IOP Publishing Physiol. Meas. 42 (2021) 045006 https://doi.org/10.1088/1361-6579/abf364

Physiological Measurement

IPEM Institute of Physics and Engineering in Medicine

RECEIVED
7 January 2021

REVISED
19 March 2021

ACCEPTED FOR PUBLICATION
30 March 2021

PUBLISHED
12 May 2021

PAPER

The effect of short and continuous absorbent patch application on local skin temperature underneath

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Keywords: absorbent patch; sweat rate; skin temperature; local

Abstract

Objective. By attaching absorbent patches to the skin to collect sweat, an increase in local skin temperature (T_{sk}) underneath the patches seems unavoidable. Yet this effect has not been quantified. The present study investigates the effect of absorbent patch application on local T_{sk} underneath. *Approach*. Ten healthy participants cycled for 60 min at an exercise intensity relative to their body surface area (40 W.m^{-2}) in three environmental conditions (temperate: 25 °C 45% RH, hot-humid: 33 °C 65% RH and hot-dry: 40 °C 30% RH). The effect of short sweat sampling (i.e. from min 25–30 to min 55–60) on T_{sk} was examined on the right scapula. T_{sk} of the left scapula served as control. The effect of continuous sweat sampling (i.e. four consecutive 15 min periods) on T_{sk} was examined on the right upper arm. T_{sk} of the left upper arm served as control. *Main results*. Neither short nor continuous application of absorbent sweat patches affected T_{sk} underneath the patches in the hot-humid and hot-dry condition ($P > 0.05$). In the temperate condition, continuous application led to a significant increase in T_{sk} underneath the patches during the first and second minute. This increase remained throughout the experiment (1.8 ± 0.6 °C; $P < 0.001$). Short application of sweat patches did not affect the local T_{sk} underneath ($P > 0.05$) in the temperate condition. *Significance*. To avoid a significant increase in local T_{sk} underneath sweat patches, continuous application should be prevented in, especially, a temperate condition. Timely removal of sweat patches should be taken into account during longer periods of collecting sweat in field or laboratories settings.

1. Introduction

Measuring local sweat rate (LSR) has become popular in research laboratories to understand sweat gland function, in sports to quantify electrolyte losses, and in industry for functional clothing design and designing thermal and sweating manikins. A convenient method to determine LSR and sweat content is the absorbent patch technique (Smith and Havenith 2011, 2012, Baker *et al* 2016, 2018, Klous *et al* 2020a, 2020b).

For the determination of LSR, Smith and Havenith proposed short sampling durations (<5 min) to prevent hidromeiosis (i.e. reduction of sweating by blockage of the sweat glands due to humid conditions) (Brown and Sargent 1965, Candas *et al* 1984) underneath the patches. Secondly, sweat sampling was recommended once a steady sweat rate has been achieved. In their studies, therefore, usually sweat was sampled for the final 5 min of a 30 min exercise period, from now on referred to as 'short sweat sampling' (Smith and Havenith 2011, 2012). However, to assess sweat composition a certain sweat volume is required to be able to perform the chemical analysis. Since commonly used analyzers for sweat have a relatively large dead volume, large volumes of sweat are required to be able to perform the intended chemical analysis (for example 0.3 ml). Based on experience from our lab, a sampling period of ~15 min is required to collect enough sweat for chemical analysis of more than two sweat components. These 15 min sampling periods are typically seen consecutively (Klous *et al* 2020a, 2020b), which is from now on referred to as 'continuous sweat sampling'.

Covering the skin with absorbent material and impermeable material on top to prevent sweat loss creates a microclimate which could elevate local skin temperature (T_{sk}) (Brebner and Kerslake 1964, Psikuta *et al* 2014, MacRae *et al* 2018). Utilizing both sweat sampling methods, an increase in local T_{sk} underneath patches seems unavoidable, which may affect LSR. Previous research reported an obvious effect of the change in T_{sk} on sweating (Kondo *et al* 1997, Wurster and McCook 1969, Libert *et al* 1979). The onset threshold for sweating was also reached earlier when having a higher T_{sk}, whereas the threshold occurred later with a lower T_{sk} (Nadel *et al* 1971a, 1971b, Cotter and Taylor 2005, Shibasaki *et al* 2006). Furthermore, eccrine sweat glands have a so-called thermal sensitivity: local heating increases and local cooling decreases LSR for a given core temperature (Nadel *et al* 1971a, 1971b, Cotter and Taylor 2005, Shibasaki *et al* 2006). This may be mediated by an increased neurotransmitter release for a given neural stimulus in case of local heating and desentization in case of cooling. However, scientific evidence to back up this theory is lacking. Recently, Gerrett *et al* (2019) showed that the reabsorption rates of eccrine sweat glands were higher, once T_{sk} increased considerably, which may in turn affect sweat content. Yet the effect of applying absorbent patches on T_{sk} has to be quantified.

The present study investigates the effect of short and continuous application of absorbent sweat patches on local T_{sk} underneath the patches. This was done in three types of environmental conditions that are representative for sweat-related research: temperate (25 °C, 45% RH), hot-humid (33 °C, 65% RH), and hot-dry (40 °C, 30% RH). It was hypothesized that both short and continuous application of absorbent sweat patches affect T_{sk}, but that the increase in T_{sk} underneath the patches would be statistically non-significant in any of the three environmental conditions.

2. Material and methods

2.1. Ethical approval

Procedures were approved by the Ethics Committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE-2020-142; amendment VCWE-2020-171). The study was conducted in accordance with the guidelines of the revised *Declaration of Helsinki* (2013). Written informed consent was obtained from all participants before participation in the study.

2.2. Participants

Ten healthy individuals (4 males, 6 females; age: 29 $\pm$ 4 years; height: 175.6 $\pm$ 8.2 cm; weight: 71.3 $\pm$ 12.5 kg) participated in this study. Participants were instructed to refrain from alcohol 24 h before the experiment, to limit caffeine consumption and to consume 500 ml of water 0–2 h before starting the experiment. No further restrictions were placed on participants diets. All participants were non-smokers, did not take any prescription medication, had no history of heat-related illnesses, cardiovascular complications and did not have any known issues with thermoregulation. Menstrual cycle phase was not controlled for in the female participants.

2.3. Design

Participants visited the laboratory three times to cycle (Lode Excalibur, Groningen, The Netherlands) for 60 min at an exercise intensity relative to their body surface area, corresponding to 40 $W.m^{-2}$ (Cramer and Jay 2014), in a climate chamber (b-Cat, Tiel, The Netherlands) set to either 25 °C 45% RH, 33 °C 65% RH or 40 °C 30% RH. Airflow in the climate chamber was standardized to 0.2 ms^{-1} for all environmental conditions. The order of tests was balanced. To account for changes due to circadian rhythms, each visit was scheduled at the same time of day ($\pm$3 h). The effect of short sweat sampling (i.e. from min 25–30 to min 55–60; figure 1) on T_{sk} was examined on the right scapula. T_{sk} of the left scapula served as control. Likewise, the effect of continuous sweat sampling (i.e. four consecutive 15 min periods; figure 1) on T_{sk} was examined on the right upper arm. T_{sk} of the left upper arm served as control.

2.4. Measurements

To confirm hydration, urine specific gravity (USG) was measured with a handheld refractometer (PAL-S, Atago, Bellevue, USA; USG $\leqslant$ 1.025) (Kenefick and Cheuvront 2012). Despite the hydration guidelines, one participant had an USG $>$ 1.025 in the temperate condition and drunk 5 $ml.kg^{-1}$ of water before resuming the experiment. Temperature sensors (Thermochron DS1922L, Maxim Integrated, USA) were attached to the left and right scapula (zone 13 as reported by Gerrett *et al* 2014) and upper arm (zone 19 as reported by Gerrett *et al* 2014). The T_{sk} sensor on the right arm was continuously covered (i.e. four consecutive sampling periods of 15 min) by absorbent material (Cutisoft, BSN Medical, Almere, The Netherlands, size: 25 cm^2 (5 $\times$ 5 cm), absorbent capacity: ~2g). The sweat collection period of 15 min was chosen because that time period is the minimum to allow for collection of enough sweat for chemical analysis and is short enough to prevent saturation of the patch. The absorbent material was covered by an impermeable layer (Parafilm-M, Bemis, Saint Louis,

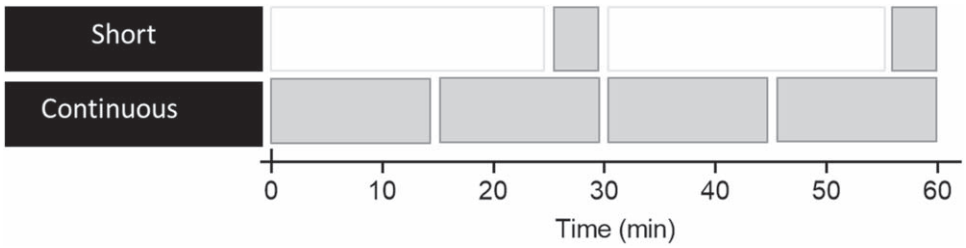

Figure 1. Schematic overview of the study design. Gray rectangles represent applications of absorbent patches to the skin. Short sweat sampling was examined on the right scapula. Continuous sweat sampling was examined on the right upper arm.

Table 1. Mean (SD) control skin temperatures of short and continuous sweat sampling in three environmental conditions ($n = 10$).

Environmental condition	Control T_{sk} -short sampling (°C)	Control T_{sk} -continuous sampling (°C)
Temperate (25 °C 45% RH)	32.7 (1.0)	33.1 (1.0)
Hot-humid (33 °C 65% RH)	36.2 (1.0)[a]	36.5 (1.0)[a]
Hot-dry (40 °C 30% RH)	36.7 (1.0)[a,b]	36.8 (1.1)[a,b]

Note. T_{sk}: skin temperature; RH: relative humidity.
[a] $P < 0.05$ from temperate.
[b] $P < 0.05$ from hot-humid.

USA, size: 30.25 cm^2 (5.5 × 5.5 cm)) and was attached to the skin by a porous adhesive (Fixomull stretch, BSN Medical, Almere, The Netherlands, size: 100 cm^2 (10 × 10 cm)). The T_{sk} sensor on the right scapula was covered by the same sweat patch from min 25–30 to min 55–60 on the arm (i.e. short sweat sampling) as proposed by Smith and Havenith (2011, 2012). The corresponding left skin sites, arm and scapula, served as control. T_{sk} sensors on the control sites were only covered by a 25 cm^2 (5 × 5 cm) piece of the porous adhesive Fixomull that is commonly used in practice to attach sensors to the skin.

2.5. Statistics

T_{sk} data were recorded and presented every minute. Statistical analysis were performed using IBM SPSS Statistics 26.0. Effects were considered significant if $P < 0.05$. Data are presented as means and standard deviations (SD). The Shapiro-Wilk test was used to check if the data was normally distributed. To assess the effect of environmental condition on control T_{sk}, a one-way ANOVA was conducted employing the independent variable environmental condition (temperate, hot-humid and hot-dry). This was done separately for the short and continuous sweat sampling method. Secondly, the effect of sweat sampling over time on T_{sk} was analyzed using a two-way ANOVA (sampling × time) for both sampling methods (short and continuous sampling) and three environmental conditions (temperate, hot-humid and hot-dry) separately. If there were significant effects, specific post-hoc analyses were conducted with the alpha adjusted accordingly using Bonferroni corrections.

3. Results

3.1. The effect of environmental condition on control T_{sk}

There was a significant main effect of environmental condition on control T_{sk} during both short and continuous sampling methods ($P < 0.001$; table 1). Post-hoc analysis revealed that for both sampling methods, control T_{sk} was significantly higher in the hot-dry and hot-humid compared to the temperate condition ($P < 0.001$; table 1). For both sampling methods, control T_{sk} was also significantly higher in the hot-dry than the hot-humid condition ($P < 0.001$; table 1).

3.2. The effect of short and continuous sweat sampling on T_{sk}

The sampling × time interaction was non-significant in the hot-humid and hot-dry condition for both sampling methods ($P \geqslant 0.177$; figure 2). In the temperate condition, there was a significant sampling × time interaction due to continuous sampling ($P < 0.001$), but not due to short sampling ($P = 0.845$). Post-hoc analysis revealed that the sampling × time interaction was significant from min 1–2 ($P \leqslant 0.047$; figure 2). This indicates that due to continuous sampling the T_{sk} pattern increased more from min 1–2 compared to control. After that, sampling and control T_{sk} patterns over time were similar ($P \geqslant 0.072$), indicating that the initially elevated T_{sk} remained throughout the protocol.

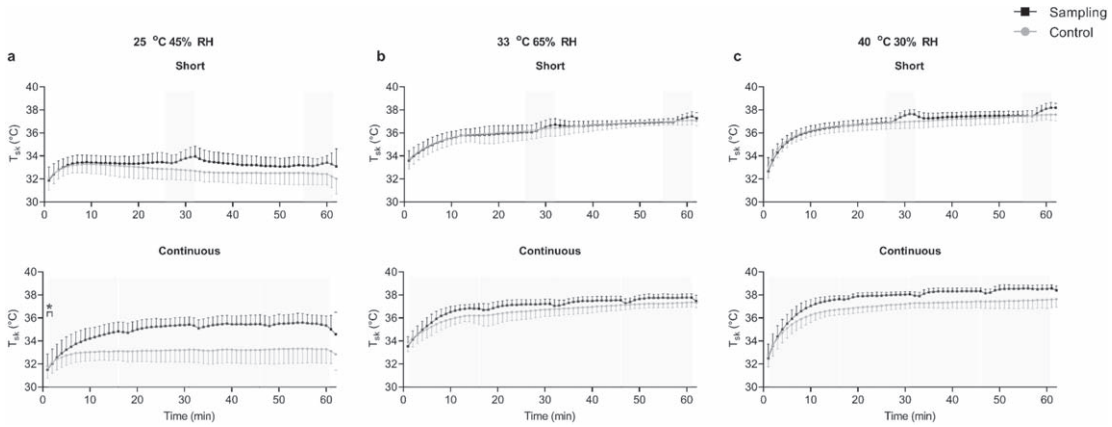

Figure 2. The effect of short application (i.e. from min 25–30 to min 55–60; upper panels) and continuous application (i.e. consecutive 15 min periods; lower panels) of absorbent sweat patches on skin temperature (T_{sk}) in (a) a temperate (25 °C 45% RH), (b) hot-humid (33 °C 65% RH) and (c) hot-dry condition (40 °C 30% RH). Values represent mean ± SD. Black squares represent the sweat sampling conditions. Gray circles represent control (i.e. no sweat sampling). The short decreases in continuous sampling represent replacement of absorbent patches. The light gray rectangles indicate sweat sampling periods. * Denotes a significant ($P < 0.05$) interaction of sweat sampling *x* time ($n = 10$).

4. Discussion

Sweat absorbent patches are a convenient sweat sampling technique for both LSR and sweat content but their impact on local microclimate T_{sk} in different conditions is not well known. This research is important because large differences in local T_{sk} can modulate the sweat response. The present study showed that neither short (i.e. from min 25–30 to min 55–60) nor continuous application (i.e. four consecutive 15 min periods) of absorbent sweat patches significantly affected T_{sk} underneath the patches in two environmental conditions (hot-humid: 33 °C 65% RH and hot-dry: 40 °C 30% RH). In a temperate condition (25 °C 45% RH), short application of sweat patches had no effect either, but continuous application led to an immediate significant increase in T_{sk} (1.8 ± 0.6 °C) underneath the patches. This elevated T_{sk} remained throughout the experiment.

4.1. Effect of absorbent sweat patch application

In the present study, there was no effect of short and continuous application of absorbent sweat patches on T_{sk} in the hot-humid condition. During heat stress, the most prominent autonomic (i.e. involuntary) thermoregulatory responses are vasodilation and evaporation of sweat. Vasodilation increases T_{sk} by internal conductive heat exchange between tissue and blood, which in turn increases convective and radiant heat loss from the skin to the environment. Convective heat loss through vasodilation is a function of the air velocity over the body surface area. In addition, convective and radiant heat loss are a function of the temperature gradient between the air and skin. If the environmental temperature is high, the temperature gradient between air and skin is small, which decreases the effectiveness of vasodilation. Therefore, in hot environments the evaporation of sweat is the most prominent autonomic thermoregulatory response (Taylor 2014, Periard *et al* 2015, Cramer and Jay 2016). The driving force for evaporation of sweat is the difference in vapor pressure between the skin and air (Parsons 2014, Cramer and Jay 2016). In a hot-humid environment, evaporation of sweat is difficult due to the high water vapor content of the air (Parsons 2014, Cramer and Jay 2016). Covering the skin with absorbent material with an impermeable layer on top also inhibits the ability to evaporate sweat. Since this heat loss mechanism is already suppressed due to the environment, the added effect of the application of sweat patches may be negligible, explaining our finding.

In the hot-dry condition, there was again a statistically non-significant T_{sk} elevation over time by applying sweat patches. In dry heat, the vapor pressure difference between skin and air is relatively large, allowing for evaporation of sweat. Due to the high environmental temperature (40 °C) compared to T_{sk} (~36.7 °C), there was most likely no heat loss but rather heat gain through convection and radiation (assuming radiant temperature was identical to air temperature) (Parsons 2014, Cramer and Jay 2016). Suppressing the evaporation of sweat, on which the body heavily relies in the hot-dry condition, could explain the slightly larger elevations in T_{sk} compared to the hot-humid condition. However, this effect did not reach statistical significance either. Because there was dry heat gain already, adding the absorbent patch probably did not contribute to any further significant increase in T_{sk}.

In contrast, there was an effect of the continuous application of absorbent sweat patches on T_{sk} in the temperate condition. In this condition, the temperature gradient between air and skin was relatively large,

allowing for convective and radiant heat loss (Parsons 2014, Cramer and Jay 2016). In addition, the vapor pressure gradient between air and skin was also relatively large, allowing for evaporation of sweat. In terms of heat loss from the human body, this condition was considered most beneficial. Thus, in the most beneficial condition, the T_{sk} effect of prolonged absorbent patch application on T_{sk} is considerable. As mentioned in the introduction, this significantly higher T_{sk} could affect the processes of sweating (Nadel *et al* 1971a, 1971b, Cotter and Taylor 2005, Shibasaki *et al* 2006, Gerrett *et al* 2019) and should therefore be avoided.

4.2. Minimal relevant difference

During single absorbent patch applications, elevations in T_{sk} ranged from 0.05 °C ± 0.1 °C to 0.8 °C ± 0.1 °C using the short method (i.e. sampling for 5 min) and from 0.4 °C ± 0.3 °C to 2.2 °C ± 0.1 °C using the continuous method (i.e. sampling for 15 min). The smallest elevations were observed in the hot-humid condition and the largest elevations in the temperate condition. In relation to this, Nadel *et al* (1971a), (1971b) showed that when maintaining a constant esophageal temperature, a 1 °C higher whole-body T_{sk} (from 34.0 °C to 35.0 °C and from 35.0 °C to 36.0 °C) corresponded to a ~0.18 $mg.cm^{-2}.min^{-1}$ higher LSR at the thigh. This was reported in the presence of a whole-body T_{sk} elevation, whilst the local T_{sk} underneath their ventilated capsule remained 34.8 °C throughout. In the present study, the T_{sk} manipulation was only local. To our knowledge, the effect of a local T_{sk} elevation on LSR is not quantified. Yet previous research suggests that a higher local T_{sk} affects neurotransmitter release at the neuroglandular junction (Ogawa 1970, Ogawa and Asayama 1986, DiPasquale *et al* 2003), causing a higher LSR. The largest mean elevation in T_{sk} (2.2 °C ± 0.1 °C; figure 1) was observed using the continuous method (fourth patch) in the temperate condition. Previous research by Gerrett *et al* (2019) reported higher reabsorption rates in the eccrine sweat gland if T_{sk} increased by more than 6 °C. The discrepancy between these values is large and therefore the eccrine sweat glands reabsorption rates are not expected to be affected by the continuous absorbent patch application. Since the sweat glands reabsorption rate determines the final sweat sodium and chloride concentrations, sweat composition is not expected to be affected by short nor continuous absorbent sweat patch application. This has important applications for field work or laboratory studies investigating sweat content.

4.3. Practical implication

The proposed method by Smith and Havenith to gravimetrically determine LSR using absorbent patch application for 5 min (Smith and Havenith 2011, 2012) generally does not allow for collection of enough sweat for chemical analysis. This relatively short application time is recommended to allow for a steady sweat rate and to prevent hidromeiosis underneath the patches, which could affect the sweat response (Brown and Sargent 1965, Candas *et al* 1984). For sweat content research, Baker and colleagues typically applied the absorbent patches upon moderate sweat absorption (~0.5 g) from different body regions. Application times ranged from ~15 min at the forehead to ~48 min at the calf, and they removed the patches before saturation (Baker *et al* 2009, 2014, 2016, 2019). During sweat testing in the field, longer sampling periods up to 60 min were reported due to practical reasons (Alvear-Ordenes *et al* 2005, Stofan *et al* 2005, Henkin *et al* 2010). In laboratory settings, absorbent patches were left on the skin for ~15–30 min (Schwartz and Thaysen 1956, Lobeck and Huebner 1962, Verde *et al* 1982, Goulet *et al* 2017, Baker *et al* 2018, Klous *et al* 2020a, 2020b). However, Morris *et al* (2013) explicitly recommend to limit patch application time to 5 min to mitigate the effect of a microenvironment on LSR. Based on experience from our lab, slightly longer consecutive sampling periods of ~15 min are required to collect enough sweat from the upper arm and back for duplicate chemical analysis of more than two components (Klous *et al* 2020a, 2020b). The scapula and upper arm were chosen respectively because of the relatively high LSR (Smith and Havenith 2011, 2012) and preferred location for wearables (Gao *et al* 2016). As was shown in the present study, only continuous sweat sampling (i.e. four continuous 15 min sampling periods) in the temperate condition (25 °C 45% RH) caused a significantly elevated T_{sk} underneath the patches (largest increase: 2.2 °C ± 0.1 °C). To avoid any detrimental effects of absorbent sweat patch application on T_{sk}, continuous sweat sampling should not be performed in temperate conditions. To summarize, timely removal of sweat patches should be taken into account during long periods of collecting sweat in field or laboratories settings.

4.4. Limitations

A limitation to the present study could be that female menstrual cycle phase was not controlled. It is known that core temperature is regulated ~0.4 °C higher in the luteal compared to the follicular phase of the menstrual cycle (Kolka and Stephenson 1993). Few studies have examined the effect of menstrual cycle phase on T_{sk} and thus far results are equivocal. Part of the studies found an increased T_{sk} in the luteal phase, whilst other observed no differences relative to the follicular phase (Marsh and Jenkins 2002, Baker *et al* 2020). In the luteal phase, the onset of sweating is delayed, yet vasodilatation is increased. The net result of these processes may be a negligible

change in T_{sk} caused by menstrual cycle phase. Secondly, since short sweat sampling was investigated on the scapula and continuous sampling on the arm, there could have been an effect of skin site on our outcomes. However, since the mean differences in control T_{sk} between skin sites were very minimal (reaching from 0.1 °C to 0.4°C; table 1), an effect of skin site is not expected. Furthermore, the effect of absorbent patch application occurred relatively fast (after 2 min of sampling) using the continuous sampling method in the temperate condition. Logically, this difference was expected to occur after at least 5 min of sampling because there were no significant differences found using the short sampling method in the same environmental condition. However, continuous sweat sampling started immediately at the onset of exercise whilst the first short sweat sampling period was 25 min into exercise (figure 1) during which we might expect to see an elevated T_{sk}. It is known that ~5–10 min are required for sweating to occur (Cotter *et al* 1997) and sweating lowers T_{sk}. Since most likely sweating (i.e. cooling the skin) did not occur during the largest part of the first continuous sweat sampling period but vasodilation did occur (i.e. heating up the skin), the fast increase in T_{sk} could be explained. However, this is true for all three conditions but only in the temperate conditions a significant T_{sk} increase was observed. Conductive and radiative heat loss through vasodilation are already limited or even heat gain occurs in the hot-humid and hot-dry condition respectively. In the temperate condition, the potential for conductive and radiative heat loss was the largest, apparently causing the largest effect of absorbents on T_{sk}. It would be interesting if future research allows for steady-state before starting a sweat sampling procedure.

5. Conclusions

Neither short (i.e. from min 25–30 to min 55–60) nor continuous application (i.e. four consecutive 15 min periods) of absorbent sweat patches affected skin temperature underneath the patches in a hot-humid (33 °C 65% RH) and hot-dry condition (40 °C 30% RH). In a temperate condition (25 °C 45% RH), short application of sweat patches did neither, but continuous application led to an elevated local skin temperature. To avoid a significant increase in local skin temperature underneath sweat patches, continuous application should be prevented in a temperate condition. Such findings should be taken into account when collecting sweat in field or laboratories settings.

Acknowledgments

We would like to thank the participants who dedicated their time to this research.

Funding

This research was supported by Eurostars under grant number 17213; and by The Dutch Research Council under grant number NWO 690462.

Conflict of interest

The authors declare that they have no conflict of interest.

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