A comparison between the technical absorbent and ventilated capsule methods for measuring local sweat rate

Nathan B. Morris,1 Matthew N. Cramer,1 Simon G. Hodder,2 George Havenith,2 and Ollie Jay1

1Thermal Ergonomics Laboratory, School of Human Kinetics, University of Ottawa, Ontario, Canada; and 2Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Leicestershire, United Kingdom

Submitted 6 September 2012; accepted in final form 9 January 2013


First published January 10, 2013; doi:10.1152/japplphysiol.01088.2012.—This study assessed the accuracy of the technical absorbent (TA) method for measuring local sweat rate (LSR) relative to the well-established ventilated capsule (VC) method during steady-state and nonsteady-state sweating using large and small sample surface areas on the forearm and midback. Forty participants (38 males and two females) cycled at 60% peak oxygen consumption for 75 min in either a temperate [22.3 ± 0.9°C, 32 ± 17% relative humidity (RH)] or warm [32.5 ± 0.8°C, 29 ± 7% RH] environment. Simultaneous bilateral comparisons of 5-min LSR measurements using the TA and VC methods were performed for the back and forearm after 10, 30, 50, and 70 min. LSR values, measured using the TA method, were highly correlated with the VC method at all time points, irrespective of sample surface area and body region (all P < 0.001). On average, ~79% of the variability observed in LSR measured with the VC method was described by the TA method. The mean difference in absolute LSR using the TA method (TA-VC with 95% confidence intervals) was −0.23 [−0.30, −0.16], −0.11 [−0.21, 0.00], −0.03 [−0.14, +0.08], and +0.02 [−0.07, +0.11] mg·cm⁻²·min⁻¹ after 10, 30, 50, and 70 min of exercise, respectively. Duplicate LSR measurements within each method during steady-state sweating were highly correlated (TA: r = 0.96, P < 0.001, n = 20; VC: r = 0.97, P < 0.001, n = 20) with a mean bias of +0.07 ± 0.14 and +0.01 ± 0.10 mg·cm⁻²·min⁻¹ for TA and VC methods, respectively. The mean smallest detectable difference in LSR was 0.12 and 0.05 mg·min⁻¹·cm⁻² for TA and VC methods, respectively. These data support the TA method as a reliable alternative for measuring the rate of sweat appearance on the skin surface.

exercise; fluid loss; heat stress; sweating; thermoregulation

THE PRODUCTION AND SUBSEQUENT evaporation of sweat is essential for maintaining core body temperature within safe limits during exercise and/or heat exposure. It follows that the measurement of local sweat rate (LSR) is an integral component of studies conducted by thermal physiologists assessing human thermoregulatory responses. Currently, the most common method for measuring LSR uses a ventilated capsule (VC). The VC method estimates LSR by measuring the difference in vapor content between influent and effluent air traveling at a known flow rate through a plastic capsule affixed to a given surface area of skin. Albert and Palmes (1) were the first to describe this method measuring vapor content with an infrared gas analyzer; a device replaced by a hygrometer in later modifications was reported by Takagi and Nakayama (33) and then Bullard (4). Typical measurement sites using the VC method include the upper-back, forearm, chest, forehead, and thigh (7, 17, 25). Whereas continuous sampling alongside measurements of a fast-responding index of core body temperature facilitates the characterization of the onset threshold and thermosensitivity of sudomotor activity, a single VC directly measures the rate of sweat production across a very small proportion (i.e., <0.02%) of total body surface area only.

Alternatively, LSR can also be estimated using various absorbency techniques. This method, which originally dates back to the 1930s (24), uses an absorbent fabric, either applied directly to the skin (27, 35) or inserted into an unventilated sweat-collection container (37). More recently, the technical absorbent (TA) method that uses patches of highly absorbent material of a fixed area placed over the skin for a short (3–5 min) period of time has been adopted to estimate a snapshot of LSR across larger skin areas. The TA method has been used to map regional variations in sweat rates across the entire body (15, 30, 31) and measured LSR in squash players (32), runners (15, 30, 31), cyclists (2, 8), National Collegiate Athletic Association football players (10), as well as participants carrying backpacks (13). Havenith et al. (15) qualitatively compared both methods and listed a number of potential methodological issues for both approaches. While their regional TA values were in general agreement with VC values previously reported in the literature, they did not simultaneously measure and compare LSR values using both methods within the same experiment. If the TA and VC methods are in close agreement, TAs would present an easy-to-use, inexpensive, portable, and reliable alternative for measuring LSR under both laboratory and field-work environments.

Potential sources of disagreement between the two methods include differences in skin surface area coverage and the associated influence of inter- as well as intraregional variability in heat-activated sweat gland density or sweat gland output (7, 21–23), as well as differences in local skin temperature at the measurement site due to greater levels of local convection with the VC method. Furthermore, the temporal lag between sweat gland stimulation and secretion and the arrival of sweat at the skin surface may lead to systematically lower LSR values with the TA method during nonsteady-state sweating due to the evaporation of some sweat and its detection prior to reaching the skin surface with the VC method. The greater local air velocity and absolute humidity gradient between the skin and air with the VC method may also induce greater LSR values (6) relative to the TA method. Finally, the skin coverage with the TA method may lead to hidromeiosis, although the high absorbent capacity and short application time should prevent this (2, 15, 30, 31).

The aim of this study was to compare LSR values measured using the TA and VC methods during nonsteady-state (early
Assessing Local Sweat Rate Using Technical Absorbents

Participants

Following approval of the experimental protocol by the University of Ottawa Research Ethics Committee (Ontario, Canada), written, informed consent was obtained from 40 (38 males and 2 females) university-aged volunteers who were unacclimated, normotensive, and nonsmokers. Participants were divided into one group (19 males and 1 female) undertaking LSR measurements on the midback and another group (19 males and 1 female) undertaking LSR measurement on the forearm. To ensure a large range of sweat rates, one-half of the participants from each group conducted their trials in a temperate environment [22.3 ± 0.9°C, 32 ± 17% relative humidity (RH)], and the other one-half conducted their trials in a warm environment [23.5 ± 0.8°C, 29 ± 7% RH]. Mean physical characteristics of each group were similar (Table 1). All data collection took place in the Thermal Ergonomics Laboratory at the University of Ottawa.

Instrumentation

**TA method.** This method was a modified version of the technique reported by Havenith et al. (15) and Smith and Havenith (30, 31) and identical to that reported in other recent studies (2, 8, 10). The TA patches (#2164 laminated Airlaid; Technical Absorbents, North East Lincolnshire, UK) consisted of a large square patch (L; back: 64 cm²; forearm: 36 cm²) and a separate, smaller (S; 4 cm²) round patch that corresponded to the internal surface area covered by a VC in the center. A 1.0-cm-wide border, separated from the main patch, surrounded the large TA patch as a guard to prevent sweat migration into the test area from adjacent areas (Fig. 1). Prior to experimentation, each patch was weighed without the border in a separate impermeable plastic bag (Ziploc) to the nearest 0.1 mg using a precision scale (Denver Instrument, Bohemia, NY). In the back group, the patches were applied to the midlateral section of the back, with the central patch placed in the same position as the central VC on the contralateral side of the back. For the forearm group, the patches were centered 6 cm distal to the antecubital fossa on the ventral surface of the forearm, with the central patch placed in the same position as the VC most proximal to the antecubital fossa on the contralateral arm. The patches and borders were removed from their bags and assembled 2 min prior to application using nonpowdered rubber gloves to prevent absorption of water and oils from the researcher’s hands. Twenty seconds prior to the start of each sampling time point (10, 30, 50, 70 min), the area of application was wiped completely dry using a paper towel. The patch assembly was then held in place on the skin with one strip of surgical tape (Transpore; 3M, London, Ontario, Canada) and a compression tee shirt (model RM20105 Dri-Star; Starter, New Haven, CT) to ensure equal pressure across the patch. After exactly 5 min, the patch assembly was removed and the border discarded, and each individual patch (L and S) was placed immediately into its original separate bags and reweighed. LSR was calculated using the difference between post- and preapplication mass, divided by the surface area of the patch [L: 60 cm² (back), 32 cm² (forearm); S: 4 cm²] and the duration of application (5 min), yielding values in mg·min⁻¹·cm⁻². The sweat rates from the L and S patches were added together to obtain the sweat rate for the entire application area (back: 64 cm²; forearm: 36 cm²).

**VC method.** For the back group, three capsules, each with an internal surface area of 4 cm², were secured vertically in a series on the midlateral side of the back, contralateral to the TA method, with a distance of 2 cm between each capsule. For the forearm group, two capsules, each with an internal surface area of 4 cm², were secured along the midline of the forearm with their centers 2 cm and 8 cm distal to the antecubital fossa, respectively, on the arm, contralateral to the TA method. The side of the body used for VC and TA measurements was balanced between participants within each body region and the two environmental conditions tested. A single tank of compressed anhydrous air supplied all capsules simultaneously at a mean flow rate of 1.7 l/min. Airflow into each individual capsule was measured using separate calibrated flow meters (model FMA-A2307; Omega Engineering, Stamford, CT). Water vapor content of the effluent air was measured either with a 473 precision dew-point mirror (RH Systems, Albuquerque, NM) or a capacitance hygrometer (HMT333; Vaisala, Helsinki, Finland), yielding values accurate to ±0.035 mg·cm⁻²·min⁻¹. All hygrometer units were factory calibrated between 0.2% and 95.8% RH at 21.8°C for the duration of the experiment.

**Table 1. Mean physical characteristics of participants**

<table>
<thead>
<tr>
<th>Location</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>BSA (m²)</th>
<th>$\text{V} O_2\text{peak mL·kg}^{-1}·\text{min}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back</td>
<td>23 (3)</td>
<td>1.75 (0.23)</td>
<td>73.3 (9.6)</td>
<td>1.90 (0.13)</td>
<td>49.5 (4.2)</td>
</tr>
<tr>
<td>Forearm</td>
<td>23 (3)</td>
<td>1.73 (0.06)</td>
<td>70.6 (8.6)</td>
<td>1.85 (0.14)</td>
<td>50.0 (5.3)</td>
</tr>
</tbody>
</table>

Values are means (SD). Body surface area (BSA) was estimated using the equation of DuBois and DuBois (11). $\text{V} O_2\text{peak}$, peak oxygen consumption.

Fig. 1. Design of technical absorbent (TA) patches (white) and absorbent borders (gray) used for data collection. Absorbent frames (1 cm wide) and small patches (4 cm²) were the same size for both locations. Large patches were 64 cm² and 36 cm² for back and forearm application, respectively.

J Appl Physiol · doi:10.1152/japplphysiol.01088.2012 · www.jappl.org
Innovative Methodology

Assessing Local Sweat Rate Using Technical Absorbents • Morris NB et al.

study. Additional testing was performed throughout the study to ensure that all three hygrometers reported identical values. Capsules were secured to the skin using surgical tape (Transpore; 3M), double-stick disks (3M Health Care, Neuss, Germany), and Collodion medical glue (Mavidon, Lake Worth, FL). For each 5-min measurement period of the TA method, average LSR values from the two (forearm)- or three (back)-capsule assembly were used for comparison.

Whole-body sweat loss. For all groups, whole-body sweat loss (WBWL) was estimated to the nearest gram using a platform scale (Combiics 2; Sartorius Canada, Mississauga, Ontario, Canada). Participants were weighed immediately prior to instrumentation and directly after de-instrumentation and toweling off. Values for WBWL are expressed in liters.

Experimental Protocol

Participants were asked to refrain from consuming caffeine or alcohol for 24 h prior to testing. In addition, they were instructed to drink plenty of water the night before and the morning of their experimental trial but were not permitted to drink any water once instrumentation was completed. The study consisted of one preliminary trial and one experimental trial. During the preliminary trial, total body mass, height, and peak oxygen consumption (\(\dot{V}O_2\text{peak}\)) were measured. \(\dot{V}O_2\text{peak}\) was determined using a cycle ergometer protocol with a 10-min warm-up at 40 W, followed by a 20-W increase every minute until physical exhaustion, in accordance with recommendations by the Canadian Society of Exercise Physiology (5a). For the experimental trial, subjects were first weighed and instrumented and then underwent a 10-min rest period. Afterward, subjects cycled for 75 min at 60% of their \(\dot{V}O_2\text{peak}\) at a pedaling cadence of 80 rpm. Upon completion of the trial, subjects were toweled off and reweighed.

Statistical Analysis

LSR data were assessed initially using a four-way mixed ANOVA to evaluate differences in 5-min mean LSR values as a function of the repeated factors of “method” (two levels: TA and VC), sample area (two levels: L and S), and sample time point (four levels: 10, 30, 50, and 70 min) and the nonrepeated factor of body region (two levels: forearm and back). Data were not further separated by temperate and warm conditions, since the purpose of these conditions was to evoke a greater range of LSRs, but the data were assessed to ensure that they were distributed normally. When significance was found, individual differences were assessed using independent t-tests. The probability of making a type I error in all tests was maintained at \(P < 0.05\) using a Bonferroni post hoc correction.

To further compare LSR data measured using VC and TA methods for each sample area size on each body region at each time point, the association between the two methods was assessed using a simple linear correlation, and the coefficient of determination (R\(^2\) statistic) was obtained to determine the amount of variability in the VC data that was explained by the TA measurements. Additionally, to assess the level of agreement between the two methods, goodness-of-fit was assessed relative to the line of identity (\(y = x\)), where a value of one would denote perfect agreement between TA and VC methods. To avoid confusion with the R\(^2\) values relative to the regression line of best fit, this regression analysis relative to the line of identity will be denoted as *\(r_y^2\).*

Bland-Altman plots (3) were also derived to measure the internal variability of each LSR method by calculating mean bias and limits of agreement using the LSR values from the 50- and 70-min samples, by which point, it was assumed that each participant would have reached a steady-state sweat rate. The full-trial sweat trace from the VC method for each participant was further used to verify steady-state sweating. The difference between these measures of LSR using each method with a 95% probability will lie within the respective limits of agreement of these plots. Limits of agreement were calculated by multiplying the SD of the mean difference between duplicate measurements by 1.96. Qualitative limits of magnitude based on the largest differences in steady-state LSR between populations reported in the literature (12, 25) were added for reference. The smallest detectable difference (internal reliability) was also calculated for each method using: \(1.96 \sqrt{2} \times \text{SE (14)}\).

RESULTS

Mean power output on the cycle ergometer was 122 \(\pm\) 11 W for the back trials and 122 \(\pm\) 12 W for the forearm trials. After 70 min of exercise, mean WBWL was 1.04 \(\pm\) 0.15 l (range: 0.86–1.27 l) in back trials and 1.01 \(\pm\) 0.17 l (range: 0.77–1.65 l) in forearm trials.

ANOVA Analyses

Mean LSR values measured using the TA and VC methods after 10, 30, 50, and 70 min of exercise are given in Table 2. The ANOVA analysis identified a significant interaction between method and “time” (\(P < 0.001\)). Specifically, LSR values measured using the VC method were greater than the values derived using the TA method after 10 min (\(P < 0.001\)) and 30 min (\(P = 0.02\)) but not after 50 min (\(P = 0.37\)) or 70 min (\(P = 0.49\)) of exercise. This observation was the same, irrespective of sample area (\(P = 0.09\)) and body region (\(P = 0.40\)).

Correlational and Goodness-of-Fit Analyses

For LSR measurements taken on the back (Fig. 2), values derived using the TA method correlated highly with those derived using the VC method, with both S and L patch sizes after 10 min (S: *\(r_y^2 = 0.95\); L: *\(r_y^2 = 0.94\)), 30 min (S: *\(r_y^2 = 0.92\); L: *\(r_y^2 = 0.95\)), 50 min (S: *\(r_y^2 = 0.90\); L: *\(r_y^2 = 0.92\)), and 70 min (S: *\(r_y^2 = 0.92\); L: *\(r_y^2 = 0.92\)) of exercise (all \(P < 0.001\)). For the L patch size, between 84% and 90% of the variability in the VC data was explained by the TA method; for the S patch size, between 73% and 85% of the variability in the VC data was explained by the TA method. Relative to the line of identity (i.e., the absolute VC data), the goodness-of-fit of the TA data showed a low level of agreement after 10 min of exercise (S: *\(r_y^2 = 0.43\); L: *\(r_y^2 = 0.35\)) but very good agreement after 30 min (S: *\(r_y^2 = 0.82\); L: *\(r_y^2 = 0.66\)), 50 min (S: *\(r_y^2 = 0.76\); L: *\(r_y^2 = 0.81\)), and 70 min (S: *\(r_y^2 = 0.83\); L: *\(r_y^2 = 0.84\)).

For LSRs measured on the forearm (Fig. 3), values recorded using the TA method again correlated highly with LSRs measured using the VC method after 10 min (S: *\(r_y^2 = 0.83\); L: *\(r_y^2 = 0.84\)), 30 min (S: *\(r_y^2 = 0.80\); L: *\(r_y^2 = 0.78\)), 50 min (S: *\(r_y^2 = 0.78\); L: *\(r_y^2 = 0.80\)), and 70 min (S: *\(r_y^2 = 0.69\); L: *\(r_y^2 = 0.70\)).

Repeatability of Steady-State Measures

To compare the internal variability of the TA and VC methods, duplicate steady-state measures of LSR were as-
Table 2. Mean local sweat rates (95% confidence intervals) for technical absorbent (TA), ventilated capsule (VC) methods, with actual and relative differences (AD and RD, respectively) between methods after 10, 30, 50, and 70 min of exercise

<table>
<thead>
<tr>
<th>Local Sweat Rate (mg·min⁻¹·cm⁻²)</th>
<th>Time (min)</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Absorbents</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA</td>
<td>Large Back</td>
<td>0.56 [0.44, 0.68]</td>
<td>0.82 [0.64, 0.99]</td>
<td>1.01 [0.79, 1.22]</td>
<td>1.12 [0.88, 1.35]</td>
</tr>
<tr>
<td>VC</td>
<td></td>
<td>0.78 [0.60, 0.96]</td>
<td>1.02 [0.82, 1.23]</td>
<td>1.11 [0.91, 1.32]</td>
<td>1.15 [0.94, 1.37]</td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td>-0.22 [-0.30, -0.14]</td>
<td>-0.21 [-0.27, -0.14]</td>
<td>-0.10 [-0.19, -0.02]</td>
<td>-0.04 [-0.13, 0.06]</td>
</tr>
<tr>
<td>VC</td>
<td>Small</td>
<td>0.52 [0.37, 0.67]</td>
<td>0.86 [0.64, 1.08]</td>
<td>1.08 [0.83, 1.34]</td>
<td>1.15 [0.90, 1.40]</td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td>-0.23 [-0.32, -0.13]</td>
<td>-0.11 [-0.19, -0.02]</td>
<td>+0.01 [-0.09, 0.14]</td>
<td>+0.04 [-0.06, 0.13]</td>
</tr>
<tr>
<td>RD (%)</td>
<td></td>
<td>-31.0 [-41.6, -20.4]</td>
<td>-13.2 [-24.4, -1.9]</td>
<td>+1.3 [-13.2, 15.8]</td>
<td>+4.4 [-6.4, 15.3]</td>
</tr>
<tr>
<td>TA</td>
<td>Large Arm</td>
<td>0.44 [0.35, 0.52]</td>
<td>0.94 [0.65, 1.22]</td>
<td>1.05 [0.76, 1.34]</td>
<td>0.98 [0.80, 1.15]</td>
</tr>
<tr>
<td>VC</td>
<td></td>
<td>0.67 [0.56, 0.79]</td>
<td>0.96 [0.75, 1.16]</td>
<td>1.04 [0.82, 1.26]</td>
<td>0.98 [0.77, 1.18]</td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td>-0.24 [-0.30, -0.18]</td>
<td>-0.03 [-0.21, 0.15]</td>
<td>-0.01 [-0.12, 0.14]</td>
<td>0.00 [-0.09, 0.10]</td>
</tr>
<tr>
<td>RD (%)</td>
<td></td>
<td>-34.8 [-41.2, -28.4]</td>
<td>-5.8 [-19.4, 7.8]</td>
<td>-1.9 [-12.2, 8.5]</td>
<td>+2.2 [-6.6, 11.0]</td>
</tr>
<tr>
<td>VC</td>
<td>Small</td>
<td>0.42 [0.33, 0.51]</td>
<td>0.87 [0.65, 1.09]</td>
<td>1.00 [0.79, 1.21]</td>
<td>1.04 [0.85, 1.24]</td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td>-0.24 [-0.31, -0.17]</td>
<td>-0.09 [-0.17, -0.01]</td>
<td>-0.05 [-0.15, 0.05]</td>
<td>+0.08 [-0.03, 0.18]</td>
</tr>
<tr>
<td>RD (%)</td>
<td></td>
<td>-36.6 [-45.4, -27.8]</td>
<td>-11.2 [-17.9, -4.5]</td>
<td>-4.5 [-14.4, 5.3]</td>
<td>+10.3 [-3.0, 20.9]</td>
</tr>
</tbody>
</table>

All data are represented in units of mg·min⁻¹·cm⁻² with the exception of RD values. Negative AD values denote TA values lower than VC values. n = 20 except for arm group after 10 min (n = 19) and both arm and back groups after 70 min (n = 19).

sessed. For the TA method, the mean LSR of 1.00 ± 0.48 mg·cm⁻²·min⁻¹ in the first (50-min) sample did not differ significantly (P = 0.364) from the mean value of 1.07 ± 0.47 mg·cm⁻²·min⁻¹ in the second (70-min) sample, but the variability of the two samples was highly correlated (r = 0.96, P < 0.001). Likewise, for the VC method, the mean measurement of 1.04 ± 0.45 mg·cm⁻²·min⁻¹ in the first sample was not different (P = 0.862) from the mean value of 1.05 ± 0.46 mg·cm⁻²·min⁻¹ in the second sample, but the variability in the first sample was highly correlated with the second sample (r = 0.97, P < 0.001). The mean bias (±95% limits of agreement) was +0.07 ± 0.28 mg·cm⁻²·min⁻¹ using the TA method and +0.01 ± 0.20 mg·cm⁻²·min⁻¹ using the VC method. Of the 75 pairs of samples analyzed, 100% fell within the limits of magnitude for both the TA method (Fig. 4A) and the VC method (Fig. 4B). With all data pooled together, the smallest detectable
difference was 0.12 mg·cm$^{-2}$·min$^{-1}$ using the TA method and 0.06 mg·cm$^{-2}$·min$^{-1}$ using the VC method. When separated according to the size of sample surface area (i.e., S and L), the smallest detectable difference using the TA method was 0.14 mg·cm$^{-2}$·min$^{-1}$ (S) and 0.10 mg·cm$^{-2}$·min$^{-1}$ (L), whereas the smallest detectable difference using the VC method was 0.06 mg·cm$^{-2}$·min$^{-1}$ (S) and 0.05 mg·cm$^{-2}$·min$^{-1}$ (L).

**DISCUSSION**

LSR values measured using the TA method were highly correlated with values measured using the VC method at all given time points, irrespective of sample surface area and body region. During the initial stages of exercise, absolute LSR values measured using the TA method were ~35% lower than LSR values measured using the VC method. However, after 30 min of exercise and thereafter, LSR values derived using the TA method showed very good agreement with the VC method on both the forearm and back using both L (64 cm$^2$) and S (4 cm$^2$) sample surface areas; the mean absolute difference between methods was <0.10 mg·min$^{-1}$·cm$^{-2}$. Furthermore, the present study demonstrated that the amount of internal variability between duplicate LSR measurements during steady-state sweating using the TA method was similar to the VC method, with the TA method sufficiently sensitive to reliably detect differences in LSR of 0.12 mg·min$^{-1}$·cm$^{-2}$ or greater.

From 30 min of exercise onward, absolute LSR values were in very good agreement between the two methods, but during the initial stages of exercise, the absolute LSR values yielded by the TA method were consistently lower. Nonetheless, under all circumstances, the VC and TA methods were highly correlated; therefore, any changes in LSR measured with the VC method would also be reliably detected with the TA method even during the first 10 min of exercise, despite the absolute values likely being different. From a practical standpoint, this apparent shortcoming of the TA method would only be cause for concern if quantitative cross-method comparisons of LSR values were conducted during the early stages of exercise. Since most researchers typically choose a single method for measuring local sweating, the potential consequences of this finding are probably quite minimal.

The discrepancy between measurement methods for absolute LSR values during the early stages of exercise was not altered by body region or sample surface area and does not seem to be due to factors associated with a low sweat rate per se, as a systematic error between methods was not observed for low rates of sweating (i.e., <1.00 mg·min$^{-1}$·cm$^{-2}$) after 50 and 70 min of exercise (Figs. 2 and 3). Rather, the under-representation of LSR (relative to the VC method) using the TA method may have arisen due to factors associated with the nonsteady-state nature of sweating after only 10 min of exercise. The large water vapor pressure gradient produced by anhydrous inflow gas used with the VC method possibly induced the evaporation of sweat from the upper portion of the excretory duct of the sweat gland in addition to the sweat on the skin surface, whereas the latter is only collected with the TA method. Especially during early stages of sweating, the time required for stop-flow pressure within the sweat gland lumen to reach a level sufficient to overcome hydrostatic pressure leads to a lag between a change in the rate of secretory coil activity and a change in the rate of appearance of sweat on the skin surface (4, 5, 28). At this stage, relatively large increases in stop-flow pressure result in marginal increases in skin surface sweat rate (28). It is possible that the preemptive evaporation of some sweat from within the upper portion of the excretory duct effectively reduced this lag so that the large increases in the rate of secretory coil activity, evident during the early...
stages of exercise (36), more rapidly increased the LSR measured with the VC method. It follows that upon reaching steady-state sweating later on during exercise, any differences between the rates of sweat production within the coil and secretion at the skin surface were probably reduced greatly (26, 28, 29), and the systematic error between VC and TA methods therefore eliminated. The observed difference in nonsteady-state LSR values between methods cannot be explained by any potential differences in skin temperature. Whereas the changes in skin temperature due to the application of a TA patch has been demonstrated for the entire body qualitatively (25, 34), “I” was the largest increase in LSR found in the literature (25), and “II” was the largest decrease in LSR found in the literature (12).

The VC method was selected as the reference technique in the present study; it has negligible analytical variability (19), and any subsequent deviations of LSR values derived using the TA method were therefore assumed to be due to analytical variability associated with the TA method. A small amount of preanalytical variability between methods may have arisen due to the use of bilateral comparisons. Kenefick et al. (19) recently demonstrated that bilateral LSR measurements on the forearm using the VC method were interchangeable; however, their mean difference of 0.07 mg·min⁻¹·cm⁻² reported between left and right forearm sweat rates (19) suggests that some variability may have been introduced that is presently attributed to the TA method. No study could be found in the literature comparing the analytical variability of bilateral sweat rates measured on the back using the VC method; however, pilot data supported similar interchangeability as the forearm, the side of the body used for each method, was balanced, and the level of agreement between measurement methods was similar for the forearm and back.

The internal reliability of the TA method demonstrates that the technique is sufficiently sensitive to detect differences in LSR as small as 0.12 mg·min⁻¹·cm⁻² between groups or conditions, in both and steady-state conditions. Whereas this resolution is double the value found in the present study for the VC method using a single capsule (0.06 mg·min⁻¹·cm⁻²), typical mean differences in LSR, reported in the literature as a function of factors, such as sex [0.6 mg·min⁻¹·cm⁻² (16)], heat acclimation [2.0 mg·min⁻¹·cm⁻² (25)], aerobic fitness at a fixed relative exercise intensity [0.9 mg·min⁻¹·cm⁻² (18)], and age [0.75 mg·min⁻¹·cm⁻² (12)], far exceed the statistically derived, smallest detectable difference of the TA method. Furthermore, differences in LSR, previously reported using the TA method for American football players [0.6–1.7 mg·min⁻¹·cm⁻² (10)], fit and unfit individuals [0.8 mg·min⁻¹·cm⁻² (8)], males and females [up to 1.4 mg·min⁻¹·cm⁻² (15, 30)], and body segments [up to 1.9 mg·min⁻¹·cm⁻² (30, 31)], are also
much greater than the methodological resolution found in the present study.

**Limitations**

Interinvestigator variability was not assessed in the present study; therefore, the replication of the TA method in laboratories other than our own could lead to greater analytical variability than reported. A potential source of error is the precision with which the surface area of a TA patch can be estimated. Presently, each patch was cut from a premeasured outline drawn on a large TA sheet; therefore, some error could have been introduced during the cutting process, leading to patches slightly smaller or larger than assumed, particularly for the small TA method comparison that used a 4-cm² circular patch. A potential solution is the use of square patches in conjunction with a simple computer program that assesses the ratio of black:white pixels of a scanned image of each patch after cutting or assuming a stable production quality of the TA to use the mass to calculate the area (15, 30, 31). Other potential sources of error include evaporation of sweat prior to weighing and the saturation of TA material. Postapplication evaporation can be overcome by immediately inserting the absorbent patch in a sealed freezer bag (with all air expelled), which is then resealed in an additional bag. Whereas previous studies have reported that <3% of the absorptive capacity of the TA material is reached after a 5-min application on an area with a high LSR (forehead), a sample time of longer than 5 min is not recommended because of the impact on local heat loss and skin temperature (2, 15, 30, 31).

**Conclusion**

LSR values measured using the TA method correlated highly with values measured using the VC method, irrespective of sample area, body region, or sample time point. On average, ~79% of the variability observed in LSR, measured with the VC method, was described by the TA method. During nonsteady-state, increasing sweating, the TA method yielded ~35% lower absolute LSR values compared with the VC method. However, during steady-state sweating, absolute LSR values measured with the TA method were in very good agreement with the VC method. These differences could be related to the difference between surface sweat collection (TA method) and deeper sweat extraction (VC method) and the dynamics of sweat traveling to the skin surface. Duplicate measures of LSR within each method during steady-state sweating demonstrated that whereas the smallest detectable difference between separate measures was double that of the VC method, the TA method was sufficiently sensitive to detect between-group/condition differences in LSR as small as 0.12 mg·min⁻¹·cm⁻². As such, the TA method offers a portable, cost-effective, and reliable alternative for measuring the rate of sweat appearance on the skin surface rather than sweat gland activity that is better represented by VC.

**ACKNOWLEDGMENTS**

The authors thank the participants for volunteering for the study. We thank Dr. Caroline Smith for information provided on the TA method.

**GRANTS**

Support for this research was provided by a Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grant (#386143-2010; O. Jay). N. B. Morris was supported by a University of Ottawa Master’s Scholarship, and M. N. Cramer was supported by a NSERC Ph.D. Scholarship.

**REFERENCES**