

1 **Simultaneous imaging of multi-pore sweat dynamics and evaporation rate measurement**
2 **using wind tunnel ventilated capsule with infrared window**

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19 **Summary**

20 Sweat evaporation is critical to human thermoregulation, but current understanding of the
21 process on 20 μ m-to-2cm scale is limited. To this end, we introduce a wind tunnel shaped
22 ventilated capsule with an infrared window for simultaneous infrared sweat imaging and
23 evaporation rate measurement. Implementing the capsule in pilot human subject tests suggests
24 that the common assumption of sweat being an isothermal film is only valid when the evaporation
25 rate is low, and sweat forms puddles on the skin. Before transitioning to this filmwise mode,
26 sweating occurs in cyclic dropwise mode, displaying a 3x higher mass transfer coefficient in the
27 same conditions. Imaging highlighted distinct phenomena occurring during and between these
28 modes including out-of-duct evaporation, pulsating droplets, temporary and eventually lasting
29 crevice filling, and individual drop-to-film spreading. In all, sweat evaporation is an impactful area
30 that our results show is ripe for exploration, which can be achieved quantitatively using the
31 introduced platform.

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38 **Keywords:** sweat evaporation, midwave infrared imaging, ventilated capsule, droplets dynamics

39 **INTRODUCTION**

40 Considerable cooling off by sweat evaporation is a distinctively human feature. Having
41 evolved about ten times higher eccrine sweat gland density than other primates^{1,2} let human
42 ancestors thrive in hot savannahs without overheating. Similarly, maximizing body,^{3,4} rather than
43 surrounding,⁵ cooling achieved by evaporation of secreted sweat is critical for coping with
44 increasingly frequent extreme heat events.^{6–8} Much like insight into underlying droplet and phase-
45 change dynamics yielded improvements in industrial applications such as ink jet printing,^{9–12} a
46 better quantitative understanding of the sweat evaporation mechanisms could yield ways to
47 optimize body cooling achieved with the process (e.g., improved fabrics,^{13–16} actively ventilated
48 clothing,^{17,18} or recommendations for fan use during heat waves^{19,20}). Such fundamental
49 knowledge could also contribute to our basic understanding of wetness perception^{21,22} and benefit
50 other applications, including the design of cosmetics^{23,24} and sweat sensors.^{25–28}

51 While sweat production and secretion onto the skin has been characterized across length
52 scales, from biochemical generation mechanisms to microfluidics of secretion and its rate
53 variation at different skin regions,^{2,21,29–34} its evaporation has been approached almost exclusively
54 from large skin regions or a whole-body perspective (i.e., microscale understanding of the process
55 is lacking).^{2,35–40} Most common efforts to study the evaporation process from large skin regions
56 use sweating instruments (from thermal manikin^{41,42} to torsos,^{43,44} plates,^{45,46} and even single
57 "ducts"^{23,47}) in the context of improving performance and safety apparel.^{48,49} The most
58 anatomically realistic of the instruments, thermal manikins, dispense water onto a hard surface
59 covered by a highly wicking and tightly fitting fabric (other approaches, including sintered porous
60 metals and skin-like artificial sweating skins, exist⁵⁰ but are not used to understand sweat
61 evaporation).⁵¹ The wet-fabric approach mimics regional evaporation in the filmwise mode with
62 fully wetted skin but cannot represent insensible or dropwise sweating modes or transitions
63 between them (e.g., sweating onset or drying). From the theoretical side, sweat is most commonly
64 treated as a thin isothermal film at underlying skin temperature.^{38,39} This film's evaporation rate is

65 modeled using the Lewis analogy that relates the convective heat transfer and mass transfer
66 coefficients through a constant.⁵² While the isothermal thin film representation is helpful in apparel
67 design and thermoregulation modeling, it cannot provide insight into finer mechanisms of sweat
68 secretion and evaporation.

69 To enable quantitative studies of the "multi-pore" scale (~20 μm to 2 cm) mechanisms of sweat
70 evaporation, we synthesized methods employed by physiologists and engineers to create a
71 platform for simultaneous sweat dynamics imaging and measurement of its evaporation rate in a
72 realistic environment. In particular, we altered the geometry of ventilated capsules used by
73 physiologists for over a century² to measure sweat secretion rate based on wind-tunnel design
74 guidelines and enabled midwave infrared imaging (MWIR: 3 to 5 μm) of the skin through addition
75 of a sapphire window. **Figure 1A** shows that traditional ventilated capsules are cylindrical^{2,53,54}
76 (with one rectangular exception⁵⁵), which induces highly swirling flow that facilitates evaporation
77 of all sweat secreted onto the skin (i.e., the point of the physiological measurement). In contrast,
78 flow simulations in **Figure 1A** show that the altered capsule with a diffuser and a rectangular flow
79 section should promote a uniform flow across the skin that might be encountered in realistic
80 situations such as walking or within a skin-clothing gap. In addition, the objective is for the flow
81 within the capsule to be repeatable and readily computationally replicable to enable systematic
82 interpretation of underlying physical mechanisms *in vivo* observation.

83 **Figure 1B** shows that the sapphire window is above the exposed skin area and enables high-
84 resolution MWIR thermographic imaging. Out of the numerous sweat visualization approaches
85 that range from applying water-sensitive coatings on skin² (or rolling films containing them across
86 forehead⁵⁶) to advanced two or three-dimensional microscopy,⁵⁷⁻⁶⁴ we selected MWIR
87 thermography because it has several advantages demonstrated in prior imaging of mental
88 sweating (i.e., rapid and short-lasting in response to non-thermal stimuli).^{65,66} The peak in the
89 absorption of water at 3 μm makes the technique sensitive even to thin films of the liquid,^{67,68} while

90 also providing fast imaging (10 Hz or more) over the relevant area (2 cm^2) with resolution sufficient
91 to capture even small sweat pores ($\sim 20 \mu\text{m}$). We validate that the altered capsule geometry yields
92 uniform flow over the surface using particle image velocimetry (PIV) and benchmark the
93 evaporation rate measurements using simple artificial surfaces, wherein liquid film of specified
94 size is formed. Next, we implement the device in a pilot human trial, yielding illustrative
95 evaporation rates and multi-pore scale sweat surface dynamics for the various stages of human
96 perspiration. We use image analysis to quantify wet skin area fraction and relate it to the
97 evaporation rate. We conclude by discussing the limitations of the ventilated capsule and imaging
98 techniques highlighted by the pilot trial and approaches to mitigate these issues.

99 **RESULTS**

100 **The diffuser section creates uniform parabolic flow in the ventilated capsule**

101 The diffuser section with a 3° expansion half angle recommended for wind tunnel design⁶⁹
102 enables a smooth transition from the circular air supply tube to the rectangular evaporation section
103 of the capsule and promotes the formation of the Hagen-Poiseuille flow. In particular, the PIV-
104 visualized plane flow field in **Figure 2A** and velocity profiles in **Figure 2B** reveal the desired
105 laminar parabolic flow,⁷⁰ that is expected of laminar conditions, within the evaporation section
106 across relevant air flow rates (up to $1 \text{ L}\cdot\text{min}^{-1}$ equivalent to mean speed of $9.25 \text{ cm}\cdot\text{s}^{-1}$). These
107 experimental flow profiles are also readily replicated using simulations (see **Figure 2B**). In
108 contrast, flow in a wide-angle diffuser with a half angle of 6° can reverse near the walls, while that
109 in a sudden tube-to-rectangle expansion transition section (i.e., half angle of 90°) creates a high-
110 velocity core and undesired stagnation regions near the walls (see the Supplemental
111 Information—SI). Having demonstrated that the 3° half angle diffuser minimizes the flow
112 separation and promotes the desired and readily computationally replicable Hagen-Poiseuille

113 flow, we integrate the humidity probe into the capsule and benchmark the evaporation rate
114 measurement.

115 **Optimization of capsule-humidity probe integration and evaporation rate validation using**
116 **artificial sweating platform**

117 We fabricated a simple heated square water film setup to systematically integrate the humidity
118 probe into the ventilated capsule and benchmark the evaporation rate measurements (see **Figure**
119 **2C** and Methods Section for details). The evaporation rate from the film can be calculated as the
120 product of the air flow rate (\dot{Q}) set by the digital flow controller and the difference in the inlet (C_{in})
121 and outlet water vapor concentrations (C_{out}):⁷⁰

122
$$\dot{m}_e = \dot{Q}(C_{out} - C_{in}) \quad \text{Eq.1}$$

123 Since we utilize ultrapure dry air, we can assume that $C_{in} = 0$ and that $\dot{m}_e = \dot{Q}C_{out}$. Therefore,
124 evaporation rate measurement only requires a single humidity probe after the exposed wet area.
125 To facilitate the adoption of the wind tunnel capsule, we chose to use the cylindrical-tip humidity
126 probe commonly employed in ventilated capsules in physiological studies (see inset in **Figure**
127 **2D**).^{53,54} Similarly, we use unit convention employed in physiology.^{53,54} Specifically, we report \dot{Q}
128 in $\text{L}\cdot\text{min}^{-1}$, C_{out} in $\text{g}\cdot\text{m}^{-3}$, and \dot{m}_e in $\text{mg}\cdot\text{min}^{-1}$ (or \dot{m}_e per cm^{-1} where relevant), which, due to the
129 canceling of conversion factors, can be conveniently obtained by multiplying the flow rate and
130 concentration in provided units.

131 To validate our evaporation rate measurements, we conducted two types of film evaporation
132 experiments at \dot{Q} of $0.5 \text{ L}\cdot\text{min}^{-1}$. First, we filled the etched square with water and let it evaporate
133 without replenishing the liquid. **Figure 2C** shows that in this experiment, the evaporation rate
134 exhibits a 20-min plateau at $1.6 \text{ mg}\cdot\text{min}^{-1}$ followed by a rapid decrease corresponding to the film
135 dry-out phase. In the second experiment, we adopted the evaporation rate benchmarking

136 approach employed previously in experiments on droplet evaporation.⁶⁸ In particular, we
137 continually supplied water to the square film at a rate of $1.6 \text{ mg}\cdot\text{min}^{-1}$ using a syringe pump. The
138 plot in **Figure 2C** shows that when water was replenished at the same rate as it evaporated, the
139 film dry out was avoided, validating our evaporation rate measurements. Next, we present the
140 results of additional efforts to ensure the probe location does not impact these measurements
141 under varied air flow rates.

142 The probe can provide an inaccurate measure of evaporated water if it is in a downstream
143 location where the vapor has not diffused across the entire cross-section of the capsule. If the
144 probe is located close to the evaporation area, the vapor concentration fields in the inset in **Figure**
145 **2D** show that only the bottom part of the cylinder is exposed to humid air. The plot in **Figure 2D**
146 shows that such partial exposure can lead to 30% underprediction of the outlet water vapor
147 concentration. We note that the underprediction of the experiments by simulations for the shortest
148 probe-test area separation distance of 2.5 cm likely stems from simplifying the probe
149 measurement area to an isotropic cylinder without specifically distributed perforations leading to
150 the sensing element (see probe image in inset in **Figure 2D**). Both simulations and experiments
151 performed using capsules with varied probe locations (see images in the inset) show that moving
152 the probe 5 cm or more downstream of the evaporation area resolves the issue, even for the
153 highest flow rate of $1 \text{ L}\cdot\text{min}^{-1}$. In that location, the entire probe surface is exposed to homogenous
154 water vapor concentration and measures values equal to those at the outlet (or measured with a
155 probe located further downstream). Next, we describe the implementation of the wind tunnel
156 ventilated capsule in pilot human trials.

157

158 **Pilot human trial: simultaneous sweat evaporation rate measurement and MWIR multi-pore**
159 **scale imaging**

160 ***Optimized experimental setup and protocol: how to mount the wind tunnel ventilated***
161 ***capsule on a subject to enable high-quality imaging***

162 To accommodate for the small depth of field of the MWIR camera, we minimized subject
163 motion and disturbance in images by placing the person in a supine position, passive heating,
164 and specialized capsule placement setup. As in many prior studies employing traditional
165 ventilated capsules,^{53,54} we heated the subjects by passing water at 48°C through tubing
166 integrated into a whole-body liquid perfused suit coupled with a constant temperature water bath
167 (see methods). Through iterative protocol design with seven subjects with two measurement sites
168 (forearm and forehead), we found the most consistent outcomes by placing the capsule on the
169 subject's forehead. We note that we exclude a "no heat strain" 34°C water perfusion period as
170 related studies⁵⁴ because, in a few cases, we observed sweat emerging from pores during this
171 step. We also found that high-quality imaging required more rigid fixing of the capsule than
172 obtained by gluing the capsules to the skin (as in prior studies). To achieve this, we fabricated a
173 wooden platform with a rail which facilitates easy positioning of the capsule over the subject's
174 forehead. We achieved coarse leveling of the subject's forehead by adjusting the level of the
175 underlying head section of the bed. For finer position and rotation adjustments, the mounting of
176 the capsule included two micrometers and rotational adjustment (see **Figure 1B**). We found that
177 MWIR videos acquired using this method can be digitally stabilized and quantitatively analyzed
178 through post-experimental image processing. Next, we describe example results of the capsule
179 implementation with single subject sweating progressing from the onset of cyclic dropwise to
180 established filmwise modes.

181 ***From the onset of cyclic dropwise to established filmwise sweating with constant air flow***
182 ***rate***

183 Within 40 min of the MWIR detection of the first sweat droplet on the skin, the fraction of the
184 wet skin increases to 0.3 while the evaporation mass flux increases from 0.15 to 0.8 $\text{mg}\cdot\text{min}^{-1}\text{cm}^{-2}$
185 (see **Figure 3A-B**). The MWIR images in **Figure 3C-F** and corresponding **Movies S1-5** show
186 the emergence and transition between the cyclic dropwise and filmwise surface sweating modes,
187 each displaying unique microscale dynamics. At the onset, sweat emerges onto the skin surface
188 in droplet (circular) mode within distinct locations corresponding to sweat pores. The droplets are
189 visible for a few seconds before the sweat evaporates and/or withdraws below the surface (i.e., it
190 is no longer observable in the MWIR image). This process reoccurs periodically; therefore, we
191 refer to it as cyclic dropwise sweating mode. While oscillating, the number of active pores, and
192 thereby wetted surface area, progressively increases with time from just 1 to 3 at the onset to
193 about 60 after 15 min (see **Figure 4A**). The wet surface area increases proportionally to the
194 number of active pores, up to 0.1 cm^2 or 0.05 (i.e., 5%) of the 1.93 cm^2 of exposed skin area (see
195 **Figure 4B**). According to a linear fit to this data, the wet area increases 0.145 mm^2 for each
196 droplet, equivalent to an average droplet having a 0.43 mm diameter. We observed about 3,500
197 individual droplets that, naturally, display a much wider range of diameters and durations. **Figure**
198 **4C** shows examples of droplets that briefly emerge from the same pore for 1-2 s and only spread
199 about 0.1 mm beyond the pore (a maximum diameter of 0.2 mm). The figure also shows an
200 example of a droplet that emerges from a different pore for 17 seconds and spreads far beyond
201 its location of origin (a maximum diameter of 0.9 mm). **Figure 4D** shows that there is a trend for
202 larger droplets lasting longer, while there are also many smaller droplets lasting more than 5 s.
203 However, the histograms of the maximum droplet diameters and durations in **Figure 4E-F** show
204 that short-lasting and small droplets occur most often. After about 15 min, new sweat surface
205 dynamics begin to emerge, indicating the beginning of a transition away from the "pure" cyclic
206 dropwise sweating mode hallmarked by the near-circular and non-interacting droplets.

207 The first feature of the shift away from pure dropwise sweating mode is the temporary filling
208 of parts of crevices connected to active pores, which is followed by the formation of lasting (i.e.,
209 not oscillating) irregularly-shaped sweat puddles and droplet-to-film transitions (see **Figure 3E-F**). In the MWIR images and movies, the filling of a crevice by sweat emerging from a pore is
210 displayed as gradual and reversible darkening of up to 0.5 mm of the lighter-colored lines in
211 contact with the droplet. Initially, this process is reversible due to the likely combination of sweat
212 evaporation and retraction into the duct. However, as the transition progresses, the sweat spreads
213 further within the crevices and can connect multiple pores. Another significant feature of the
214 transition to filmwise mode is that many sweat droplets are present for longer duration, attain
215 irregular shape, and have gradually decreasing MWIR contrast at the edges. This trend is
216 highlighted in an example in **Figure 3F** of a near-circular dark droplet gradually spreading into
217 irregularly-shaped and substantially lighter puddle with difficult-to-define edges. Physically, these
218 image contrast changes stem from sweat droplets with a shape likely resembling a partial
219 spherical cap spreading into a shallow, film-like puddle. The top surface of the droplet is
220 substantially cooler than the skin temperature (i.e., is darker in the MWIR image) due to
221 evaporation and thermal resistance of the water droplet. In contrast, despite evaporating, a thin
222 sweat film poses a smaller thermal resistance, and therefore, its surface has a temperature much
223 closer to that of the nearby exposed skin.

225 The proliferation of the droplet-to-film spreading during the filmwise sweating stage translates
226 into a gradual increase in the evaporation mass flux and an increase in the rate sweat covers the
227 skin surface (see **Figure 3A-B**). However, the rate of surface wetting within the observation area
228 was slow compared to nearly entirely sweat-flooded skin on the outside of the capsule.
229 Considering the increasingly limited utility of the MWIR imaging of the established filmwise mode
230 (i.e., poor contrast making quantitative evaluation challenging) and the subject's comfort, we

231 accelerated the flooding of the skin surface by removing the capsule for 5 min. Next, we describe
232 experiments conducted to explore sweat dynamics during forced drying out of the film.

233

234 ***The drying out of filmwise sweating with stepwise increasing air flow rate***

235 We reattached the wind tunnel capsule on the nearly entirely sweat-covered subject's
236 forehead to observe sweat evaporation dynamics during forced drying out of the filmwise mode.
237 We doubled the air flow rate in three sequential steps. In particular, we set the air flow rate during
238 the sequential steps to 0.1, 0.2, 0.4, and 0.8 L·min⁻¹, with each step lasting 4 to 5 min. During the
239 experiment, we determined the step duration *in situ* based on the observed rate of change in
240 vapor concentration. The plots in **Figure 5A-B** show that after each step change in the air flow
241 rate, the probe measured vapor concentration and evaporation mass flux decay in a near
242 exponential fashion with an average fit-determined time constant of 1.5 min. This observation
243 implies that after 4 to 5 min, the evaporation mass flux values were within 5 to 10% of the quasi-
244 steady-state value, confirming our decision of time-window selection during the experiment is
245 appropriate.

246 The corresponding MWIR images in **Figure 5C** show that as the flow rate is increased, the
247 initial near-isothermal sweat film progressively recedes, exposing a substantially warmer surface
248 that is dotted by multiple cooler puddles corresponding to active pores (or pore ensembles) from
249 which sweat is continually expelled. Many of these exposed puddles cyclically enlarge and
250 decrease in size every few seconds, matching the oscillation period in the dropwise mode (see
251 **Movie S6**). After 5 min of the 0.8 L·min⁻¹ step, we decreased the air flow rate to the initial 0.1
252 L·min⁻¹. Within 5 min, the evaporation mass flux reaches the same value as at the end of the
253 corresponding prior step (ii vs. vi), while the distinct sweat puddles diffuse into wider and lower
254 contrast features (films) (**Figure 5B-C**). Next, we discuss our results in the context of prior

255 physiological literature, highlighting the pluses of evaluating sweating using our method and its
256 current limitations.

257

258 **DISCUSSION**

259 **The measured sweat evaporation rates and observed sweat dynamics match prior reports**

260 The sweat evaporation rate and multi-pore scale surface dynamics quantified using the wind
261 tunnel ventilated capsule closely match prior literature reports. Before heating of the subject, the
262 skin surface is dry, and the evaporation mass flux is $0.11 \text{ mg}\cdot\text{min}^{-1}\text{cm}^{-2}$, which is typical of
263 imperceivable perspiration^{2,30,54} (average of values from numerous studies yields a forehead
264 transepidermal water loss of $0.08 \text{ mg}\cdot\text{min}^{-1}\text{cm}^{-2}$).³⁰ After 25 min of heating, when the MWIR
265 observable sweat secretion onto the skin begins, the evaporation mass flux increases slightly to
266 $0.15 \text{ mg}\cdot\text{min}^{-1}\text{cm}^{-2}$. Subsequently, the time series in **Figure 3A** shows that the evaporation mass
267 flux increases to $0.8 \text{ mg}\cdot\text{min}^{-1}\text{cm}^{-2}$ over 40 min, which closely matches Rutherford et al.
268 measurements despite some differences in the subject heating protocol.⁵⁴ The time series in
269 **Figure 3B** shows that during this time, the fraction of wet area quantified using MWIR images
270 increases to 0.3, while the images visualize the sweating modes and related features.

271 The most prominent feature of dropwise sweating is its cyclic nature, which has been studied
272 for at least 80 years.^{64,66,71–78} While observed using various techniques, the reported cycle period
273 matches ours of 1.5 to 13 s (average of 6.2 s), which can be directly correlated to the oscillatory
274 sympathetic nerve activation of the sweat gland.⁷⁷ As previously reported in the literature for
275 thermal sweating on the forehead^{74,78} and other body parts,⁷³ **Figure 4A** shows that the number
276 of active sweat pores increases with time. The total number of active pores that we observed (up
277 to ~ 60 per 1.93 cm^2 , so $\sim 30 \text{ pore}\cdot\text{cm}^{-2}$) is lower than the ~ 150 to $185 \text{ pore}\cdot\text{cm}^{-2}$ average distilled

278 from numerous studies in the literature.³⁰ However, for individual subjects, such numbers can vary
279 drastically (e.g., 20 to 90 pore·cm⁻² for the same experiment⁷⁴). In addition, MWIR imaging is only
280 helpful in detecting the active pores in the early stages of sweating and not during profuse
281 sweating, which is often studied in physiology when more glands might be active (and, therefore,
282 a sweat film forms). This is likely why MWIR imaging has been used predominantly to study
283 mental sweating, which is too short for the transition from dropwise to filmwise mode.^{65,66}
284 Accordingly, prior MWIR sweat imaging studies did not observe the temporary crevice filling, pore
285 bridging through crevices, and droplet-to-film spreading features that occur during the sweating
286 mode transition (**Figure 3C**).

287 The spreading of sweat from pores into the crevices and eventual pore bridging is likely
288 facilitated by local stratum corneum hydration that causes water contact angle to decrease,
289 facilitating sweat flow into the skin "trough." The stratum corneum is the epidermis's outermost
290 layer, and its near-complete hydration takes about 5 min of continuous contact with the liquid.⁷⁹
291 In our experiments, the contact of the stratum corneum with sweat is cyclic, explaining why it took
292 at least 15 min before we observed crevice filling and, therefore, the hydration process. The
293 hydration process likely makes the surface more hydrophilic, facilitating the flow into the crevice
294 through capillary forces.⁸⁰ The contact of the stratum corneum with water droplets has been
295 reported to cause a gradual decrease of the contact angle over a few minutes.^{81,82} Our wettability
296 measurements were performed outside the capsule and only during major shifts in the
297 experiments (e.g., taking the capsule off), but do show that the contact angle decreased from
298 about 60 to 70° (matching the typical contact angle of unwashed skin⁸²) to below 10° (i.e.,
299 spreading into a film on sweaty skin) during the 40 min observation period. Consequently, the
300 stratum corneum hydration-enhanced wettability seems like a plausible mechanism driving the
301 crevice filling. However, a deeper investigation of the topic is warranted since the wettability of
302 skin is highly complex and, dependent on a myriad of factors, can range from highly hydrophobic

303 to hydrophilic.⁸¹⁻⁸³ Eventually, individual droplets begin to be connected through the sweat within
304 the crevices, initiating gradual flooding of the surface beyond the pores.

305 Bridging of pores via crevices and drop-to-film spreading, not classical droplet coalescence,
306 are the main mechanisms underlying switching the sweating mode to filmwise. In particular, even
307 in humid conditions, skin flooding through pinned droplet coalescence that drives dropwise-to-
308 filmwise condensation transition is unlikely because the typical sweat pore separation distance is
309 greater than the radius of most sweat droplets. Besides hands and feet, the forehead has one of
310 the highest sweat pore densities on the body. The average 185 pore·cm⁻² forehead pore density³⁰
311 translates to about 0.7 mm separation distance on a hypothetical square grid distribution. The
312 cumulative distribution histogram in **Figure 4E** shows that 95% of maximum droplet diameters
313 are below 0.7 mm, making coalescence of two large droplets emerging from neighboring pores
314 highly unlikely. Our observations show that instead of coalescing, most individual droplets on the
315 surface spread into a film (see **Figure 3F and Movie S6**). The 3 to 5 min period for this transition
316 correlates with the time required for hydration of the stratum corneum, suggesting a decrease in
317 skin wettability surrounding the droplet as a likely underlying mechanism. Therefore, the transition
318 from dropwise to filmwise sweating and progressive covering of the skin with a patchy sweat film
319 occurs through crevice-mediated pore bridging and drop-to-film transition, both likely driven by
320 stratum corneum hydration. Collectively, these pore-level sweat features contribute to an increase
321 in the rate of surface wetting between the two modes (see **Figure 3B**), but the impact of this
322 process is only illuminated when it is directly compared against the measured sweat evaporation
323 rate.

324

325 **Simultaneous sweat evaporation rate measurement and quantitative imaging reveal that**
326 **the mass transfer coefficient in dropwise mode is 3x higher than in filmwise mode**

327 Employing the wind tunnel ventilated capsule, we can simultaneously quantify and relate to
 328 each other the sweat evaporation rate and multi-pore scale surface dynamics in realistic
 329 conditions that can be readily replicated computationally and experimentally with artificial
 330 sweating surfaces. **Figure 6A** synthesizes the time series in **Figure 3** into a single plot relating
 331 the measured sweat evaporation mass flux and the wet area (or its fraction). In this perspective,
 332 the drastic difference in the regional slope makes the dropwise and filmwise modes immediately
 333 distinguishable. In particular, the rate of increase of the evaporation mass flux with wet area in
 334 the dropwise mode is more than three times higher than that in the filmwise mode. Remarkably,
 335 the simple square water film evaporation experiments and simulations varying the square area
 336 quantitatively replicate the filmwise sweat evaporation results (see **Figure 6A**, the surface
 337 temperature in additional simulations and experiments was set to 34°C corresponding to the
 338 average observed in MWIR images of the filmwise mode).

339 The observed differences between dropwise and filmwise sweating modes can be
 340 quantitatively understood by considering the basic equation used to calculate the evaporation rate
 341 from an isothermal water or sweat film that covers a "wet" area (A_{wet}) that is only a fraction of the
 342 total area (A_{total}):⁷⁰

$$343 \quad \dot{m}_e = A_{wet} h_m (C_{sat}(T_{sur}) - C_{\infty}) = \omega A_{total} h_m (C_{sat}(T_{sur}) - C_{\infty}) \quad \text{Eq.2}$$

344 Where $\omega = A_{wet}/A_{total}$ is the wet surface area fraction, h_m is the mass transfer coefficient,
 345 $C_{sat}(T_{sur})$ is the saturation water vapor concentration at the exterior film surface temperature
 346 (T_{sur}), and C_{∞} is the water vapor concentration outside the mass boundary layer. Since for our
 347 experiments $C_{\infty} \approx 0$, we can re-cast **Eq.2** in terms of evaporation mass flux (\dot{m}_e''):

$$348 \quad \dot{m}_e'' = \dot{m}_e / A_{total} = \omega h_m C_{sat}(T_{sur}) \quad \text{Eq.3}$$

349 This leads to the derivative of the evaporation mass flux vs. wet surface area fraction (i.e., slope
350 in **Figure 6A**) being:

351
$$\frac{d\dot{m}_e}{d\omega} = h_m C_{sat}(T_{sur}) \quad \text{Eq.4}$$

352 The surface temperature, and therefore the $C_{sat}(T_{sur})$, does not vary substantially between the
353 two sweating modes. Consequently, the drastic difference between the slope for the two sweating
354 modes stems from the tripling of the mass transfer coefficients between the filmwise and dropwise
355 modes.

356 A large part of the three-fold difference between the mass transfer coefficient in the dropwise
357 and filmwise sweating modes is geometrical, but other more nuanced mechanisms are also likely
358 to contribute. Sweat emerges from pores driven by a positive pressure gradient³⁴ and has been
359 observed on fingertips⁶⁰ and assumed in simulations⁶⁴ to have a spherical cap shape. Accordingly,
360 a two-fold increase in the mass transfer coefficient could be attributed to the geometrical
361 difference between the surface of a circle imaged by MWIR and the hypothetical hemispherical
362 shape of the sweat droplets.⁶⁴ Naturally, the evaporation of a droplet that is replenished from
363 beneath is highly complex^{68,84,85} and unlikely to result in a doubling of the evaporation rate
364 compared to evaporation of a wet circle. However, even the idealized "geometrical" doubling of
365 the mass transfer coefficient requires additional mechanisms to explain the three-fold difference
366 between the two sweating modes. The most likely explanation is that substantial evaporation
367 occurs within the duct before the sweat emerges onto the skin^{32,86} and can be observed with the
368 MWIR camera. Such "out-of-the duct" evaporation has been implied by large sweat loss of
369 subjects exposed to arid conditions despite their skin remaining dry.^{30,87,88} In all, our pilot
370 experiments indicate that sweat evaporation in the dropwise mode is substantially different than
371 in the filmwise mode. As for the latter mode, the quantitative agreement of our *in vivo* results with
372 simulations and experiments of evaporating square films implies that it can be approximated as

373 the evaporation of a partial, isothermal, thin sweat film. However, substantially more complex
374 trends emerge when the filmwise sweat evaporation rate increases under higher air flow rates.

375

376

377 **At high evaporation rates, the filmwise sweating mode is more complex than the**
378 **isothermal thin film assumption**

379 The filmwise evaporation mass flux increases with air flow rate despite the MWIR observable
380 surface area decreasing substantially (see **Figure 6B** and **Figure 5C**). In addition, the evaporation
381 mass flux measured on the skin increases faster with air flow rate than simulations of isothermal
382 thin square film and corresponding experiments would suggest (see **Figure 6B**). This trend holds
383 even if the temperature of the simulated film is increased from 34 to 36.5°C or its area is increased
384 from 0.64 to 1 cm². It is rather apparent in the MWIR imaging (see **Figure 5C** and **Movie S6**) that
385 filmwise sweating under a high evaporation rate is more complex than an isothermal film
386 representation. Besides the re-appearance of pulsating sweat, albeit in puddles, not droplets,
387 large temperature gradients emerge on the surface. The higher local surface temperature does
388 not necessarily imply it is dry; sweat films as thin as 60 μm have been measured using optical
389 coherence tomography (OCT).⁵⁷ Instead, the large temperature gradients likely indicate that the
390 thickness of the sweat films across different puddles is highly varied.

391 We can use thermal circuit analysis to support the assertion that non-uniform surface
392 temperature at high evaporation flux implies non-uniform water film thickness. In particular, we
393 can estimate that for evaporation mass flux of 2 mg·min⁻¹cm⁻², which with latent heat of sweat of
394 2430 kJ·kg^{4,70} at 30°C is equivalent to an evaporative heat flux of about 800 W·m⁻², a 60 μm and
395 a 2 mm thick water film would result in 0.07°C and 2.7°C skin-to-exterior film surface temperature

396 difference. In contrast, at the lower evaporation mass flux of $0.8 \text{ mg} \cdot \text{min}^{-1} \text{cm}^{-2}$, which is equivalent
397 to an evaporative heat flux of about $325 \text{ W} \cdot \text{m}^{-2}$, the temperature drop even across the 2 mm thick
398 water film is only 1°C . These calculations explain why, at the lower evaporative mass fluxes
399 observed at $0.1 \text{ L} \cdot \text{min}^{-1}$, the exterior temperature in filmwise mode is relatively uniform (e.g., see
400 MWIR image for 40 min in **Figure 3F**). This characteristic leads to a uniform surface water vapor
401 concentration and evaporation rate, which enables quantitative agreement of the *in vivo*
402 measurements with simulated and experimentally measured evaporation from square water films.
403 In contrast, such agreement between *in vivo* and simulated/experimental square film results
404 breaks down when the evaporation rate is higher because the non-uniform thickness of water film
405 puddles on the skin leads to a highly non-uniform exterior temperature, water vapor concentration,
406 and evaporation rate. Therefore, even the filmwise sweat evaporation rate in many conditions
407 does not agree with the commonly assumed isothermal thin film sweat representation.

408 In summary, to quantitatively study the sweat evaporation process on the $20 \mu\text{m}$ to 2 cm scale,
409 we introduced a wind tunnel-shaped ventilated capsule with a sapphire window that enables
410 simultaneous evaporation rate measurement and multi-pore level imaging. The addition of the
411 diffuser with a 3° half-angle provides parabolic flow within the rectangular section that is more
412 realistic than the "cyclone" within traditional cylindrical capsules and could mimic real conditions
413 (e.g., flow in-between clothing and skin or slow walking in calm wind conditions). We showed that
414 this flow can be readily replicated computationally and over artificial sweating surfaces, facilitating
415 quantitative interpretation of the *in vivo* experiments. For example, coupling of our experimental
416 method with thermofluidic and bioheat transfer simulations developed by Drexelius et al.⁶⁴ could
417 be used to validate or advance modeling to provide accurate sweat droplet evaporation rate
418 prediction solely based on infrared imaging.⁶⁴ We demonstrated that the humidity probe integrated
419 into the capsule provides accurate evaporation rate measurements across 0.1 to $1 \text{ L} \cdot \text{min}^{-1}$ inlet
420 air flow rate using experiments with square water films and complementary multiphysics

421 simulations. We also developed the experimental setup and protocols for implementing the wind
422 tunnel ventilated capsule with MWIR imaging in human subject experiments.

423 The pilot human subject experiment employing the wind tunnel ventilated capsule suggests
424 that the common representation of sweat as an isothermal thin film is only locally applicable in
425 limited cases and revealed numerous features of multi-pore level sweating dynamics. In
426 particular, our preliminary results suggest that the mass transfer coefficient for sweat evaporation
427 in the cyclic dropwise mode is three times higher than in the filmwise mode. In addition, the
428 agreement of square film simulations and experiments with in vivo results in **Figure 6A** shows
429 that the latter mode is well approximated by an isothermal film only under low to moderate
430 evaporative mass flux (e.g., 0.5 to 0.8 $\text{mg}\cdot\text{min}^{-1}\text{cm}^{-2}$). Under more intense evaporation, the large
431 heat flux likely leads to substantial differences in temperature drop across thin and thick water
432 puddles and, therefore, a highly non-isothermal exterior surface (e.g., see bottom images in
433 **Figure 5C**). Besides variations in temperature of the film puddles, the in vivo experiments also
434 directly showed or implied several other multi-pore scale sweating features illustrated in **Figure**
435 **6C**, including out-of-duct evaporation and pulsating droplets in the cyclic mode and stratum
436 corneum hydration mediated crevice filling, pore bridging through crevice filling, and drop-to-film
437 evolution in the transition to and in the filmwise mode. Although our results are preliminary, as we
438 imaged only a single glabrous skin site on one subject, they suggest a plethora of intriguing micro-
439 to-macroscale liquid-phase phenomena occurring during sweating that significantly impact its
440 evaporation. Considering how important it is to our thermoregulation in hot climates and other
441 applications, sweat evaporation is an impactful area that is ripe for exploration, which can be
442 achieved quantitatively using the introduced experimental platform.

443

444

445 **Limitations of Study**

446 Implementing our method in the pilot human trial highlighted several limitations of the current
447 ventilated capsule design and MWIR sweat imaging. In keeping the ventilated capsule design and
448 experimental setup close to that used in physiological studies,^{53,54} we limited the lower end of
449 evaporation rates that we can impose. In particular, by only having a single humidity probe at the
450 capsule's outlet, we are restricted to using "ultrapure" dry air ($C_{in} = 0$). Consequently, even at the
451 lowest air flow rate of $0.1 \text{ L}\cdot\text{min}^{-1}$, we measured a mass evaporation flux that would be, in average
452 terms, in typical lab conditions (e.g., 24°C and 30% relative humidity) equivalent to the forehead
453 being exposed to a high wind speed of $8.5 \text{ m}\cdot\text{s}^{-1}$ (estimated using Eq.2 with $\omega = 0.3$, $T_{sur} = 34^\circ\text{C}$,
454 $\bar{h}_m = 0.00091\bar{h}_t$ via the Lewis analogy,³⁹ where $\bar{h}_t = 6.1V_{air}^{0.5}$ is the average heat transfer
455 coefficient for the head and V_{air} is the wind speed³⁹). We note that the transfer coefficients are
456 high because over the short length of the exposed skin segment the boundary layers are thin. If
457 treated as flow over a 1.5 cm short plate (not over the entire head), the measured \bar{h}_t would
458 correspond to free stream velocity of only $0.3 \text{ m}\cdot\text{s}^{-1}$. While increasing the system cost, this issue
459 can be easily resolved by adding an inline humidification component and a second humidity probe
460 upstream of the diffuser. We also note that to be suitable for the limiting case of sweat evaporation
461 without any air flow,⁶⁴ the sapphire window would have to be heated to prevent fogging up of its
462 internal surface. The humidity probe that we also adopted from physiological studies^{53,54} is highly
463 accurate ($\pm 0.18 \text{ g}\cdot\text{m}^{-3}$) but has a response time of about 5 to 10 s that is too slow to detect
464 evaporation rate oscillations due to cyclic sweat secretion.⁷⁵ If these fine evaporation rate
465 characteristics are of interest, another humidity probe must be utilized. Response time of the
466 MWIR camera is fast (up to 60 Hz) and succeeds in imaging the pulsating sweat emerging from
467 pores in the early sweating stages. However, we also observed several issues when employing
468 this imaging technique to study sweat.

469 The most pronounced issues we observed with sweat imaging using MWIR are the small
470 depth of field of the macro-lens and difficulty interpreting images when temperature gradients on
471 the skin are small. The small depth of field is particularly visible during in vivo experiments when,
472 even with a relatively rigidly mounted capsule, slight movement of the subject can cause skin to
473 "bow" and become unfocused within part of the viewing area. While our setup included a manual
474 micrometer on the camera mounting, we found that continual focusing using the micrometer is
475 challenging, a problem that might be addressed by an electronic micrometer. Even when the full
476 image is in complete focus, small temperature gradients make quantitative image analysis
477 challenging (e.g., it is difficult to judge where are the edges of the water film patches in advanced
478 filmwise sweating in the bottom of **Figure 3F** or in **Figure 3C**). Quantitative MWIR of water
479 droplets is also known to be challenging.⁶⁷ In our pilot trials, we observed that large (~1 mm
480 diameter) sweat droplets with very high contrast appeared to cast a low contrast "ring-shadow"
481 around them that disappeared when the droplets evaporated. This shadow could correspond to
482 a physical process of interest, such as local thin film spreading, hydration of the stratum corneum,
483 or conductive cooling of the skin around the droplet. However, it could also be caused by a fraction
484 of the infrared radiation emitted from the skin within the ring area being absorbed by the side of
485 the droplet.

486 While some progress in interpreting infrared images of sweat can be made with clever
487 comparison of before and after sweat droplet appearance images^{62,63} or by interpreting using
488 thermofluidic simulations the temperatures of droplet and its surrounding,⁶⁴ it is difficult to
489 implement during extended sweating when pores rarely become dry or when the surrounding
490 might also be wet. A potential approach to addressing most of the issues with MWIR imaging is
491 correlative imaging with another technique. In particular, optical coherence tomography (OCT),
492 ⁵⁷⁻⁶¹ appears to be particularly well suited to this task as it provides cross-sectional images of skin
493 and its surface that would be ideal for aiding interpretation of MWIR images (e.g., droplet shape

494 and film thicknesses). It is worth noting that other imaging techniques might be better suited for
495 studying evaporation from single pores (diameter of 20 to 60 μm), as both MWIR and OCT in-
496 plane spatial resolution is at best around 10 μm (OCT⁵⁸) to 15 μm (MWIR). Lastly, we highlight
497 that since this was only a pilot study demonstrating the implementation of the capsule and
498 providing illustrative outcomes, results from the final subject (out of seven) with a fully optimized
499 capsule and MWIR procedure are provided. We note that experiments with this subject were
500 repeated three times over 10 days at the end of January of 2024, with comparable sweating mode
501 and evaporation rate temporal evolution observed each time (the results with most optimized
502 procedure from the last experiments were analyzed using image processing and are presented
503 in the paper).

504

505

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512

513 **Author Contributions**

514 Conceptualization: K.R. and S.A.K.; Methodology: K.R., S.A.K., H.N.E., and G.P.; Software: K.R.,
515 B.B., K.K.; Validation: A.K.J., C.T.J., R.R., V.K.N., K.S., A.J., and K.R.; Formal Analysis: K.R.,

516 C.T.J, A.K.J.; Investigation: A.K.J., C.T.J., R.R., V.K.N., K.S., A.J., K.K., and S.A.K., Resources:
517 K.R., S.A.K., H.N.E., G.P.; Data Curation: K.R.; Writing-Original Draft: K.R., A.K.J, C.T.J., A.J.;
518 Writing-Review & Editing: all authors; Visualization: K.R., C.T.J., A.K.J., A.J.; Supervision: K.R.
519 and S.A.K; Project Administration: K.R.; Funding Acquisition: K.R. and S.A.K.

520 **Declaration of Interests**

521 The authors declare no competing interest.

522

523

524 **Figure 1. A.** Comparison of velocity distributions in a central vertical plane and streamlines within
525 traditional cylindrical and the wind tunnel ventilated capsules at air flow rate of $0.5 \text{ L}\cdot\text{min}^{-1}$; **B.**
526 annotated image showing the arrangement of the wind tunnel capsule for simultaneous
527 measurement of the sweat evaporation rate and multi-pore scale imaging on a passively heated
528 subject's forehead, and **C.** an example through-sapphire window Midwave Infrared image of
529 sweat droplets evaporating from the skin surface.

530

531 **Figure 2. A.** Air velocity distribution on a central plane in a wind tunnel ventilated capsule with
532 two acrylic windows with air flow rate of $0.3 \text{ L}\cdot\text{min}^{-1}$ visualized using Particle Image Velocimetry
533 (PIV); **B.** comparison of PIV-measured and simulated x-averaged (according to axis definitions in
534 A) y-velocity profiles for air flow rates of 0.3 , 0.6 , and $1 \text{ L}\cdot\text{min}^{-1}$, and **C.** an example of experimental
535 measurement of an artificial 0.64 cm^2 square water film evaporation rate when the film is allowed
536 to evaporate and when it is replenished to maintain equilibrium via a syringe pump; inset shows
537 the schematic of the experimental setup; and **D.** impact of humidity probe distance from
538 evaporation area quantified using 0.64 cm^2 square water film experiments and simulations at 0.5

539 and 1 L·min⁻¹ air flow rate (to facilitate comparison, the ratio of average probe to average outlet
540 water vapor concentrations is plotted); the insets show the evaporation sections of capsules with
541 different probe locations (diffuser not attached), the perforated probe tip, and water vapor
542 concentration profiles at 1 L·min⁻¹ and two probe locations.

543

544 **Figure 3. From the onset of cyclic dropwise to established filmwise sweating:** **A.** The sweat
545 evaporation mass flux measured with 0.1 L·min⁻¹ air flow rate and per the 1.93 cm² evaporation
546 area and **B.** corresponding absolute and relative wet surface area (i.e., covered by sweat)
547 obtained from analyzing MWIR imaged surface sweat dynamics including **C.** onset and **D.**
548 established cyclic dropwise sweating and **E.** transition to **F.** the filmwise mode.

549

550 **Figure 4. Droplet characteristics during cyclic dropwise sweating:** **A.** The number of active
551 pores (droplets) vs. time within the 1.93 cm² evaporation area (the red line shows 1-min moving
552 average) and **B.** the wet area vs. number of active pores (the red line shows a linear fit to the data
553 whose equation is displayed); **C.** diameter vs. time plot showing examples of a long-lasting and
554 large droplet (orange line) as well as multiple sequential (i.e., from same pore) brief and small
555 droplets (blue line); **D.** maximum diameter vs. duration of the droplets; **E-F.** probability and
556 cumulative distribution function (CDF) histograms of **E.** the maximum diameter and **F.** droplet
557 duration.

558

559 **Figure 5. Forced drying out of filmwise sweating through increased air flow rate:** The time
560 series of **A.** the flow rate (blue line) and water vapor concentration (orange line) measured by the

561 probe (C_{probe}) for the 1.93 cm^2 evaporation area and corresponding **B.** evaporation mass flux and
562 **C.** six MWIR images corresponding to time points **i-vi** indicated in **B.**

563

564 **Figure 6. Synthesis of the evaporation rate measurement and MWIR image analysis: A.**
565 evaporation mass flux vs. wet area (or wet area fraction) under constant air flow rate ($0.1 \text{ L}\cdot\text{min}^{-1}$); results for simulated and measured evaporation from square water films with a varied area are
566 also shown; and **B.** the forced "dry out" experiments: the quasi-steady state evaporation mass
567 flux vs. air flow rate; simulations and measured evaporation of isothermal square water films at
568 34°C and 0.64 cm^2 are also shown (additional simulation for 36.5°C and area of 1 cm^2 are also
569 included); **C.** Schematic summary of the directly observed or implied pore or multi-pore scale
570 processes underlying sweat evaporation including out-of-duct evaporation, cyclic dropwise
571 evaporation, temporary crevice filling, drop-to-film spreading through stratum corneum (SC)
572 hydration, pore bridging via crevice, and film puddles with non-uniform exterior temperature.

574

575

576 **STAR Methods**

577 **RESOURCE AVAILABILITY**

578 **Lead contact**

579 Further information and requests for resources and reagents should be directed to and will be
580 fulfilled by the lead contact, Konrad Rykaczewski (konradr@asu.edu)

581 **Materials availability**

582 This study did not generate new materials.

583 **Data and code availability**

584 **Data**

585 The stabilized grayscale MWIR video and corresponding binary video resulting from image
586 processing of the infrared data of the entire 45 min sweating process at $0.1 \text{ L} \cdot \text{min}^{-1}$ have been
587 deposited on Mendeley Data and are publicly available as of the date of publication. DOIs are
588 listed in the key resources table.

589 **Code**

590 This paper does not report original code.

591

592 **EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS**

593 The Arizona State University Institutional Review Board approved the human subject
594 experiments. Since this was only a pilot study demonstrating the implementation of the capsule
595 and providing illustrative outcomes, results from the final subject (out of seven) with a fully
596 optimized capsule and MWIR procedure are provided. The subject was a 40 years old Caucasian
597 male of eastern European ancestry, had a height of 175 cm, and weighed 69 kg. We note that
598 experiments with this subject were repeated three times over 10 days at the end of January of
599 2024, with comparable sweating mode and evaporation rate temporal evolution observed each
600 time (the results with most optimized procedure from the last experiments were analyzed using
601 image processing and are presented in the paper).

602

603 **METHOD DETAILS**

604 **Capsule fabrication and sensor integration**

605 The digitally designed diffuser and evaporation sections of the capsule were 3D printed (Prusa
606 i3 MK3S with 0.1 mm 'detail' setting, 30% infill) using polyethylene terephthalate glycol (PETG,
607 Overture 1.75 mm) filament. All printed parts were coated three times with epoxy (XTC 3D) to
608 seal any potential gaps. To facilitate conformal coating, the epoxy was diluted with acetone before
609 each application. After curing the coating for 24 h at 22 to 24°C, excess parts blocking, for

610 example, the flanges were manually filed down. Custom gaskets (square or circular) were made
611 for the flange joining the capsule sections, for the 2.54 cm diameter and 0.5 cm thick sapphire
612 window (Thorlabs WG31050-E1 with anti-reflective coating), and interface with the acrylic artificial
613 sweating surfaces were made using splicing kit (McMaster Carr 9410K11). The diffuser section
614 and evaporation section were connected using a flange that has eight holes with a diameter of
615 2.6 mm and are fastened together with M2 screws (McMaster-Carr 90116A020) and nuts
616 (McMaster-Carr 94150A305). One of the flanges has groove for an O-ring (cross section of 2.5
617 mm with internal diameter of 21.95 mm). Another flange with four holes was printed on the outlet
618 of the evaporation section for a cap that is used during outlet air leak test. In the test, the capsule
619 is fully closed (see image of the cap in Figure S2) and pressurized to about 8000 Pa, as measured
620 by an inline pressure gauge. The cap was laser cut to a diameter of 39 mm, had a laser etched
621 groove for an O-ring, and was secured to the capsule's flange using has four set of screws.
622 Indicating good sealing capability, the capsule can hold the pressure for over 10 min.

623 The high accuracy ($\pm 0.8\%$ relative humidity or $\pm 0.18 \text{ g}\cdot\text{m}^{-3}$) compact humidity probe (Vaisala
624 HMP9) with digital transmitter (Vaisala Indigo202, powered through wall plugged power adapter)
625 was inserted into a 7.9 mm hole on the side of the evaporation section using a grommet (Buna-
626 N, MS 35489-91). We calibrated the probe using saturated aqueous salt solution in a closed
627 container.⁸⁹ We placed the probe through a hole with a grommet in an airtight plastic storage
628 container with a 29.5 mL capacity along with the salt solution. We made the saturated solution
629 with distilled water and NaCl (ACS reagent, $\geq 99.0\%$, Sigma Aldrich). After closing, we allowed the
630 system to reach equilibrium over 24 h. The standard reference point is $75.5 \pm 0.2\%$ relative
631 humidity (RH) at 20°C, however, if temperature cannot be maintained at $\pm 0.1^\circ\text{C}$, drift of the
632 humidity reading exceeding 0.5 % is expected. We did not control lab temperature and had drift
633 up to 1.2 °C, resulting in a larger uncertainty ($75.4 \pm 2.8\%$ with temperature of $22.3 \pm 0.6^\circ\text{C}$ (± 1
634 standard deviation)).

635

636 The capsule was perfused with Ultra Zero Air (Airgas, less than 2 ppm of water) from the high-
637 pressure cylinder. The pressure from the cylinder drives the air flow that was regulated using a
638 digital mass flow controller (Alicat Scientific, MC-1SLP-D-DB9M/5m, standard accuracy of $\pm 0.1\%$
639 of full scale or $\pm 0.6\%$ of the reading, powered through wall plugged power adapter). We fabricated
640 over 10 of the wind tunnel ventilated capsule devices over two years of the project and did not
641 observe any device-to-device differences in heated square water film platform experiments. We
642 note that to assess the 3D printed and coated part compatibility with moist environments, we
643 tested the rate of water absorption by the device. In particular, we 3D printed and coated with
644 epoxy two samples immersed in water for 24 h. The mass of the samples before and after the 24
645 h immersion as shown in Table S1, demonstrating a negligible water absorption level ($\sim 1\%$ or
646 lower).

647 We note that very high air flow rate could locally decrease skin temperature through
648 evaporation. In general, sweat secretion rate is modulated by core, mean skin, and local skin
649 temperature. However, the agreement between sweat secretion rate measurements done using
650 traditional high flow rate ventilated capsules and absorbent pads implies that any local
651 temperature decrease within capsule has negligible impact on the secretion rate.⁹⁰ The Figure
652 S1, Table S1, and Figure S2 in the SI describes further related details of the capsule geometry,
653 humidity probe calibration procedure, ventilated capsule water absorption (below 1% in 24 h of
654 soaking), and air pressure sealing tests.

655

656 **Heated square film platform**

657 We developed a simple platform for dispensing square 0.5 mm thin heated water films at
658 highly controlled flow rates to optimize the capsule design and benchmark its evaporation rate
659 measurement. The setup consists of four layered acrylic plates that house a 3 cm by 4 cm by 0.5
660 cm aluminum block whose temperature is set using two thin film polyimide heaters (Icstation

661 Polyimide Heating Elements Film, 5V, 1W, Stripboard Mat) with feedback provided by an
662 embedded T-type thermocouple. The heater is controlled using on/off basis with a benchtop
663 controller (Omega CSi8D) with AC-to-DC converter attached to the power output (5 V DC). The
664 metal block has a horizontal channel (2 mm inner diameter) for the supply and preheating of the
665 water that is connected to a vertical channel that dispenses the liquid onto the top surface of the
666 block. The flow of water is set using a syringe pump (NE-300 Just Infusion Syringe Pump) with a
667 plastic dispensing needle (McMaster Carr 75115A671) with a luer lock connection to the syringe
668 pump side being embedded into the 2 mm internal diameter hole in the aluminum block. The
669 water "reservoir" on the metal surface is created using an o-ring (Silicone 70 durometer 568-011)
670 that is pressed against the metal with a 3.1 mm thick acrylic plate. The latter has patterns etched
671 on both sides using a laser cutter (Full Spectrum Laser PS20), with a gasket groove on the bottom
672 and 0.5 mm deep upper square with an area varying between 0.16 to 1 cm². The water reservoir
673 is connected to the bottom of the etched square through a 0.1 mm laser-cut hole. Laser-etching
674 produces a micro-textured and hydrophilic surface that facilitates film formation within the square.
675 To conduct experiments with external film temperature at about 34°C, the heater set point was
676 adjusted for each flow rate based on input from MWIR images. Images of the setup are shown in
677 Figure S3.

678

679 **Coupled multiphysics simulations**

680 The multiphysics simulations were performed using Comsol Multiphysics 6.1 and coupled
681 Laminar Flow, Heat Transfer in Moist Air, and Dilute Species Mass Transport physics. Only the
682 internal air domain was simulated with inlet conditions being a fully developed laminar flow within
683 the round supply tube at a typical temperature of the lab (23°C) and water vapor concentration
684 approximated as 0 g·m⁻³. For all physics, the outlet of the capsule was set to "Open Boundary"
685 condition. The exposed "skin" area of 15 by 15 mm was treated as isothermal at 34°C with a

686 centrally placed square (0.16 to 1 cm²) having "Wet" boundary condition in the mass transport
687 physics (i.e., water vapor concentration is equal to saturation concentration at the surface
688 temperature). The mesh refinement study and images of the utilized mesh are shown in Figure
689 S4, while further details of the model formulation are described elsewhere.⁵

690

691 **PIV measurements**

692 The planar PIV was performed using a New Wave Nd:YAG laser with an output power of 130
693 mJ/Pulse and a 11-megapixel TSI PowerView CCD camera. A series of optics were used to
694 redirect the laser, passed through a cylindrical lens to make a thin sheet about 1 mm wide, and
695 passed through the nozzle to illuminate the streamwise-spanwise plane, as shown in Figure 2A.
696 The laser emits 532 nm light and was used to illuminate the seeding particles in the camera's field
697 of view. A Laskin nozzle filled with olive oil provided the necessary seeding particles for these
698 experiments. A calibration target was used to convert the images from the camera into real-world
699 coordinates to obtain the velocity vectors. The data was processed on LaVision Davis 11 using
700 multi-pass grid refinement to the final interrogation window of 32 x 32 pixel² (with a 50% overlap).
701 This gives a final vector spacing of 0.08 mm·vector⁻¹ in x- and y-directions.

702

703 **Experimental setup for human trials**

704 An experiment setup for human trials consists of the ventilated capsule, constant temperature
705 bath (VWR AP28R-30-V11B), water tube perfused full body heating suit with a hood (Compcooler
706 Full Body Cooling Garment with stretchable fabric XS/S and M/L), custom machined MWIR
707 camera mount, adjustable reclining chair for subject (Paddie Electric Height Adjustable Bed Chair,
708 Electric Lift Massage Table 3-Section Folding), heated gloves, and additional heated blankets
709 (Homlyns, 127 by 152 cm with 120V). A capacitive skin hydration meter (Delfin MoistureMeter
710 SC) was used to measure skin hydration outside of the capsule throughout the experiments, with
711 initial values of about 30 (no unit) increasing to over 100 by the end of the 40 min experiment. A

712 Sony A7Siii camera with Venus Optics Laowa 24mm f/14 Probe Lens is used to image
713 representative water droplets (~1-5 μ L) of the subject's skin near the capsule. The water contact
714 angles before heating varied between 60 to 75° and were below 10° as the capsule was taken off
715 between experiments (measured nearby but not on the imaging site).

716 The capsule mount consists of a gliding rail (Firgelli, 30 cm) attached to a wooden platform
717 that is itself secured using a robust camera arm (AmScope Articulating Stand with Clamp and
718 Focusing Rack for Stereo Microscopes) to a nearby table and allows for rapid and significant
719 movement of the capsule (i.e., moving in and out of the site area). The capsule mounting on the
720 rail has an assembly of two manual micrometers (Newport with 2 cm travel) that can be adjusted
721 with high precision without moving the subject. The capsule diffuser itself was manually screwed
722 into a 17.2 mm inner diameter machine screw nut (which also provided a ~30° rotational
723 adjustment) that was secured to the micrometer using a thin aluminum plate and four screws.

724 The full body heating suit comprises many tubes distributed across the entire surface area for
725 uniform heating. As in related studies,^{53,54} water at 48°C supplied through the constant
726 temperature bath is circulated in the suit. The values of temperatures and flow rates of water
727 entering and exiting the suit are also monitored with the help of a rotameter and T-type
728 thermocouples. The experiments are performed in a supine posture, with the major adjustment of
729 the human subject position with respect to the MWIR camera carried out by adjusting the chair.
730 An additional micrometer was added to the camera mount to adjust focus without touching the
731 lens. A heated blanket is placed on the chair to minimize heat losses from the circulated water to
732 the surroundings. Subsequently, a 76.2 cm wide waterproof exam paper (TOA Disposable
733 Polypaper waterproof exam paper) is used to cover the blanket and prevent its saturation with the
734 subject's sweat. Afterward, the subject wearing the heated suit was asked to lie on the chair. The
735 subject was covered with another layer of the exam paper and a second heated blanket. In
736 addition, the subject also wore a pair of heated gloves to cover the hands. The capsule's contact
737 with the skin was sealed using double-sided skin tape (skin-compatible double-sided tape,

738 BearKig) placed onto the capsule surrounding the skin opening. Images of the experimental setup
739 are shown in Figure S7.

740

741 **Experimental protocol for the pilot human trial**

742 The Arizona State University Institutional Review Board approved the human subject
743 experiment. All participants were screened using inclusion criteria (between 18 and 55 years old
744 with no history of significant health issues such as high blood pressure or current symptoms that
745 mild hyperthermia might exacerbate) and provided written informed consent before participating.
746 The subjects were asked to avoid alcohol the night prior to experiments and have a caffeine-free
747 light breakfast and at least 0.5 L of water two hours before the experiment.

748 As a first step upon arrival, the subjects were asked to weigh themselves without clothing, a
749 process that was repeated after the experiment to determine total sweat loss. Wearing T-shirt and
750 shorts, the subjects put on the full body suit. The capsule was purged before every experiment to
751 remove any absorbed moisture due to ambient air exposure. Before laying down on the chair, the
752 subjects were instrumented with an external core temperature sensor (CORE sensor).
753 Throughout the experiment, the core temperature increase was typically 0.5°C to 0.8°C, as
754 expected from our heating procedure.⁵⁴ After the subject lay down, the capsule was mounted on
755 their forehead while heating with 48°C water was started. Sweating was typically detectable with
756 the MWIR camera and visually after about 20 to 25 min of heating. The subject comfort level was
757 verbally assessed throughout the experiment, which was terminated early if the subject was
758 uncomfortable. When requested, the subject was given a weighed amount of water throughout
759 the experiment. After the experiment, the subjects were asked to weigh themselves, rest, and
760 drink water for 15 min. About 0.75 to 1 kg net water loss was indicated through weight change
761 and accounting for water intake.

762

763 **MWIR imaging and image analysis**

764 The MWIR videos were captured using a FLIR MWIR 6701 camera with a 50 mm f2.5 macro
765 lens. The instrument has a detector with 3 to 5 μm spectral range and 640×512 pixel count. The
766 images were recorded at 10 Hz (camera range is 0.0015 Hz to 60 Hz), double the acquisition
767 rates used in prior MWIR studies on mental sweating.⁶⁶ The lens zoom was extended to provide
768 an image of the exposed skin area within the ventilated capsule, translating to 26.7 μm per pixel
769 spatial resolution. The movies were exported from the FLIR Research Studio software (Teledyne
770 FLIR) in .avi format and grayscale and imported into FIJI/ImageJ 2.14.0.⁹¹ Once the temperature
771 scale was cropped, the unavoidable shaking in the recording related to the subject's breathing
772 was removed using the Image Stabilizer plugin with default settings. The over 25,000 images
773 covered over 40 min of sweating in different modes and were converted to binary (wet/dry) using
774 Auto Local Thresholding. However, the details of the process required adjustment to the different
775 modes of sweating. In particular, the iterative trial demonstrated that best outcomes were
776 achieved for established cyclic dropwise sweating using the Phansalkar auto local threshold with
777 radius varying from 15 to 25 pixels, while in the filmwise mode, the mid-gray auto local threshold
778 with a radius of 35 pixels was preferred. Post thresholding, several additional processing steps
779 on the binary images were performed to minimize noise and smooth the droplet shapes, including
780 "binary/close", "binary/dilate", and "filter/Gaussian blur" with 2 pixel radius (the latter was followed
781 by another single-value based thresholding step to re-convert to binary). We note, however, that
782 even blending of the approaches using "image calculator" often yielded imperfect results, as
783 visually judged by comparison of the original and processed videos. Consequently, multiple
784 manual edits were also conducted to eliminate major artifacts.

785 The total area and individual droplet areas within each binary image was determined using
786 the "analyze/analyze particles" function. To determine the maximum diameter and duration of
787 each droplet across multiple sequential images, the image stacks with varying time were analyzed
788 using the "analyze/3D object counter" function (with time treated as the "z-axis"). To remove noise,
789 "droplets" that only lasted two slices were filtered out. While this substantially reduced the total

790 number of analyzed droplets (down to 3,500), it had negligible impact on the total area within each
791 slice (analyzed using the “analyzed particles” function in post-3D filtered stack).

792

793 QUANTIFICATION AND STATISTICAL ANALYSIS

794 All experiments employing the heated square film platform were repeated three times. The
795 random error for the evaporation rate was calculated using 2-sided T-student distribution with
796 95% confidence interval based on standard deviation of the experimentally measured, $\sigma_{\dot{m}}$, as
797 $U_{random} = 4.3\sigma_{\dot{m}}$. The systematic error based on measurement uncertainties was calculated from
798 error propagation of Equation 1 with $C_{in} = 0$ (i.e., $\dot{m}_e = \dot{Q}C_{out}$), resulting in $U_{systematic} =$
799 $\sqrt{\dot{Q}^2 U_{C_{out}}^2 + C_{out}^2 U_{\dot{Q}}^2}$ (where $U_{C_{out}}$ and $U_{\dot{Q}}$ are the instrument uncertainties associated with the
800 concentration and air flow described above). The total error was subsequently calculated as

801 $U_{total} = \sqrt{U_{systematic}^2 + U_{random}^2}$.

802

803 Supplemental Video Data

804 Video S1. Onset of cyclic dropwise sweating (5x speed).

805 Video S2. Cyclic dropwise sweating (5x speed).

806 Video S3. Transition to filmwise: sweat spreading into skin crevices (5x speed).

807 Video S4. Transition to filmwise: sweat bridges pores within crevices (5x speed).

808 Video S5. Filmwise sweating (5x speed).

809 Video S6. Transition to filmwise: drop-to-film transition (20x speed).

810

811

812 References

813 1. Aldea, D., Atsuta, Y., Kokalari, B., Schaffner, S.F., Prasasya, R.D., Aharoni, A., Dingwall,
814 H.L., Warder, B., and Kamberov, Y.G. (2021). Repeated mutation of a developmental
815 enhancer contributed to human thermoregulatory evolution. *Proceedings of the National
816 Academy of Sciences* **118**, e2021722118.

817 2. Kuno, Y. (1956). Human perspiration. Thomas, Spring-field.

818 3. Havenith, G., Richards, M.G., Wang, X., Brode, P., Candas, V., den Hartog, E., Holmér,
819 I., Kuklane, K., Meinander, H., and Nocker, W. (2008). Apparent latent heat of
820 evaporation from clothing: attenuation and “heat pipe” effects. *J Appl Physiol* **104**, 142–
821 149.

822 4. Havenith, G., Bröde, P., Hartog, E. den, Kuklane, K., Holmer, I., Rossi, R.M., Richards,
823 M., Farnworth, B., and Wang, X. (2013). Evaporative cooling: effective latent heat of
824 evaporation in relation to evaporation distance from the skin. *J Appl Physiol* **114**, 778–
825 785.

826 5. Rykaczewski, K. (2020). Rational design of sun and wind shaded evaporative cooling
827 vests for enhanced personal cooling in hot and dry climates. *Appl Therm Eng*, 115122.

828 6. Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y.,
829 Kovats, R.S., Ma, W., and Malik, A. (2021). Hot weather and heat extremes: health risks.
830 *The Lancet* **398**, 698–708.

831 7. Ebi, K.L., Vanos, J., Baldwin, J.W., Bell, J.E., Hondula, D.M., Errett, N.A., Hayes, K.,
832 Reid, C.E., Saha, S., and Spector, J. (2021). Extreme weather and climate change:
833 population health and health system implications. *Annu Rev Public Health* **42**, 293.

834 8. Jay, O., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats,
835 R.S., Ma, W., and Malik, A. (2021). Reducing the health effects of hot weather and heat
836 extremes: from personal cooling strategies to green cities. *The Lancet* **398**, 709–724.

837 9. Derby, B. (2010). Inkjet printing of functional and structural materials: fluid property
838 requirements, feature stability, and resolution. *Annu Rev Mater Res* **40**, 395–414.

839 10. Brutin, D., and Starov, V. (2018). Recent advances in droplet wetting and evaporation.
840 *Chem Soc Rev* **47**, 558–585.

841 11. Plawsky, J.L., Fedorov, A.G., Garimella, S. V, Ma, H.B., Maroo, S.C., Chen, L., and Nam,
842 Y. (2014). Nano-and microstructures for thin-film evaporation—A review. *Nanoscale and
843 microscale thermophysical engineering* **18**, 251–269.

844 12. Zang, D., Tarafdar, S., Tarasevich, Y.Y., Choudhury, M.D., and Dutta, T. (2019).
845 Evaporation of a Droplet: From physics to applications. *Phys Rep* **804**, 1–56.

846 13. Li, X., Guo, W., and Hsu, P. (2023). Personal Thermoregulation by Moisture-Engineered
847 Materials. *Advanced Materials*, 2209825.

848 14. Lei, M., Li, Y., Liu, Y., Ma, Y., Cheng, L., and Hu, Y. (2020). Effect of weaving structures
849 on the water wicking–evaporating behavior of woven fabrics. *Polymers (Basel)* **12**, 422.

850 15. Peng, Y., Li, W., Liu, B., Jin, W., Schaadt, J., Tang, J., Zhou, G., Wang, G., Zhou, J.,
851 Zhang, C., et al. (2021). Integrated cooling (i-Cool) textile of heat conduction and sweat
852 transportation for personal perspiration management. *Nat Commun* **12**, 6122.
853 <https://doi.org/10.1038/s41467-021-26384-8>.

854 16. Raccuglia, M., Heyde, C., Lloyd, A., Hodder, S., and Havenith, G. (2018). Spatial and
855 temporal migration of sweat: from skin to clothing. *Eur J Appl Physiol* **118**, 2155–2169.

856 17. Morris, N. B., Kjellstrom, T., Ioannou, L. G., Gao, C., Morabito, M., Messeri, A., Levi, M.,
857 Baldasseroni, A., Havenith, G., and Foster, J. (2019). Heat Shield Project D3. 6: Report
858 on Solutions to Mitigate Heat Stress for Workers of the Agricultural Sector.

859 18. Ioannou, L.G., Foster, J., Morris, N.B., Piil, J.F., Havenith, G., Mekjavić, I.B., Kenny, G.P.,
860 Nybo, L., and Flouris, A.D. (2022). Occupational heat strain in outdoor workers: A
861 comprehensive review and meta-analysis. *Temperature* 9, 67–102.
862 <https://doi.org/10.1080/23328940.2022.2030634>.

863 19. Ravanelli, N.M., Hodder, S.G., Havenith, G., and Jay, O. (2015). Heart rate and body
864 temperature responses to extreme heat and humidity with and without electric fans.
865 *JAMA - Journal of the American Medical Association* 313, 724–725.
866 <https://doi.org/10.1001/jama.2015.153>.

867 20. Gagnon, D., Romero, S.A., Cramer, M.N., Jay, O., and Crandall, C.G. (2016). Cardiac
868 and thermal strain of elderly adults exposed to extreme heat and humidity with and
869 without electric fan use. *JAMA - Journal of the American Medical Association* 316, 989–
870 991. <https://doi.org/10.1001/jama.2016.10550>.

871 21. Filingeri, D., and Havenith, G. (2015). Human skin wetness perception: psychophysical
872 and neurophysiological bases. *Temperature* 2, 86–104.

873 22. Filingeri, D. (2011). Neurophysiology of skin thermal sensations. *Compr Physiol* 6, 1429–
874 1491.

875 23. Lolla, V.Y., Shukla, P., Jones, S.D., and Boreyko, J.B. (2020). Evaporation-Induced
876 Clogging of an Artificial Sweat Duct. *ACS Appl Mater Interfaces* 12, 53403–53408.

877 24. Keshavarzi, F., Knudsen, N.Ø., Komjani, N.M., Ebbesen, M.F., Brewer, J.R., Jafarzadeh,
878 S., and Thormann, E. (2022). Enhancing the sweat resistance of sunscreens. *Skin*
879 *Research and Technology* 28, 225–235.

880 25. Davis, N., Heikenfeld, J., Milla, C., and Javey, A. (2024). The challenges and promise of
881 sweat sensing. *Nat Biotechnol*, 1–12.

882 26. Zhang, B., Li, J., Zhou, J., Chow, L., Zhao, G., Huang, Y., Ma, Z., Zhang, Q., Yang, Y.,
883 Yiu, C.K., et al. (2024). A three-dimensional liquid diode for soft, integrated permeable
884 electronics. *Nature*. <https://doi.org/10.1038/s41586-024-07161-1>.

885 27. Yang, H., Ding, H., Wei, W., Li, X., Duan, X., Zhuang, C., Liu, W., Chen, S., and Wang, X.
886 (2024). Skin-interfaced microfluidic sweat collection devices for personalized hydration
887 management through thermal feedback. *Lab Chip* 24, 356–366.

888 28. Liu, Y., Li, X., Yang, H., Zhang, P., Wang, P., Sun, Y., Yang, F., Liu, W., Li, Y., and Tian,
889 Y. (2023). Skin-interfaced superhydrophobic insensible sweat sensors for evaluating
890 body thermoregulation and skin barrier functions. *ACS Nano* 17, 5588–5599.

891 29. Baker, L.B. (2019). Physiology of sweat gland function: The roles of sweating and sweat
892 composition in human health. *Temperature* 6, 211–259.

893 30. Taylor, N.A.S., and Machado-Moreira, C.A. (2013). Regional variations in transepidermal
894 water loss, eccrine sweat gland density, sweat secretion rates and electrolyte
895 composition in resting and exercising humans. *Extrem Physiol Med* 2, 1–30.

896 31. Smith, C.J., and Havenith, G. (2011). Body mapping of sweating patterns in male athletes
897 in mild exercise-induced hyperthermia. *Eur J Appl Physiol* 111, 1391–1404.

898 32. Gerrett, N., Griggs, K., Redortier, B., Voelcker, T., Kondo, N., and Havenith, G. (2018).
899 Sweat from gland to skin surface: production, transport, and skin absorption. *J Appl*
900 *Physiol* 125, 459–469.

901 33. Coull, N.A., West, A.M., Hodder, S.G., Wheeler, P., and Havenith, G. (2021). Body
902 mapping of regional sweat distribution in young and older males. *Eur J Appl Physiol* 121,
903 109–125.

904 34. Sonner, Z., Wilder, E., Heikenfeld, J., Kasting, G., Beyette, F., Swaile, D., Sherman, F.,
905 Joyce, J., Hagen, J., and Kelley-Loughnane, N. (2015). The microfluidics of the eccrine
906 sweat gland, including biomarker partitioning, transport, and biosensing implications.
907 *Biomicrofluidics* 9, 031301.

908 35. Candas, V., Libert, J.P., and Vogt, J.J. (1979). Human skin wettedness and evaporative
909 efficiency of sweating. *J Appl Physiol* 46, 522–528.

910 36. Candas, V., Libert, J.P., and Vogt, J.J. (1979). Influence of air velocity and heat
911 acclimation on human skin wettedness and sweating efficiency. *J Appl Physiol* 47, 1194–
912 1200.

913 37. Tam, H.-S., Darling, R.C., Downey, J.A., and Cheh, H.Y. (1976). Relationship between
914 evaporation rate of sweat and mean sweating rate. *J Appl Physiol* 41, 777–780.

915 38. Parsons, K. (2014). Human thermal environments: the effects of hot, moderate, and cold
916 environments on human health, comfort, and performance (CRC press).

917 39. Wissler, E.H. (2018). *Human Temperature Control: A quantitative Approach* 1st ed.
918 (Springer).

919 40. PARK, S.J., and TAMURA, T. (1992). Distribution of evaporation rate on human body
920 surface. *The Annals of physiological anthropology* 11, 593–609.

921 41. Holmér, I. (2004). Thermal manikin history and applications. *Eur J Appl Physiol* 92, 614–
922 618. <https://doi.org/10.1007/s00421-004-1135-0>.

923 42. Psikuta, A., Allegrini, J., Koelblen, B., Bogdan, A., Annaheim, S., Martínez, N., Derome,
924 D., Carmeliet, J., and Rossi, R.M. (2017). Thermal manikins controlled by human
925 thermoregulation models for energy efficiency and thermal comfort research – A review.
926 *Renewable and Sustainable Energy Reviews* 78, 1315–1330.
927 <https://doi.org/10.1016/j.rser.2017.04.115>.

928 43. Gholamreza, F., Su, Y., Li, R., Nadaraja, A.V., Gathercole, R., Li, R., Dolez, P.I., Golovin,
929 K., Rossi, R.M., Annaheim, S., et al. (2022). Modeling and Prediction of
930 Thermophysiological Comfort Properties of a Single Layer Fabric System Using Single
931 Sector Sweating Torso. *Materials* 15. <https://doi.org/10.3390/ma15165786>.

932 44. Wang, F. (2011). Physiological Model Controlled Sweating Thermal Manikin: Can it
933 replace human subjects? *Journal of Ergonomics* 01, 0–2. [https://doi.org/10.4172/2165-7556.1000e103](https://doi.org/10.4172/2165-
934 7556.1000e103).

935 45. Gao, H., Deaton, A.S., and Barker, R. (2022). A new test method for evaluating the
936 evaporative cooling efficiency of fabrics using a dynamic sweating hot plate. *Meas Sci
937 Technol* 33, 125601.

938 46. Huang, J. (2006). Sweating guarded hot plate test method. *Polym Test* 25, 709–716.

939 47. Kim, H., Michielsen, S., and DenHartog, E. (2020). New wicking measurement system to
940 mimic human sweating phenomena with continuous microfluidic flow. *J Mater Sci* 55,
941 7816–7832.

942 48. Rossi, R.M. (2017). High-performance sportswear (Elsevier Ltd.)
943 https://doi.org/10.1016/B978-0-08-100904-8.00017-1.

944 49. Guan, M., Annaheim, S., Camenzind, M., Li, J., Mandal, S., Psikuta, A., and Rossi, R.M.
945 (2019). Moisture transfer of the clothing–human body system during continuous sweating
946 under radiant heat. *Textile Research Journal*, 0040517519835767.

947 50. Rabost-Garcia, G., Farré-Lladós, J., and Casals-Terré, J. (2021). Recent Impact of
948 Microfluidics on Skin Models for Perspiration Simulation. *Membranes* (Basel) 11, 150.

949 51. Koelblen, B., Psikuta, A., Bogdan, A., Annaheim, S., and Rossi, R.M. (2017). Comparison
950 of fabric skins for the simulation of sweating on thermal manikins. *Int J Biometeorol* 61,
951 1519–1529.

952 52. Incropera, F.P., DeWitt, D.P., Bergman, T.L. and Lavine, A.S. (2011). Fundamentals of
953 heat and mass transfer.

954 53. Meade, R.D., Louie, J.C., Poirier, M.P., McGinn, R., Fujii, N., and Kenny, G.P. (2016).
955 Exploring the mechanisms underpinning sweating: the development of a specialized
956 ventilated capsule for use with intradermal microdialysis. *Physiol Rep* 4, e12738.

957 54. Rutherford, M.M., Akerman, A.P., Notley, S.R., Meade, R.D., Schmidt, M.D., and Kenny,
958 G.P. (2021). Regional variation in the reliability of sweat rate measured via the ventilated
959 capsule technique during passive heating. *Exp Physiol* 106, 615–633.

960 55. Lamke, L.-O. (1970). An instrument for estimating evaporation from small skin surfaces.
961 *Scand J Plast Reconstr Surg* 4, 1–7.

962 56. Nicolaidis, S., and Sivadjian, J. (1972). High-frequency pulsatile discharge of human
963 sweat glands: myoepithelial mechanism. *J Appl Physiol* 32, 86–90.

964 57. Jonathan, E. (2008). In vivo sweat film layer thickness measured with Fourier-domain
965 optical coherence tomography (FD-OCT). *Opt Lasers Eng* 46, 424–427.

966 58. Kato, K., Al-Sobaihi, S., Al-Busani, H., Nishizawa, A., Ohmi, M., Yokozeki, H., and
967 Namiki, T. (2021). Analysis of sweating by optical coherence tomography in patients with
968 palmoplantar hyperhidrosis. *J Dermatol* 48, 334–343.

969 59. Ohmi, M., Nohara, K., Ueda, Y., Fuji, T., and Haruna, M. (2005). Dynamic observation of
970 sweat glands of human finger tip using all-optical-fiber high-speed optical coherence
971 tomography. *Jpn J Appl Phys* 44, L854.

972 60. Ohmi, M., Tanigawa, M., Wada, Y., and Haruna, M. (2012). Dynamic analysis for mental
973 sweating of a group of eccrine sweat glands on a human fingertip by optical coherence
974 tomography. *Skin research and technology* 18, 378–383.

975 61. Ohmi, M., and Wada, Y. (2016). Dynamic analysis of mental sweating of eccrine sweat
976 gland of human fingertip by time-sequential piled-up en face optical coherence
977 tomography images. In 2016 38th Annual International Conference of the IEEE
978 Engineering in Medicine and Biology Society (EMBC) (IEEE), pp. 3918–3921.

979 62. Sagaidachnyi, A., Mayskov, D., Fomin, A., Zaletov, I., and Skripal, A. (2022). Separate
980 extraction of human eccrine sweat gland activity and peripheral hemodynamics from
981 high-and low-quality thermal imaging data. *J Therm Biol* 110, 103351.

982 63. Mayskov, D.I., Fomin, A. V, Volkov, I.U., Zaletov, I.S., Skripal, A. V, and Sagaidachnyi,
983 A.A. (2022). Statistical and spectral properties of spatio-temporal skin temperature
984 oscillations derived by sweat gland activity: thermal imaging exploration. In *Optical
985 Technologies for Biology and Medicine* (SPIE), pp. 197–203.

986 64. Drexelius, A., Fehr, D., Vescoli, V., Heikenfeld, J., and Bonmarin, M. (2022). A simple
987 non-contact optical method to quantify in-vivo sweat gland activity and pulsation. *IEEE*
988 *Trans Biomed Eng* **69**, 2638–2645.

989 65. Krzywicki, A.T., Berntson, G.G., and O’Kane, B.L. (2014). A non-contact technique for
990 measuring eccrine sweat gland activity using passive thermal imaging. *International*
991 *Journal of Psychophysiology* **94**, 25–34.

992 66. Koroteeva, E.Y., and Bashkatov, A.A. (2021). Thermal signatures of liquid droplets on a
993 skin induced by emotional sweating. *Quant Infrared Thermogr J*, 1–11.

994 67. Chandramohan, A., Weibel, J.A., and Garimella, S. V (2017). Spatiotemporal infrared
995 measurement of interface temperatures during water droplet evaporation on a nonwetting
996 substrate. *Appl Phys Lett* **110**, 041605.

997 68. Gleason, K., Voota, H., and Putnam, S.A. (2016). Steady-state droplet evaporation:
998 Contact angle influence on the evaporation efficiency. *Int J Heat Mass Transf* **101**, 418–
999 426.

1000 69. Hernández, M.A.G., López, A.I.M., Jarzabek, A.A., Perales, J.M.P., Wu, Y., and Xiaoxiao,
1001 S. (2013). Design methodology for a quick and low-cost wind tunnel. *Wind tunnel designs*
1002 and their diverse engineering applications, 1.

1003 70. Bergman, T.L., Lavine, A.S., Incropera, F.P., and Dewitt, D.P. (2011). *Fundamentals of*
1004 *heat and mass transfer* (John Wiley & Sons, Inc).

1005 71. Randall, W.C. (1946). Sweat gland activity and changing patterns of sweat secretion on
1006 the skin surface. *American Journal of Physiology-Legacy Content* **147**, 391–398.

1007 72. Albert, R.E., and Palmes, E.D. (1951). Evaporative rate patterns from small skin areas as
1008 measured by an infrared gas analyzer. *J Appl Physiol* **4**, 208–214.

1009 73. Machado-Moreira, C.A., and Taylor, N.A.S. (2017). Thermogenic and psychogenic
1010 recruitment of human eccrine sweat glands: Variations between glabrous and non-
1011 glabrous skin surfaces. *J Therm Biol* **65**, 145–152.

1012 74. McGregor, I.A. (1952). The sweating reactions of the forehead. *J Physiol* **116**, 26.

1013 75. Nilsson, A.L., Nilsson, G.E., and Öberg, P.A. (1982). On periodic sweating from the
1014 human skin during rest and exercise. *Acta Physiol Scand* **114**, 567–571.

1015 76. Nishiyama, T., Sugenoya, J., Matsumoto, T., Iwase, S., and Mano, T. (2001). Irregular
1016 activation of individual sweat glands in human sole observed by a videomicroscopy.
1017 *Autonomic Neuroscience* **88**, 117–126.

1018 77. Ogawa, T., and Sugenoya, J. (1993). Pulsatile sweating and sympathetic sudomotor
1019 activity. *Jpn J Physiol* **43**, 275–289.

1020 78. Schwarck, J.B., Burdon, C.A., Taylor, E.A., Peoples, G.E., Machado-Moreira, C.A., and
1021 Taylor, N.A.S. (2019). Thermogenic and psychogenic sweating in humans: Identifying
1022 eccrine glandular recruitment patterns from glabrous and non-glabrous skin surfaces. *J*
1023 *Therm Biol* **82**, 242–251.

1024 79. Morin, M., Ruzgas, T., Svedenhag, P., Anderson, C.D., Ollmar, S., Engblom, J., and
1025 Björklund, S. (2020). Skin hydration dynamics investigated by electrical impedance
1026 techniques *in vivo* and *in vitro*. *Sci Rep* **10**, 17218.

1027 80. Quéré, D. (2008). Wetting and Roughness. *Annu Rev Mater Res* **38**, 71–99.
1028 <https://doi.org/10.1146/annurev.matsci.38.060407.132434>.

1029 81. Bromberg, L., Liu, X., Wang, I., Smith, S., Schwicker, K., Eller, Z., and German, G.K.
1030 (2017). Control of human skin wettability using the pH of anionic surfactant solution
1031 treatments. *Colloids Surf B Biointerfaces* 157, 366–372.

1032 82. Ginn, M.E., Noyes, C.M., and Jungermann, E. (1968). The contact angle of water on
1033 viable human skin. *J Colloid Interface Sci* 26, 146–151.

1034 83. Eudier, F., Savary, G., Grisel, M., and Picard, C. (2019). Skin surface physico-chemistry:
1035 Characteristics, methods of measurement, influencing factors and future developments.
1036 *Adv Colloid Interface Sci* 264, 11–27.

1037 84. Akkus, Y., Çetin, B., and Dursunkaya, Z. (2019). An iterative solution approach to
1038 coupled heat and mass transfer in a steadily fed evaporating water droplet. *J Heat
1039 Transfer* 141.

1040 85. Akkus, Y., Çetin, B., and Dursunkaya, Z. (2020). A theoretical framework for
1041 comprehensive modeling of steadily fed evaporating droplets and the validity of common
1042 assumptions. *International Journal of Thermal Sciences* 158, 106529.

1043 86. Bullard, R.W. (1971). Studies on human sweat gland duct filling and skin hydration. *J
1044 Physiol (Paris)* 63, 218–221.

1045 87. MacPherson, R.K., and Newling, P.S.B. (1954). Salt concentration and rate of
1046 evaporation of sweat. In *JOURNAL OF PHYSIOLOGY-LONDON (CAMBRIDGE UNIV
1047 PRESS 40 WEST 20TH STREET, NEW YORK, NY 10011-4211)*, pp. P74–P74.

1048 88. Hancock, W., Whitehouse, A.G.R., and Haldane, J.S. (1929). The loss of water and salts
1049 through the skin, and the corresponding physiological adjustments. *Proceedings of the
1050 Royal Society of London. Series B, Containing Papers of a Biological Character* 105, 43–
1051 59.

1052 89. ASTM (1985). Standard practice for maintaining constant relative humidity by means of
1053 aqueous solutions. Preprint at The American Society for Testing and Materials.

1054 90. Morris, N.B., Cramer, M.N., Hodder, S.G., Havenith, G., and Jay, O. (2013). A
1055 comparison between the technical absorbent and ventilated capsule methods for
1056 measuring local sweat rate. *J Appl Physiol* 114, 816–823.
1057 <https://doi.org/10.1152/japplphysiol.01088.2012>.

1058 91. Rasband, W.S. (2011). imagej. <http://imagej. nih. gov/ij/>.

1059

1060