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高齢者の熱中症予防のためのウエアラブル発汗計の開発

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【抄録】

我々はこれまでに熱中症の危険を予知するためのウエラブル小型発汗計を開発してきた。今回の研究では、発汗によって生じる血液濃縮度を血液・尿検査と血液バゾプレシン濃度測定を用いて定量的に評価し、熱中症の危険を告知する時点の決定方法を開発し、その時点の正確度合いについて枯渇感を自己申告出来る装置を開発して検証した。その結果、温熱性発汗量、血液濃縮度、枯渇感、血中バゾプレシン濃度の変化から熱中症発症の危険度を推定出来る事を実証した。

１．研究の目的

我々は、スエーデンで開発された高感度湿度センサーを用いて、手掌部の発汗量を高感度で連続的に、しかも簡便に測定できる局所発汗量連続記録装置を開発しました。その装置は医用機器として認定され、厚生労働省から保険適用の許可を得て研究、臨床の現場で活用されています(**図１**)。

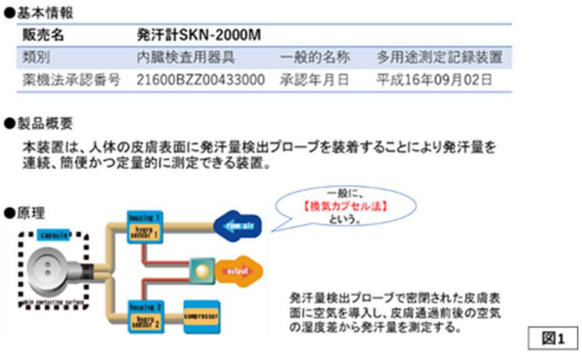

図1

１－１今回の研究目的

我々はこれまでに熱中症の危険を予知するためのウエラブル小型発汗計を開発してきた。(**図２**)。今回の研究では、発汗によって生じる血液濃縮度を血液・尿検査と血液バゾプレシン濃度測定を用いて定量的に評価し、熱中症の危険を告知する時点の決定方法を開発し、その時点の正確度合いについて枯渇感を自己申告出来る装置を開発して検証した。

図２小型ウエアラブル発汗計

２．研究方法

２－１枯渇感告知装置の開発

温熱性発汗を呈している時に感じる枯渇感を生体に装着したスマートホォンのアイコンをタッチすると無線で我々が既に開発した小型・ウエアラブル発汗計の記録上に同時に表示出来る装置を開発する。

２－２ヒト臨床研究

ヒト臨床研究を倫理委員会に申請して認可を受け、開発した小型発汗計と枯渇感告知スマートホンをボランテアの頸部ならびに前腕部にそれぞれ装着して、踏み段昇降の運動負荷を 30 分行い発汗量、告知られた枯渇感を同時記録する。併せて、運動負荷前後で、体重測定、採血、採尿を行い、血液濃縮度、血液バゾプレシン濃度変化、尿量、尿浸透圧変化を測定する。

２－３熱中症発生の危険度を告知するする時点の決定方法

発汗量、体重減少量、枯渇感発生タイミング、血中バゾプレシン濃度変化量、尿量、尿浸透圧変化の相関関係から血液濃縮度と熱中症発生の危険度を推定、告知するする時点を決定する。

３．研究成果

３－１枯渇感告知計の開発

温熱性・運動性発汗を起こしている時に感じた枯渇感を告知するスマートホン装置を開発した(**図 3**)。この装置は、温熱・運動性発汗時に感じた枯渇感を感じた際、スマートホンに表示された「枯渇感+（少し喉が乾いた。)」「枯渇感++（かなり喉が乾いた。)」「枯渇感+++（我慢できないほど喉が渇いた。)」のアイコンをタッチすると、そのタイミングが発汗曲線の上に記録されるように出来ている。測定データは Microsoft Excel でも表示可能な csv 形式として保存され、枯渇感を感じた時点に発汗量がどのように変化したかを記録・解析することができる。

図 3

３－２ヒト臨床実験結果

発汗量、体重減少量、枯渇感発生時点、血中バゾプレシン濃度変化、尿量、尿浸透圧変化の相関関係から血液濃縮と熱中症発生の危険度を検出するタイミングを決定するために１６名のボランテアで実験を行った。**図 4A の a,b** はその実験結果の典型例である。a は 40 歳台の女性,b は 40 歳男性が踏み段昇降運動を 30 分間行った時の頸部発汗量、枯渇感の告知時点（+、++、+++)、熱中症の危険告知時点(●)を示している。熱中症の危険告知時点は涸渇感の告知時点、血液バゾプレシン濃度上昇率、発汗曲線の増加率の相関関係から、発汗曲線の 2 次微分値が正から負に転じる時点（発汗曲線の傾きが鈍化し始めた時点）が妥当であると結論した。図 4B は熱中症の危険告知時点(横軸の 0 点)と被検者が枯渇感を感じた時点の 12 例のまとめたものである。4 例の被検者は 30 分の運動でも枯渇感を感じなかった。図から判るように 12 例中 9 例では熱中症の危険告知時点(横軸の 0 点)あるいはその

数分以内に枯渇感を訴えている。

A

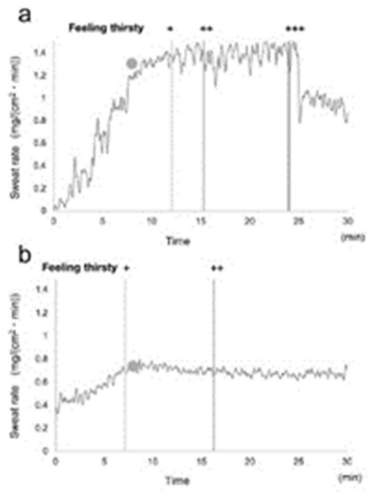

図 4A a: 40 歳女性、b: 40 歳台男性の 30 分運動時の発汗曲線、枯渇感告知時点（+、++、+++)、熱中症の危険告知時点(●)の典型例

B

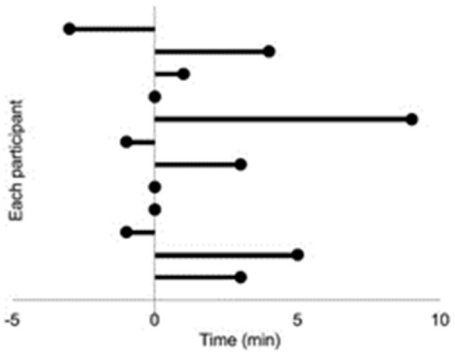

図 4B 熱中症の危険告知時点（横軸 0）と枯渇感告知時点(●）の 12 被検者の結果

４．結論

すでに開発した小型ウエラブル発汗計はヒトの臨床実験でその性能を評価してみると使用しやすく有用である事が確認できた。手掌部発汗計に比べ測定性感度は落ちるものの、小型カプセルを測定部位に両面テープで貼り付け、送信機をポケットなどに入れて使用すれば身体の動きなどに影響されることなく測定できる事を確認した。今回開発した枯渇感告知システムも小型ウエラブル発汗計と併用することで利用価値が高まる事を確認した。ヒト臨床実験で、熱中症の危険告知時点は発汗曲線の２次微分値が正から負に変わる時点が妥当である事が証明された。

５．考察

この研究で、小型ウエラブル発汗量測定計と今回開発した枯渇感告知システムを活用することで熱中症の危険を科学的根拠に基づいて告知する事が可能になった

６．謝辞

ヒトの臨床実験に参加頂いたボランテアの方々に心より御礼申し上げます。さらに本研究を経済面でご支援いただいた三井住友海上福祉財団研究助成に感謝致します。

７．今後の課題

研究目的の最終ゴールである老人介護施設で使用し、個々人の水分摂取習慣を把握して、毎日の生活での水分投与量を個々人で調節して熱中症を予防するヒト臨床研究を行いたいと考えている。

８．参考文献

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９．研究成果の公表方法

英文論文で発表すると同時に､新聞､テレビなどの公共報道を介して公表する。

Heatstroke risk informing system using wearable perspiration ratemeter

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We constructed an informing system to users for the heatstroke risk using a wearable perspiration ratemeter and the users' thirst responses. The sweating ratemeter was constructed with a capacitive humidity sensor in the ventilated capsule. The timing point for informing heatstroke risk was decided to change from positive to negative on the second derivative of sweating curve. In addition, a wearable self-identification and -information system of thirst response was constructed with a smartphone. To evaluate the validity of wearable apparatus, we aimed to conduct human experiments of 16 healthy subjects with the step up and down physical exercises. The blood and urine samples of the subjects were collected before and after the 30-min physical exercise. The concentrations of TP, Alb, and RBC increased slightly with the exercise. In contrast, the concentrations of vasopressin in all subjects remarkably increased with the exercise. In almost subjects, they identified their thirst response until several min after the informing for heatstroke risk. In conclusion, the wearable ratemeter and self-information system of thirst response were suitable for informing system of heatstroke risk. The validity of timing point for informing heatstroke risk was confirmed with changes in the thirst response and concentrations of vasopressin in blood.

1.Aim of Research

To inform the risk to expose heatstroke to the user via a sound from the smartphone, we constructed (1) a new designed wearable perspiration ratemeter by modifying the original, (2) a wireless self-identifcation and self-information system with the smartphone for thirst response, and (3) a system that informs the heatstroke risk to the users. In addition, to evaluate the validity the timing point to inform automatically for the heatstroke risk to the user using a changing point of negative value on second diferentiation of sweating curve, we conducted human experiments with a-30 min step up and down physical exercise and simultaneously recorded exercise-induced sweating on the neck and the thirst response. Te changes in the concentrations of vaso-pressin, blood and urine samples, body weight, and heart rate before and after the exercise are measured to evaluate the relationship between the vaso-pressin release and the self-identifcation of thirst response related to the activation of osmo-receptors in the hypothalamus.

2.Method of Research

2-1.Ethical approval

The study was approved by the Ethical Committee for Human Clinical Studies at the School of Medicine, Shinshu University (CRB3200010, approval no. 4445 on 6th August 2019). All study data and procedures were performed in accordance with the principles outlined in the Declaration of Helsinki. The study is registered in the WHO International Clinical Trial Registry Platform (13th/August/2022,https://www.who.int/clinical-trials-registry-platform: jRCT-1032220270, Analysis of mental and thermal sweating in human subjects using galvanic skin response and domestic-made perspirationratemeter).

2-2.Construction of wearable perspiration ratemeter and self-information apparatus with a smart- phone.

Previously we constructed a high-sensitive perspiration ratemeter which is suitable for measuring active palmar sweating. Tus, a maximum value in the step response is obtained at approximately 0.63 s. The sensitivity of the electrical performance is 0.1/1 mg water loss/1 min. With the modifcation of original perspiration ratemeter, we constru-

cted a wearable concise rate-meter with a capacitive humidity sensor, a small fan, and a lithium-ion battery in the venti-lated capsule. To inform the self-identifed thirst response to the observer, we also constructed a wearable self-identifcation and self-information apparatus of thirst response with a smartphone.

2-3.Subjects.

In total, 16 healthy participants (mean age: 41.6±3.3 years old; eight males and eight females) were enrolled in the present experiments. The body mass index (BMI) of the males and females were 23.7±0.7 and 21.5±0.5, respectively. The minimum number of participants was recommended by the ethical committee for the clinical obser-vation study. Hence, the minimum number we chose was suitable for obtaining a valid conclusion. All the participants provided written and oral informed consent after the detailed explanation and table showing of experimental design, methods, expected results, scientific background and value, compensatory medical tools for harmful damage, and stopping guidelines by the corresponding author. All the data and procedures were confirmed to the tenets of the Declaration of Helsinki. The collected data were stored in Shinshu University School of Medicine with responsibility. All human experiments were conducted in the afternoon from 1:00 to 4:00 pm, considering maximal and stable activity of sympathetic nerve fibers in human circadian rhythm. The temperature and moisture of the examination room were maintained within the range of 22–23 °C and 40–50%, respectively, using air condi-tioners.

2-4.Experimental protocols

This study was a randomized trial human experiments. A total of 16 healthy participants were enrolled in this study. The subjects were inhibited from water intake and excretion of urine for 1 h before and during the experiments. Immediately before a 30-min step up and down exercise, blood and urine samples were collected from the participants. A wearable per-spiration ratemeter and a self-identifcation and self-information apparatus with a smartphone for thirst response were positioned on their necks and forearms. The step up and down physical exercise lasted for 30 min. The strength of the exercise was approximately 70 Nm, that is, a moderate level, and the average of their pulse rates was approximately 120.9 beats per min. After the 30-min exercise, their blood and urine samples were collected. In addition, their body weights were measured before and after the physical exercise. To evaluate the exercise-induced hemoconcentration, the concent-rations of total protein (TP), albumin (Alb), and red blood cells (RBL) in their blood samples were measured by a clinical examin-ation laboratory in Shinshu University Hospital. In addition, to investigate the relationship between the thirst response and changes in the concentration of vasopressin, the concentrations of vasopressin in blood were measured before and after the 30-min physical exercise by SRL Co. Inc. (ISO 15189-accredited by Japan Accreditation Board, RML 00080, Tokyo, Japan). To investigate the relationship between water loss per body surface area and the decreased level of body weight, we used the formula 71.84× height0.725× weight0.425× 10−416. The body mass index (BMI) was also calculated by body weight/body height2 (kg/m^2).

2-5.Statistical analysis

All the data were represented as the mean ±standard errors of the mean. Statistical significance was analyzed using the Student's t-test for unpaired observations (Microsoft Excel, version 16.54). $p<0.05$ was considered statistically significant. The relationship between the wearable ratemeter output and water loss in the sweating was compared using linear regression. The Pearson correlation coefficient, r was obtained (Microsoft Excel, version 16.54).

3.Results of Research

3-1.Construction of wearable

per-spiration ratemeter
To measure large amounts of exercise-induced sweating, we constructed a new wearable perspiration ratemeter (Fig. 1). It is extremely small (55 mm×17 mm×46 mm) and lightweight (35 g). Instead of the airflow circulating system of the original ratemeter, a small fan (UB393-700, Sunon, Japan) is equipped on the top of the ventilated capsule to perfuse air from the upper to the lower chamber. A capacitive humidity sensor (BME280, Bosch, USA) is fixed in each chamber, and a lithium-ion battery is used for the power supply. Both the difference of humidity between the lower and upper chambers and the temperature of the perfused air are calculated in the sweating rate using a microcomputer system. Thus, the absolute amount of water loss per constant time and area of the skin surface is registered on a chart recorder.

Figure 1

3-2.Wearable self-identifcation and self-information apparatus of thirst response.
To evaluate the relationship between thirst response and exercise-induced sweating, we constructed a self-identifcation and self-information apparatus for thirst response during physical exercise using the wearable smartphone. Figure 2 shows the schematic of the apparatus. When the participants were thirsty, they selected a thirst level among three levels of thirst (mild+, middle++, and severe+++) and subsequently touched the level on the display of the smartphone. The apparatus was placed on the participants' forearms. By using the apparatus, both the level and timing point were recorded simultaneously on the sweating curve of the users.

Figure 2

3-3.Evaluation of the constructed system informing the heatstroke risk in human subjects with physical exercise.
To evaluate the validity of timing point for informing the heatstroke risk to users, with human experiments we investigated the relationship between the informing point for the heatstroke risk and the self-identification point of thirst response, and relationship between the self-identification of thirst response and changes in the concentration of vasopressin in blood, urine volume and urine osmolality.
Effects of physical exercise on sweating on the neck and thirst level of participants. Figure 3A illustrates the representative exercise-induced sweating curves measured using the wearable perspiration ratemeter on the necks of two participants: (a) 40-years old female and (b) 40-years old male. In addition, the timing point of the thirst levels is shown using three levels of thirst responses (grade;+, mild;++, strong;+++, severe) on the same sweating curves. The participants were thirsty for several minutes following the informing points of heatstroke risk (●), which were electrically decided as the value of the second derivative of sweating curve changed from positive

to negative.
Figure 3B demonstrates the data of 12 participants for the relationship between the informing point for heatstroke risk and the self-identification of thirst response. The rest 4 participants did not identify the thirst response during the 30 min physical exercise. The time point informed the heatstroke risk represents zero in the abscissa of Fig. 3B. The plus and minus values in the abscissa show the time identified thirst response in each participant
after and before informing time for heatstroke risk (zero value), respectively. Seven participants identified their hirst response during 0–10 min after the informing time. Only 3 participants noticed the thirst response around 1–3 min before the informing time.

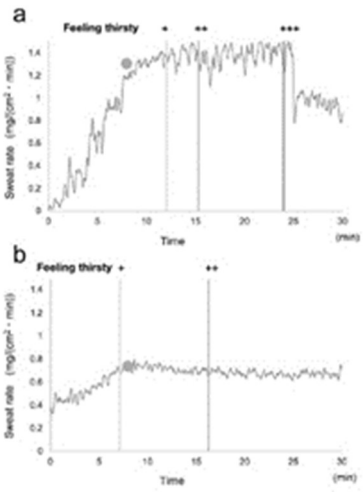

Figure 3A

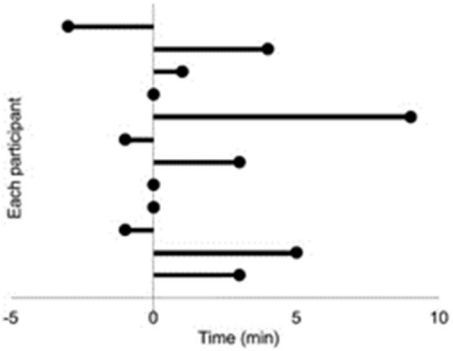

Figure 3B

4.Conclusion

Several studies on the advantages of fluid ingestion on thermoregulatory and cardiovascular responses during progressive dehydration-related hemoconcentration have been reported. However, the contribution of exercise-induced sweating in dehydration-related hemoconcentration and information systems for heatstroke risks, to the best of our knowledge, has not yet been evaluated. Therefore, we developed a wearable sweating ratemeter for informing the users of heatstroke risk.

5.Future Area to Take Note, and Going Forward

The constructed system will be needed in the future to evaluate in detail with additional clinical experiments included old persons. Especially, we should reevaluate, in the future, the suitability to decide the informing point for heatstroke risk.

6.Means of Official Announcement of Research Results

In the future, we have attempted to publish the present results in the official international journal. We also have a plan to demonstrate the present results in the newspapers or using the television system.

7.References

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