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Technical note

Development of a small wireless device for perspiration monitoring

Kazuhiro Ogai[a,*], Masakazu Fukuoka[b], Kei-ichiro Kitamura[c], Kiyoshi Uchide[d], Tetsu Nemoto[c]

[a] Wellness Promotion Science Center, Institute of Medical, Pharmaceutical and Health Sciences, Kanazawa University, 5-11-80 Kodatsuno, Kanazawa, Ishikawa 920-0942, Japan
[b] Advanced Research Center for Human Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa, Saitama 359-1192, Japan
[c] Department of Clinical Laboratory Science, Graduate School of Medical Science, Kanazawa University, 5-11-80 Kodatsuno, Kanazawa, Ishikawa 920-0942, Japan
[d] Asanogawa General Hospital, Naka 83, Kosaka-machi, Kanazawa, Ishikawa 920-8621, Japan

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ABSTRACT

A small and wireless device that can capture the temporal pattern of perspiration by a novel structure of water vapor collection combined with reusable desiccant has been developed. The novel device consists of a small cylindrical case with a temperature/relative humidity sensor, battery-driven data logger, and silica gel (desiccant). Water vapor of perspiration was detected by the change in relative humidity and then adsorbed by silica gel, allowing continuous recording of perspiration within a closed and wireless chamber, which has not been previously achieved. By comparative experiments using the commercially-available perspiration monitoring device, the developed device could measure perspiration as efficiently as the conventional one, with a normalized cross coefficient of 0.738 with 6 s delay and the interclass correlation coefficient [ICC(2, 1)] of 0.84. These results imply a good agreement between the conventional and developed devices, and thus suggest the applicability of the developed device for perspiration monitoring.

1. Introduction

Perspiration, or sweating, is one of the most fundamental phenomena in human physiological events. The main result of systemic sweating is cooling effect for thermoregulation by sweat evaporation [1], which is called "thermal sweating." There is another type of sweating called "emotional (or mental) sweating." Emotional stresses (e.g., rising tension, upset, and concentration) trigger sweating, particularly on the face, palm, and sole via sympathetic nervous tone [2-4]. To date, a number of diseases have been reported to be associated with sweating abnormalities such as thyroid diseases [5], dysautonomia [6], menopause [7], and social anxiety disorder [8]. In addition, the perspiration monitoring can be utilized for prediction or diagnosis of nervous disorders such as brachial plexus avulsion (BPA) [9] and reflex sympathetic dystrophy [10]. Especially, the monitoring of sympathetic activity such as perspiration might be important for the early diagnosis of obstetric BPA [11], because it is often difficult for neonates to express their symptoms verbally. In light of the possible applications of ubiquitous perspiration monitoring such as a prediction or diagnosis of perspiration-related disorders, a small, convenient, and sensitive device for perspiration monitoring has been desired.

A skin conductance meter was used as an indirect method for estimation of sweating [12], and a simple humidity meter was employed to measure water evaporation from the skin [13,14]. Recently, wearable, adhesive, and tattoo-like sweat monitoring device have been proposed [15-17], although they are more intended for prediction of sweat electrolytes rather than perspiration amount, or they give an indirect index of perspiration. At this time the latest perspiration measurement device involves colorimetric detection by a digital camera, which requires special setup [18]. As a more direct measurement of water exchange, the vapor pressure diffusion method and ventilated chamber method were developed [19,20]. The vapor pressure method utilizes the theory that the amount of water exchange (F) in natural flow is calculated as $F = D(\partial p/\partial x)$, where D is the temperature- and atmospheric pressure-dependent diffusion coefficient, p is the water vapor pressure, and x is distance from the surface [19]. Because p can be calculated from relative humidity and temperature, at least four sensors [(humidity + temperature) × two points] are required. In addition, this method relies on the assumption that the state of the outer atmosphere is unchanging, which is unlikely in daily perspiration monitoring. To address this, a closed chamber system with water vapor condenser was proposed [21,22], although the coolant

* Correspondence author. Tel.: +81 76 265 2590; fax.: +81 76 265 2590.
E-mail address: kazuhiro@staff.kanazawa-u.ac.jp (K. Ogai).

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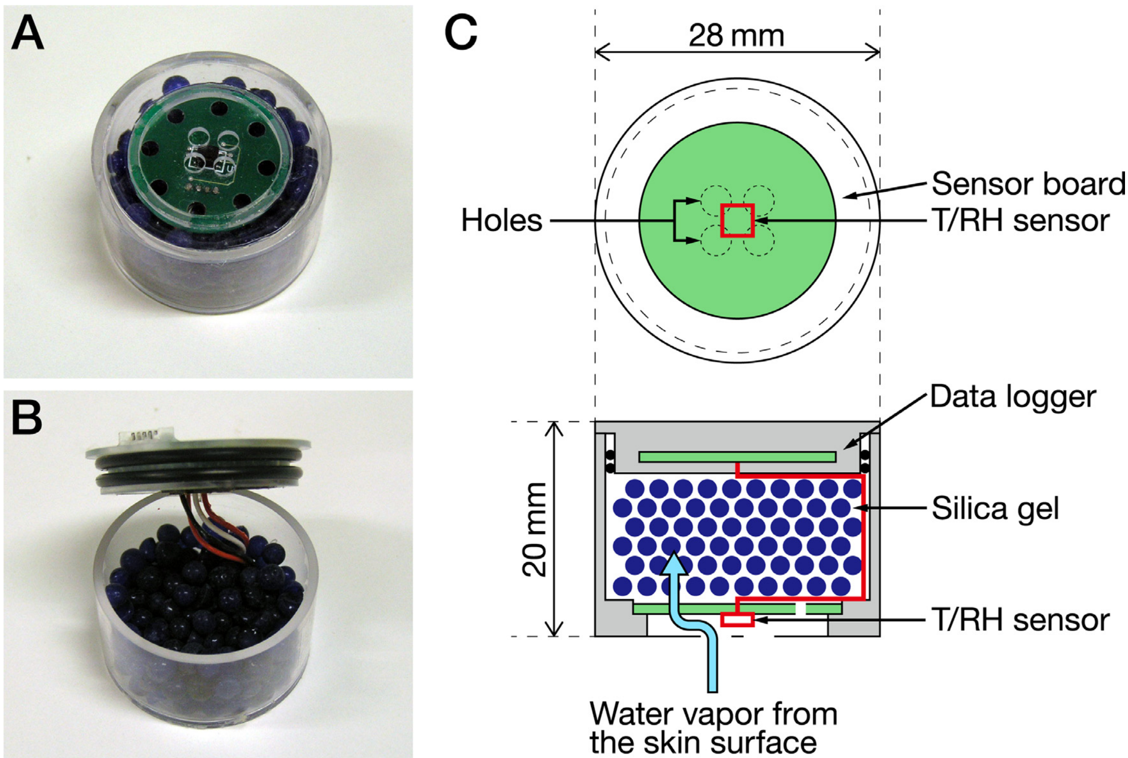

Fig. 1. Outline of the developed device. ((A) and (B)) Exterior of the device. A small plastic cylinder (A) contains a temperature/relative humidity (T/RH) sensor, electric boards, and silica gel (B). (C) Schematic of the device.

(Peltier device) is required and thus power consumption would be measurable. The theory of the ventilated chamber method is similar to that of the vapor pressure method, except this method uses forced and constant airflow. The constant airflow is injected into a small chamber adjacent to the skin, and the air with evaporated water vapor is collected in an outlet chamber. The amount of water exchange is then calculated with the airflow rate and difference of humidity between inlet and outlet air [19,20,23]. However, it is difficult to contain air ventilator and chambers in one small package such that it can be of practical use in daily life. Therefore, it was considered beneficial to develop a small device that could monitor perspiration and allow prediction of emotional and physiological status.

The aim of this study was to develop a small device for perspiration monitoring and compare its performance with a conventional sweat meter and stress analyzing method under conditions of mental stress.

2. Materials and methods

2.1. Developed device

Fig. 1 shows the exterior (Fig. 1A and B) and structure (Fig. 1C) of the developed device. A custom-made data logger circuit with battery, dry silica-gel (Wako Pure Chemical Industries, Ltd., Osaka, Japan), and a small temperature/relative humidity (T/RH) sensor (SHT-21, Sensirion AG, Zürich, Switzerland; accuracy of temperature is ±0.3 °C, accuracy of relative humidity is ±2%, calibrated at Industrial Research Institute of Ishikawa, Japan) with a sampling rate of 1 Hz was encapsulated in this order in a small plastic chamber toward measuring windows facing the skin (Fig. 1C).

2.2. Perspiration rate calculation

The theory of this equipment is based on the vapor pressure method [19,21] with modifications. Fig. 2 illustrates the method of perspiration measurement in the developed equipment. According to the Fick's law of diffusion, the flux of water vapor J (g m^{-2} s^{-1}) between two points can be calculated as Eq. (1):

$$J = -D\frac{\mathrm{d}H}{\mathrm{d}x} \tag{1}$$

where D (m^2 s^{-1}) is a diffusion coefficient of water vapor in the air, dH (g m^{-3}) is a difference of concentration of water vapor, and dx (m) is a distance between two points. In the developed equipment, two different fluxes of water vapor: from the skin surface to the T/RH sensor (Fig. 2A, green arrow; **s–w**), and from the sensor to the dry chamber (Fig. 2A, blue arrow; **w–d**), can be theorized. The flux difference between (**s–w**) and (**w–d**) could be detected as a change of humidity in T/RH sensor. The water exchange between the skin and silica gel via T/RH sensor should satisfy Eq. (2):

$$V\frac{\Delta H_x(t)}{\Delta t} = A_1J_1 - A_2J_2 = A_1D\frac{H_1(t) - H_x(t)}{L_1} - A_2D\frac{H_x(t) - H_2}{L_2} \tag{2}$$

where V (m^3) is a volume of wet chamber in which the T/RH sensor exists; $H_1(t)$, $H_x(t)$, and H_2 (g m^{-3}) are the concentrations (i.e., absolute humidity) of water vapor at the skin surface, T/RH sensor, and dry chamber, respectively; A_1 and A_2 (m^2) are the areas of windows at (**s–w**) and (**w–d**) junctions, respectively; J_1 and J_2 are the fluxes of (**s–w**) and (**w–d**), respectively; L_1 and L_2 (m) are the distances of (**s–w**) and (**w–d**), respectively (Fig. 2A). H_2 is assumed to be constant due to a buffering effect of desiccant (preliminary experiment is shown in Fig. S1). Because J_1 in Eq. (2) simply represents the flux of total water vapor from the skin surface [i.e., perspiration and constant transepidermal water loss (TEWL)], Eq. (2) can be solved for J_1 as following Eq. (3):

$$W(t) = J_1 = \frac{V}{A_1}\frac{\Delta H_x(t)}{\Delta t} + \frac{A_2}{A_1}\frac{D(t)}{L_2}(H_x(t) - H_2) \tag{3}$$

where the rate of water vapor diffusion from the skin $W(t)$ (g m^{-2} s^{-1}) can be calculated only by measuring $H_x(t)$ with T/RH

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