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Quantitative Analysis of Sweat Evaporation Loss in Epidermal Microfluidic Patches

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Part I. Figure S1--Figure S6.



Figure S1. The changes of m_A , m_{AS} and m_{AT} with time in PDMS covers and PDMS sidewalls. (a) The changes of m_A , m_{AS} and m_{AT} with time in a PDMS cover with the typical thickness of 200 µm. (b) The changes of m_A , m_{AS} and m_{AT} with time in a PDMS sidewall with the typical thickness of 5 mm.



Figure S2. The design of the microfluidic patch used for evaporation experiments through PDMS cover (a) and PET cover (b).



Figure S3. Photographs of the patches used for the evaporation experiment along the channels (a), and through the covers (b).



Figure S4. The design of the microfluidic patch used for evaporation experiment along microchannels.



Figure S5. Evaporation loss of water on water surface.



Figure S6. Evaporation loss rate of water in the evaporation experiments through PDMS covers (a), through PET covers (b), and along the channels (c).

Part II. Calculation process of R_{int}+R_{cov} for PET cover

The total cover area for the sixteen PET-based reservoirs is 12.56 cm². Over 31 hours, the cumulative mass loss due to permeative evaporation is 0.030g. Thus, the evaporation flux of the PET cover in this thickness was calculated to be 0.030 g \div $(12.56 \text{ cm}^{-2}) \div (31 \times 3600 \text{ s}) = 2.14 \times 10^{-8} \text{ cm}^2 \cdot \text{s}^{-1}$. The evaporation resistance along the permeative evaporation pathway can be derived from Eq (17), in which C_{sa} represents the mass concentration of water at the water-cover interface, determined by the saturation absorption rate of the material. For PET material, the saturation absorption rate is determined by the experiment as 0.377%, and the density of the PET is 1.08 g·cm⁻³. In this case, $C_{\rm sa}$ can be calculated by $C_{\rm sa} = 0.377 \times 10^{-2} \times 1.38$ g·cm⁻³ = 5.2×10⁻³ g·cm⁻³. Under experimental conditions of 26 °C and humidity of 51%, the mass concentration of water vapor in the air is 13.26×10⁻⁶ g·cm⁻³ g·cm⁻³. Then we can obtain the total evaporation resistance is 242990 s·cm⁻¹ according to Eq. (17). For the cover with the thickness of 12.5 µm, the sum of the interface resistance and diffusion resistance $(R_{int}+R_{cov})$ is equal to 242990 s·cm⁻¹. Using the same method, the values of $(R_{int}+R_{cov})$ for the covers with the thicknesses of 25, 38, and 50 µm can be figured out as 409548, 630990 and 748457 s·cm⁻¹, respectively.

Part III. Calculation process of evaporation resistance along channels

During the 306-minute experimental period, a cumulative evaporation loss of 0.0097 g was observed through 14 channels. The cross-section area of each channel is 0.00714 cm². The evaporation flux is calculated to be 5.28×10^{-6} g·cm⁻²·s⁻¹ according to Eq.(26). Under current experimental conditions, the concentration difference in Eq.(25) is 16.29×10^{-6} g·cm⁻³, so the total evaporation resistance is 3.09 s·cm⁻¹ according to Eq.(25). The diffusion resistance of the channel (R_{ch}) can be calculated as 3.09-1.42 =1.67 s·cm⁻¹. Using the same method, R_{ch} for the lengths of 1.0, 1.5, and 2.0 cm were calculated to be 4.06, 5.36, and 8.07 s·cm⁻¹, respectively.

Part IV. Calculation of evaporation loss of Sweat in the Flow State within Microfluidic Patch

During the sweat sampling process, the spaces of the reservoir and channels are continuously filled with sweat. The newly incoming sweat into the microfluidic patch increases the contact area between the sweat and the cover, while reducing the distance between the sweat front and the outlet of the channel. Assuming the average sweat rate of the sampling area is Q, the sweat density is ρ , and the height of the channel and reservoir is h, the evaporation loss of sweat through the cover during the sampling process is m_A , which is a function that varies with time t.

(1) Calculation of evaporation loss of sweat through covers

The contact area between the sweat and the cover (S_{cov}) can be obtained by dividing the volume of sweat in the patch by the channel height.

$$S_{\rm cov} = \frac{1}{h} \left(Qt - \frac{m_A}{\rho} \right)$$
(SI-1)

Eq. (16) can be rewritten as:

$$m_A = \int \frac{J_{\text{cov}4}}{h} (Qt - \frac{m_A}{\rho}) dt$$
(SI-2)

It can be further written as ordinary differential equations:

$$\frac{\mathrm{d}m_A}{\mathrm{d}t} = \frac{J_{\mathrm{cov}4}}{h} \left(Qt - \frac{m_A}{\rho}\right) \tag{SI-3}$$

By solving the above ordinary differential equation, with m_A as the dependent variable and time *t* as the independent variable, the evaporation loss mass through the cover during the sweat collection process can be obtained.

(2) Calculation of evaporation loss of sweat along channels

During the sweat collection process, the distance between the sweat front in the microfluidic channel and the outlet of the channel is

$$L(t) = L_0 - \frac{1}{S_{\rm ch}} \left(Qt - \frac{m_B}{\rho} \right)$$
(SI-4)

According to Eqs. (17) and (26), it can be derived that

$$m_B = S_{\rm ch} D_{\rm air} (C_{\rm sa} - C_{\infty}) \int \left[L_0 - \frac{1}{S_{\rm ch}} \left(Qt - \frac{m_B}{\rho} \right) \right]^{-1} dt$$
(SI-5)

It can be expressed in the form of the differential equation:

$$\frac{\mathrm{d}m_{B}}{\mathrm{d}t} = \frac{S_{\mathrm{ch}}D_{\mathrm{air}}(C_{\mathrm{sa}} - C_{\infty})}{L_{0} - \frac{1}{S_{\mathrm{ch}}}\left(\mathcal{Q}t - \frac{m_{B}}{\rho}\right)} \tag{SI-6}$$

Taking the reciprocal of both sides of the equation above:

$$\frac{\mathrm{d}t}{\mathrm{d}m_B} = \frac{1}{S_{\mathrm{ch}}D_{\mathrm{air}}(C_{\mathrm{sa}} - C_{\infty})} \left[L_0 - \frac{1}{S_{\mathrm{ch}}} \left(Qt - \frac{m_B}{\rho} \right) \right]$$
(SI-7)

First, the equation represented by $t=t(m_B)$ will be obtained by solving the ordinary differential equation where t is the dependent variable and m_B is the independent variable. Then, evaporation loss along the channel during sweat sampling process represented by $m_B=m_B(t)$ can be obtained by solving the inverse function of $t=t(m_B)$.

Part V. The evaporation loss of sweat in microfluidic patches worn on the skin

For PDMS microfluidic patches, the height and diameter of the reservoir are typically 200 µm and 3 mm, respectively. The thickness of the cover is approximately 200 µm. This analysis below is exemplified at an ambient temperature of 30°C. Under the conditions above, it is estimated that a single reservoir experiences an evaporation loss through the cover of approximately 0.062μ L per hour, constituting 4.4% of the total sweat volume in reservoirs whose volume is 1.41 μ L. Reducing the thickness of the cover to 100 µm approximately doubles the evaporation loss to about 0.124 µL, which accounts for 8.79% of the total sweat volume. Suppose three pressure-relief channels, each with the size of 2.5 mm in length, 100 µm in width, and 200 µm in height, are implemented to release the backpressure within the reservoir and prevent the retention of air bubbles during sequential sweat collection. In that case, the sweat's evaporation loss along these channels is approximately 0.027 μ L, representing 1.9% of the total sweat volume. For commonly utilized dimensions, the permeative evaporation loss through the cover significantly exceeds that along the channels. For PDMS patches, the total sweat evaporation loss in the reservoirs can reach about 6.3% to 10.7% per hour. If the temperature changes, the diffusion coefficient and the saturation water absorption rate of the material will also change. The impact of temperature on parameters related to evaporation loss is detailed in Part VI of this supplementary information.

<u>Part VI. The impact of temperature on material-related parameters</u>

in the diffusion equation

The temperature variations will affect the following four aspects: (1) The material's saturation water uptake, which will affect the C_{sa} . (2) The diffusion coefficient (D_{cov}), which thereby affect the evaporation resistance (R_{cov}). (3) The saturated water vapor concentration in the air ($C_{\text{sa-g}}$) and the ambient water vapor concentration (C_{∞}). (4) The diffusion coefficient of water vapor in the air (D_{air}).

(1) The influence of temperature on D_{cov}

The temperature dependency of the diffusion coefficient is manifested in^[S1]

$$D_{\rm cov} = D_0 \exp\left(-\frac{E_{\rm a}}{RT}\right)$$
(SI-8)

where E_a is the diffusion activation energy of the diffusing substance in the cover material (J·mol⁻¹), *R* is the ideal gas constant (J·mol⁻¹·K⁻¹), and *T* is the temperature (K). According to Eq. (SI1), the relationship between the diffusion coefficients at two different temperatures is given by:

$$\frac{D_{\rm cov}(T_1)}{D_{\rm cov}(T_2)} = \exp\left[\frac{E_{\rm a}}{RT}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]$$
(SI-9)

Thus, given the diffusion coefficient and diffusion activation energy of water in the cover material at a specific temperature, the diffusion coefficient at another temperature can be obtained.

(2) The influence of temperature on D_{air}

The diffusion coefficient of water vapor in air at a certain temperatures can be determined by^[S2]

$$D_{air} = \left(\frac{9.218 \times 10^{-4}}{p}\right) \left(\frac{T^{2.5}}{T + 245}\right)$$
(SI-10)

where *p* is the air pressure (Pa).

(3) The influence of temperature on C_{sa}

The mass concentration of water at the sweat-cover interface is determined by the saturation water uptake of cover material, which is determined by^[S3]

$$S_{1} = \exp\left(-\frac{u_{\rm r}^{\rm p} - u_{\rm r}^{\rm l}}{RT}\right)$$
(SI-11)

where u_r^p and u_r^l denote the excess chemical potentials of the cover material and water, respectively.

(4) The influence of temperature on $C_{\text{sa-g}}$

The saturated water vapor content at different temperatures can be obtained from the corresponding standard table.

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