female participants also wore a sports bra.

Measurements

A detailed explanation of how direct calorimetry measures whole-body heat loss and heat storage has been described in a previous publication (Kenny and Jay 2013). Also, a full technical description of the fundamental principles and performance characteristics of the Snellen calorimeter is available (Reardon et al. 2006). In summary, direct calorimetry measured whole-body evaporative loss and dry heat exchange (radiation, conduction, convection), yielding an accuracy of ± 2.3 W for the measurement of total heat loss. Indirect calorimetry was used to measure metabolic heat production. The change in body heat content (ΔH_b) was subsequently calculated by subtracting the total amount of heat production and heat loss over the 2 h sessions. The amount of evaporation required to achieve heat balance (E_{req}) was calculated from the sum of the rate of metabolic heat production and dry heat loss.

Local sweat production was measured using the ventilated capsule technique. A 3.8 cm^2 plastic capsule was attached to 3 skin sites (upper trapezius, forearm, and thigh) with an adhesive ring and topical skin glue (Collodion HV, Mavidon Medical products, Lake Worth, Fla., USA). Compressed dry air was passed through the capsule at a rate of 1 L·min^{-1}. Water content of the effluent air was measured using high precision dew point mirrors (model 473, RH systems, Albuquerque, N.M., USA). Local sweat rate was calculated using the difference in water content between effluent and influent air multiplied by the flow rate and normalized for the skin surface area under the capsule.

Laser Doppler velocimetry was employed for measuring skin blood flow (PeriFlux System 5000, Main control unit; PF5010 LDPM). A laser Doppler probe (Perimed integrating probe 413, Järfälla, Sweden) was affixed to the forearm's surface in an area that did not seem overly vascular upon visual inspection and provided stable readings at rest. To measure maximal skin blood flow, the heater housing the laser Doppler probe was heated to 44 °C until maximal skin vasodilation was achieved (approx. 40 min) (Taylor et al. 1984). Cutaneous vascular conductance (CVC) was subsequently calculated as the ratio of skin blood flow perfusion units to mean arterial pressure and expressed as a percentage of maximum.

Visceral temperature was measured using a telemetric pill (VitalSense ingestible capsule thermometer is a Class II Medical Device according to 21 DFR 8982.1845; Mini Mitter Company Inc.) that moves freely and unobstructed through the digestive tract and is generally eliminated within 48 h of ingestion (McKenzie and Osgood 2004). The telemetric pill provides an estimate of internal body temperature.

Mean skin temperature was calculated as the weighted average of 4 skin temperature measurements: bicep (30%), chest (30%), quadriceps (20%), and back calf (20%) (Ramanathan 1964).

Systolic and diastolic blood pressures were determined using a Finometer (Finapres Medical Systems, Amsterdam, the Netherlands) from the beat-to-beat recording of the right middle finger arterial pressure waveform with the volume-clamp method (Penaz 1973) and physical criteria (Wesseling et al. 1995). Blood pressure measurements were used to calculate mean arterial pressure (diastolic blood pressure + 1/3 × pulse pressure).

Heart rate was monitored, recorded continuously, and stored using a Polar coded WearLink and transmitter, Polar RS400 interface, and Polar ProTrainer 5 software (Polar Electro Oy, Finland).

Urine samples and body mass were obtained prior to the start and immediately following the experimental sessions. Urine-specific gravity was determined using a handheld total solids refractometer (model TS400, Reichter Inc., Depew, N.Y., USA). Venous blood samples were also obtained prior to and immediately following each session, while participants remained seated upright, via a single venipuncture (Becton, Dickinson and Company [BD], Franklin Lakes, N.J., USA). The samples were transferred directly into serum with no additive and plasma K_2EDTA 5.4 mg BD Vacutainer® tubes (BD, Franklin Lakes, N.J., USA). The K_2EDTA blood was mixed by inversion and used to measure hematological parameters (Beckman Coulter, Miami, Fla., USA). Haemoglobin and hematocrit values were used to estimate the percent changes in plasma and blood volumes according to the method of Dill and Costill (1974).

Thermal discomfort was evaluated using the ASHRAE 7-point scale (TS; Scale "0 = Neutral" to "7 = Very, Very Hot") and was recorded every 10 min.

Statistical analysis

All dependent variables were compared between groups for each experimental condition (dry and humid) separately using a 2-way analysis of variance (ANOVA) with the repeated factor of time (levels: 30, 60, 90, and 120 min) and nonrepeated factor of age (levels: younger and older). Independent *t* tests were used for post hoc analysis when a main effect of group was observed. The values at 30, 60, 90, and 120 min were obtained by averaging the last minute of data collected during that time period. Independent *t* tests were also used to compare participant characteristics and the cumulative change in body heat content measured over the 120 min exposure. The level of significance for all analyses was set at $p \leq 0.05$. Analyses were performed using commercially available statistical software (GraphPad Prism 6.0, GraphPad Software, La Jolla, Calif., USA). All values are reported as mean ± standard error (SE). Note that visceral temperature was not measured in 1 of the younger participants in the hot–humid condition as well as in 2 older participants in both conditions; skin blood flow was only measured in ten younger and eight older participants.

Results

Younger versus older adults: hot–dry ambient condition

Calorimetry

Metabolic heat production, total heat loss, evaporative heat loss, E_{req}, and dry heat exchange during the hot–dry condition are presented in Fig. 1A and 1B. Metabolic heat production remained fairly consistent ($p = 0.219$), and there was no difference between groups ($p > 0.999$) during the dry heat exposure. Total heat loss, which combines evaporative heat loss and dry heat exchange, increased progressively ($p < 0.001$) for both groups ($p = 0.584$), mainly due to a progressive reduction in dry heat gain ($p < 0.001$). Moreover, the rate of dry heat gain significantly differed between groups ($p = 0.032$). At 60, 90, and 120 min, the rate of dry heat gain was 11 W ($p = 0.022$), 10 W ($p = 0.021$), and 12 W ($p = 0.008$), respectively, greater in older adults compared with younger adults. The difference in dry heat gain at 30 min fell just short of significance ($p = 0.056$). Evaporative heat loss on the other hand, remained constant throughout ($p = 0.291$) and was almost identical between groups ($p = 0.758$), averaging 104 ± 7 W in younger and 103 ± 7 W in older adults. E_{req}, calculated as the sum of metabolic heat production and dry heat exchange, remained stable during the dry heat exposure session ($p = 0.139$) and did not significantly differ between groups ($p = 0.328$). However, due to the greater rate of dry heat gain measured in older adults, E_{req} (and therefore the net heat load) was higher by an average of approximately 11 W in older adults. Following the 2 h exposure, the cumulative change in body heat content was significantly greater in the older age group relative to the younger group ($p = 0.018$) (Fig. 2B).

Local heat loss responses

Data from local sweat rates measured on the upper back, forearm, and thigh are presented in Table 1, whereas CVC data are presented in Table 2. Local sweat rates did not significantly increase during the session (all $p > 0.400$); however, sweat rate was significantly different between groups on the upper back ($p = 0.011$). Older adults had a greater sweat rate at 30 ($p = 0.035$), 60 ($p = 0.012$), 90 ($p = 0.005$), and 120 min ($p = 0.003$). Local sweating on the forearm ($p = 0.066$) and thigh ($p = 0.194$) were not different between groups. CVC remained the same throughout the session ($p = 0.182$). There was a difference between groups ($p = 0.019$) whereby CVC was higher in older adults at 60 ($p = 0.003$), 90 ($p = 0.010$), and 120 min ($p = 0.015$).

Core and skin temperatures

Visceral temperature during the hot–dry exposure is presented in Fig. 2A, whereas mean skin temperature data are presented in Table 1. Both visceral ($p < 0.001$) and mean skin ($p = 0.006$) temperatures increased over the 2 h but the differences between groups were not statistically significant ($p = 0.107$ and $p = 0.381$, respectively).

Cardiovascular responses and hydration status

Heart rate and mean arterial pressure data are presented in Table 2. Neither of these variables changed over the course of the exposure (heart rate: $p = 0.163$; mean arterial pressure: $p = 0.248$) as well, younger and older adults appeared to experience similar

Fig. 1. (A and C) Required amount of evaporative heat loss to achieve heat balance (E_{req}) (circles), evaporative heat loss (triangles) and dry heat exchange (squares). (B and D) Metabolic heat production (circles) and total heat loss (triangles). Data collected during passive exposure to a hot–dry (36.5 °C, 20% relative humidity) and hot–humid (36.5 °C, 60% relative humidity) condition for a duration of 2 h. Data for the younger group is presented in open symbols, whereas data for the older group is presented in dark filled symbols. * denotes a significant difference between groups. All values are presented as means ± SE.

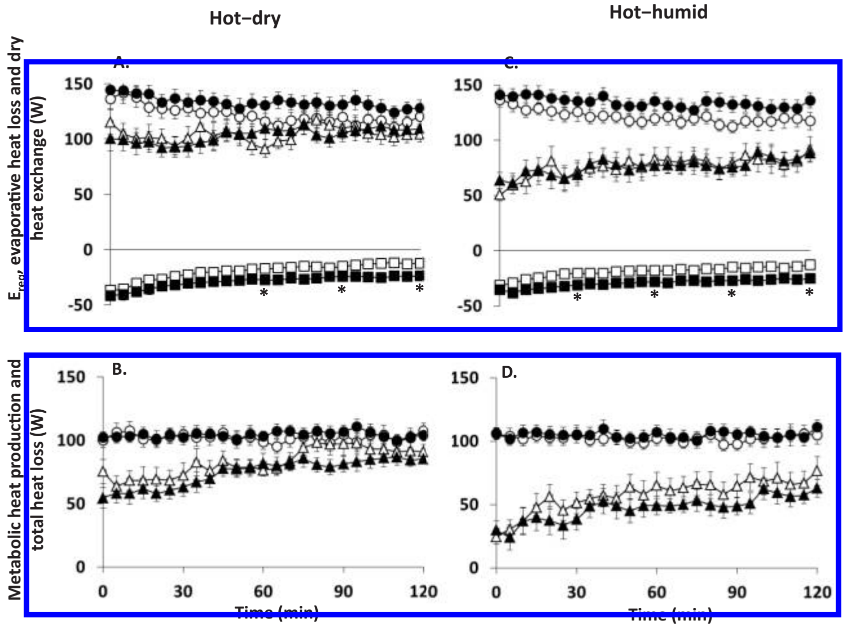
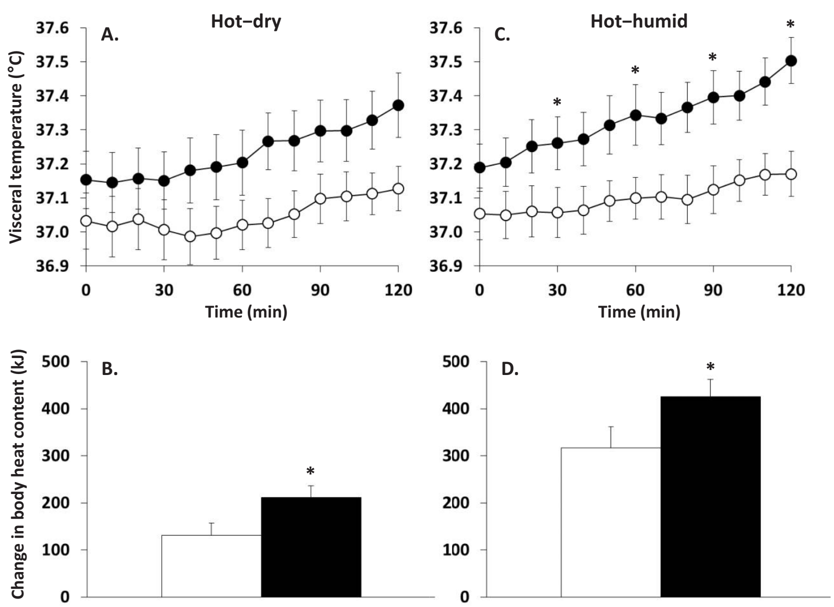


Fig. 2. (A and C) Visceral temperatures. (B and D) Cumulative change in body heat content. Data collected during passive exposure to a hot–dry (36.5 °C, 20% relative humidity) and hot—humid (36.5 °C, 60% relative humidity) condition for a duration of 2 h. Data for the younger group is presented in open symbols, whereas data for the older group is presented in dark filled symbols. * denotes a significant difference between groups. All values are presented as means ± SE.



levels of cardiovascular strain (heart rate: $p = 0.210$; mean arterial pressure: $p = 0.964$). The changes in blood volume (younger: –2.5 ± 0.5%; older: –3.9 ± 0.6%, $p = 0.077$), plasma volume (younger: –4.5 ± 0.8%; older: –6.6 ± 1.1%, $p = 0.101$), and urine-specific gravity (younger: 0.004 ± 0.001; older: 0.007 ± 0.001, $p = 0.219$) were not significantly different between groups. There was a trend for change in body weight to differ between groups ($p = 0.057$). Older adults had a slightly greater change in weight (–0.63 ± 0.05 kg) relative to younger adults (-0.51 ± 0.04 kg).

Thermal discomfort

Participants were asked to indicate their level of thermal discomfort throughout the exposure. Although perceived thermal discomfort did not increase or decrease during the session ($p = 0.245$), there was a significant difference between groups ($p = 0.051$). Older adults consistently rated their thermal sensation higher than that of younger adults and this was significantly different at 60 min (3.1 ± 0.4 vs. 2.2 ± 0.3, $p = 0.044$) and 120 min (3.1 ± 0.4 vs. 1.9 ± 0.3, $p = 0.008$).

Table 1. Local sweating rates and mean skin temperature during passive exposure to dry and humid heat.

	LSR (mg·min⁻¹·cm⁻²)						T_{Sk} (°C)	
	Arm		Back		Leg			
Min.	Younger	Older	Younger	Older	Younger	Older	Younger	Older
Hot–dry								
0	0.18±0.03	0.20±0.03	0.19±0.04	0.22±0.03	0.21±0.02	0.20±0.03	34.11±0.12	34.19±0.15
30	0.15±0.03	0.17±0.02	0.14±0.03	0.22±0.03*	0.18±0.02	0.17±0.02	34.47±0.13	34.36±0.18
60	0.14±0.03	0.21±0.02	0.14±0.03	0.24±0.03*	0.19±0.02	0.19±0.02	34.56±0.12	34.35±0.18
90	0.13±0.02	0.18±0.02	0.12±0.02	0.22±0.03*	0.21±0.02	0.15±0.01	34.57±0.11	34.40±0.19
120	0.11±0.02	0.20±0.03	0.12±0.02	0.23±0.03*	0.21±0.02	0.16±0.02	34.69±0.10	34.44±0.17
Hot–humid								
0	0.39±0.04	0.51±0.06	0.35±0.04	0.43±0.04*	0.48±0.04	0.39±0.03	34.41±0.10	34.28±0.07
30	0.33±0.03	0.43±0.04	0.30±0.04	0.41±0.05*	0.43±0.04	0.34±0.02	34.74±0.10	34.55±0.10
60	0.33±0.04	0.46±0.05	0.28±0.03	0.42±0.06*	0.42±0.03	0.31±0.02*	34.80±0.08	34.65±0.14
90	0.31±0.03	0.41±0.04	0.28±0.03	0.41±0.06*	0.39±0.03	0.30±0.02*	34.84±0.08	34.65±0.16
120	0.33±0.04	0.42±0.04	0.26±0.02	0.41±0.05*	0.40±0.03	0.31±0.02*	34.87±0.07	34.63±0.14

Note: Values are presented as mean ± SE. LSR, local sweat rate; T_{Sk}, mean skin temperature. *denotes a significant difference between younger and older adults.

Table 2. Cutaneous vascular conductance, heart rate, and mean arterial pressure responses during passive exposure to dry and humid heat.

	CVC (% of max)		HR (beats·min⁻¹)		MAP (mmHg)	
	Younger	Older	Younger	Older	Younger	Older
Hot–dry						
0	18.4±1.4	21.0±1.9	78±4	77±3	85±2	95±3
30	19.0±1.8	23.7±1.8	80±4	78±3	94±3	95±5
60	17.6±1.3	24.5±1.6*	79±5	75±3	94±3	91±6
90	17.1±0.9	22.8±1.8*	84±5	74±2	94±2	97±6
120	17.2±1.0	22.6±1.9*	86±4	75±2	96±3	96±5
Hot–humid						
0	20.6±2.3	25.9±2.3	84±4	79±3	88±3	93±3
30	23.4±3.5	31.0±4.0	83±4	76±3	95±3	93±2
60	22.1±2.8	31.7±3.4*	86±4	81±4	95±3	93±2
90	21.6±3.0	33.8±3.7*	85±4	78±4	93±2	89±2
120	20.2±1.8	32.7±3.6*	86±5	80±3	94±2	92±2

Note: Values are presented as mean ± SE. CVC, cutaneous vascular conductance; HR, heart rate; MAP, mean arterial pressure. *denotes a significant difference between younger and older adults.

Younger versus older adults: hot–humid ambient condition

Calorimetry

We present the rates of metabolic heat production, total heat loss, evaporative heat loss, E_{req}, and dry heat exchange during the hot–humid experimental session in Fig. 1C and 1D. Similar to the hot–dry session, metabolic heat production remained constant (p = 0.139) and was not different between groups (p = 0.535). Total heat loss increased as the session progressed (p < 0.001). This was partly driven by a reduced rate of dry heat gain in both age groups (p < 0.001). Older adults had a significantly greater rate of dry heat gain compared with younger adults (p = 0.019). Significant differences between groups were observed at 30 (+11 W, p = 0.011), 60 (+10 W, p = 0.032), 90 (+12 W, p = 0.032), and 120 min (+12 W, p = 0.021). In contrast to the hot–dry session, evaporative heat loss increased significantly over the course of the humid heat exposure (p < 0.001), albeit this was similar between groups (p = 0.814). As a result of a greater rate of dry heat gain, the average E_{req} in older adults exceeded that of younger adults by approximately 13 W, although the difference between groups did not reach statistical significance (p = 0.109). The net amount of heat that was stored (and therefore the change in body heat content) over the 2 h hot–humid session was significantly greater in older adults relative to the younger adults (p = 0.037) (Fig. 2D).

Local heat loss responses

Local sweat rates on the upper back was significantly different between groups (p = 0.025); older adults had a greater sweat rate at 30 (p = 0.016), 60 (p = 0.012), 90 (p = 0.016), and 120 min (p = 0.004). Sweating on the forearm fell short of being significantly greater in older adults (p = 0.056). Finally, local sweating on the thigh was significantly greater in younger adults (p = 0.010). Significant differences occurred at 60 (p = 0.030), 90 (p = 0.018), and 120 min (p = 0.031). CVC remained significantly higher in older adults (p = 0.042) in the hot–humid condition compared with younger adults. CVC was significantly different between groups at 60 (p = 0.031), 90 (0.016), and 120 min (p = 0.005).

Core and skin temperatures

Both visceral (p < 0.001, Fig. 2C) and mean skin (p = 0.004) temperatures increased as the session progressed. Whereas mean skin temperature did not significantly differ between groups (p = 0.213), the increase in visceral temperature was significantly greater in older adults (p = 0.019). Differences were observed at 30 (p = 0.040), 60 (p = 0.023), 90 (p = 0.011), and 120 min (p = 0.001).

Cardiovascular responses and hydration status

Heart rate became significantly higher as the session progressed (p = 0.010), although this was similar in younger and older adults (p = 0.242). No differences in mean arterial pressure were measured over the course of the session (p = 0.236) and responses were similar between groups (p = 0.390). Younger and older adults had similar changes in blood volume (younger: –2.7 ± 0.5%; older: –2.5 ± 0.6%, p = 0.441), plasma volume (younger: –4.9 ± 0.9%; older: –3.9 ± 0.7%, p = 0.464) and urine-specific gravity (younger: 0.005 ± 0.002; older: 0.004 ± 0.002, p = 0.442). The difference in weight before and after the session fell short of statistical significance but tended to be more elevated in older adults (younger: –0.49 ± 0.02 kg, older: –0.59 ± 0.04 kg, p = 0.057).

Thermal discomfort

Thermal discomfort became increasingly greater over the course of the hot–humid exposure (p = 0.002) and older adults reported a higher thermal sensation (p = 0.033). This was significantly different at 30 (3.0 ± 0.2 vs. 2.1 ± 0.2, p = 0.004), 60 (3.2 ± 0.3 vs. 2.2 ± 0.2, p = 0.007), and 90 min (3.1 ± 0.3 vs. 2.3 ± 0.3, p = 0.043).

Discussion

In the present study, older adults had a greater change in body heat content compared with younger adults during short exposures to a hot–dry (36.5 °C, 20% RH) and hot–humid (36.5 °C, 60% RH) environment. This was in large part because heat load was more elevated in older adults during the exposures, owing to a greater rate of dry heat gain. This added heat load was not compensated for by a greater rate of evaporative heat loss, causing a greater rate of heat storage throughout the sessions that resulted in a progressively greater change in body heat content among older adults.

A number of studies reported decrements in thermoregulatory function in older adults during passive exposure to extreme ambient conditions ranging from 40–90 °C with durations of 10 to 240 min (Armstrong and Kenney 1993; Drinkwater et al. 1982; Dufour and Candas 2007; Miescher and Fortney 1989; Sagawa et al. 1988; Shoenfeld et al. 1978). In the present study, we were concerned with investigating whole-body heat loss and heat storage under a lower environmental heat load as Canada does not typically experience such extreme temperatures, yet heat-related injuries and (or) deaths are still prevalent (Pengelly et al. 2007). The results from our study indicate that during exposure to a hot environment, with relatively low humidity, whole-body evaporative heat loss was similar between younger and older adults. Even so, older adults stored 38% more heat than their younger counterparts. It is important to note that older adults had a greater rate of dry heat gain (approx. 10 W), owing to the slightly lower mean skin temperature (and therefore greater air to skin temperature gradient). As shown in Fig. 1A, the amount of evaporative heat loss required to achieve balance (determined as the sum of metabolic heat load ± dry heat exchange) was actually more elevated in older adults compared with the younger group throughout the session. The average rate of evaporative heat loss required for older adults to achieve heat balance was approximately 133 W, whereas for young adults this was only approximately 122 W. Despite the slightly greater heat load, we did not observe a concomitant increase in the rate of whole-body evaporative heat loss in older adults. Evaporative heat loss accounted for approximately 85% of the evaporative heat loss required for heat balance in younger adults, but only approximately 77% in older adults. The net effect over the 2 h exposure was a greater cumulative increase in body heat content.

Canadian climates tend to be very humid in the summer. In fact, it is not uncommon for humidity indices (e.g., Humidex) to reach 45 °C with some extreme readings recorded as high as 51–53 °C during heat waves (Government of Canada 2013*a*). Such extreme conditions can severely impede thermoregulatory control by reducing the amount of heat that can be dissipated to the environment through evaporative heat loss; the primary physiological mechanism for cooling (McLellan et al. 1996; Taylor 2006). In the present study, evaporative heat loss was reduced to a similar extent (approx. 26%) in the hot–humid relative to the hot–dry condition in both younger and older adults. Consequently, heat storage increased by 59% in younger adults and 50% in older adults, compared with the amount of heat that was stored during the hot–dry condition. The change in body heat content remained higher in older adults (by 26%) compared with younger adults, again largely due to a greater rate of dry heat gain (approx. 10 W). Interestingly, local sweat rate was greater by approximately 55% and 49% (average from the three sites measured) for younger and older adults, respectively, in the humid condition compared with the dry environment, yet both groups stored more heat. Considering that the local sweat rate was somewhat more elevated in older adults (0.38 ± 0.04 vs. 0.31 ± 0.05 $mg{\cdot}min^{-1}{\cdot}cm^{-2}$) but that they still stored more heat would suggest that sweating efficiency was reduced to a greater degree in older individuals, thereby leading to increased thermal strain (Candas et al. 1979).

Core temperature measurements are commonly used to assess thermal stress among individuals in a variety of scenarios involving exposure to the heat. There is growing evidence from many population groups that core temperature measurements can severely underestimate whole-body heat storage as core temperature is only indicative of heat content within a specific region of the body (Kenny and Jay 2013). Our results indicate that core temperature increased progressively in younger (+0.09 ± 0.06 °C) and older adults (+0.22 ± 0.08 °C) during the hot–dry condition. In the hot–humid condition, the increase in visceral temperature was significantly more elevated in older adults (+0.32 ± 0.06 °C) than younger adults (+0.12 ± 0.04 °C). The change in core temperature, however, does not adequately reflect the much greater change in body heat content, and therefore the level of thermal strain experienced in each group. In fact, the small change in visceral temperature under both environmental conditions could lead to the misguided conclusion that the risk of developing a heat injury is relatively low. Conversely, the change in mean body temperature can more accurately be estimated using the change in body heat content measured by direct calorimetry with the equation $\Delta T_b = \Delta H_b/(b_m \times C_p)$ where ΔT_b is the change in mean body temperature, ΔH_b is the change in body heat content, b_m is body mass, and C_p is specific heat of the participant. Based on this equation, the estimated increase in mean body temperature would be approximately 0.52 °C and approximately 0.76 °C in younger and older adults, respectively, during the hot–dry exposure. For the hot–humid condition, the change in mean body temperature would actually be as high as approximately 1.34 °C (younger) and approximately 1.58 °C (older) after just 2 h. So although visceral temperature measurements may suggest minimal health risks in both groups under the conditions tested, it is important to keep in mind that mean whole-body temperature is much more elevated, with the greatest increase observed in older adults.

Perspectives

The main question behind the present study was whether or not exposure to extreme environmental conditions, which are representative of Canadian climates, poses a greater threat to the health of older adults relative to their younger counterparts. Increases in heat waves could be particularly concerning in places like Canada where summertime temperatures are generally mild, and temperatures fluctuate considerably throughout the year. As a result, individuals residing in such climates do not tend to be acclimatized to hot weather conditions and are likely more susceptible to the potential harmful effects of extreme heat compared with those living in countries and (or) cities where high summertime heat and humidity are common. In the present study, 2 h of exposure to a dry and humid heat stress resulted in greater body heat storage among older adults, suggesting a greater level of thermal strain compared with younger individuals. This is supported by the fact that older adults reported a higher level of thermal discomfort after only 60 and 30 min for the hot–dry and hot–humid environments, respectively. Nonetheless, there are a few things to consider when interpreting our study findings. First, the older adults in this study were healthy and not taking any medications. Thus, older adults with chronic medical conditions (e.g., diabetes, cardiovascular disease, respiratory disease, etc.) and (or) taking medication may be more vulnerable than the older adults who participated in the present study (Kenny and Jay 2013; Kenny et al. 2010). Moreover, the experimental sessions were conducted in a laboratory setting and did not factor in additional heat that could be gained through solar radiation. Also, the temperature selected to mimic the upper temperature extremes in Canada (i.e., 36.5 °C) may not be representative of extreme temperatures in large metropolitan cities, which could be even higher as a result of the "urban heat island effect" (Kovats and Hajat 2008; Lundgren et al. 2013). Finally, the exposure was purposely selected to be short. This was the first time that we used the direct calorimeter to assess whole-body heat loss and heat storage in a group of vulnerable older adults who had no prior experience in our laboratory. There are certain risks involved with doing these types of studies where participants are enclosed in a capsule-like device for an extended period of time. Given that previous studies had observed marked differences between younger and older adults after just 30 min (Dufour and Candas 2007; Miescher and Fortney 1989), we opted to only do a 2 h exposure. In reality, older adults may spend longer than 2 h exposed to high temperatures and (or) humidity during heat waves, hence our findings underline a critical need to examine age-related changes in the heat stress responses during prolonged exposure (i.e., >4 h).

In summary, exposure to dry heat as well as humid heat posed a significantly greater thermal challenge for older adults as evidenced by greater changes in body heat content. Initiatives to increase awareness regarding the potential health risks associated with exposure to the heat, particularly when humidity is high, maybe necessary to protect older individuals against heat illness.

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