Cooling Effects of Wearer-Controlled Vaporization for Extravehicular Activity

Kunihiko Tanaka; Daiki Nagao; Kosuke Okada; Koji Nakamura

INTRODUCTION: The extravehicular activity suit currently used by the United States in space includes a liquid cooling and ventilation garment (LCVG) that controls thermal conditions. Previously, we demonstrated that self-perspiration for evaporative cooling (SPEC) garment effectively lowers skin temperature without raising humidity in the garment. However, the cooling effect is delayed until a sufficient dose of water permeates and evaporates. In the present study, we hypothesized that wearer-controlled vaporization improves the cooling effect.

METHODS: Six healthy subjects rode a cycle ergometer under loads of 30, 60, 90, and 120 W for durations of 3 min each. Skin temperature and humidity on the back were measured continuously. Subjects wore and tested three garments: 1) a spandex garment without any cooling device (Normal); 2) a simulated LCVG (s-LCVG) or spandex garment knitted with a vinyl tube for flowing and permeating water; and 3) a garment that allowed wearer-controlled vaporization (SPEC-W).

RESULTS: The use of s-LCVG reduced skin temperature by 1.57 ± 0.14°C during 12 min of cooling. Wearer-controlled vaporization of the SPEC-W effectively and significantly lowered skin temperature from the start to the end of cycle exercise. This decrease was significantly larger than that achieved using s-LCVG. Humidity in the SPEC-W was significantly lower than that in s-LCVG.

DISCUSSION: This preliminary study suggests that SPEC-W is effective in lowering skin temperature without raising humidity in the garment. The authors think it would be useful in improving the design of a cooling system for extravehicular activity.

KEYWORDS: extravehicular mobility unit, liquid cooling and ventilation garment, perspiration, priming, humidity.

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A space suit for extravehicular activity (EVA) is closed, airtight, and pressurized to protect the human body from the vacuum of space. The space suit currently used by the United States—the extravehicular mobility unit (EMU)—is pressurized with 100% oxygen at 0.29 atm (220 mmHg or 29.6 kPa) during EVA.[8,13] Working in an EMU generates heat from the human body and the heat cannot escape from the enclosed insulated suit. Without any effective way to remove heat from the suit, astronauts become uncomfortably hot, leading to heat exhaustion.[2]

To keep the inside of the EMU at a constant temperature of 27°C, a liquid cooling and ventilation garment (LCVG) is currently worn by all astronauts performing EVA. The LCVG has two major components, namely the liquid cooling garment and a ventilation unit.[3,11] The liquid cooling garment is constructed of elastic Spandex and vinyl tubes knitted into the garment. The ventilation unit or airflow duct is sutured over the garment. The vinyl tubes cover the surface of the garment and impair water-vapor transportation from the body. Thus, water vapor is condensed and perspiration is accumulated in the layer near the skin. The accumulation makes astronauts uncomfortable.[10]

Previously, we demonstrated that a cooling garment with self-perspiration, which is a vaporing function where water permeates from knitted shorter tubes, effectively cools the body. The self-perspiration for evaporative cooling (SPEC) suit cools the body without raising humidity in the garment.[11] However, the cooling effect does not begin at the start of water perfusion and is delayed until sufficient water permeates and evaporates. We now hypothesize that the cooling effect is improved if the

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wearer controls the vaporization directly, especially at the onset of perfusion. To test this hypothesis, we developed a wearer-controlled vaporing function for the SPEC suit and evaluated its performance.

METHODS

Subjects

Six healthy male subjects with a mean ± SE of age, height, and weight of 21 ± 0.3 yr, 170.8 ± 3.0 cm, and 60.5 ± 4.1 kg, respectively, were recruited for the study. The subjects were not medicated and had no past history of cardiovascular disease. The study was approved by the Institutional Review Board at the Gifu University of Medical Science, and informed written consent was obtained from all subjects.

Equipment

The subjects wore three types of garments. All garments were based on elastic underwear made with spandex and were tightly fitted to the upper body. The first was a spandex garment without any additional cooling device (Normal). The second was a simulated LCVG (s-LCVG).[12] A vinyl tube having the same structure as that of the current LCVG for flowing water (with an inner diameter of 1.6 mm, outer diameter of 3.2 mm, and length of 12.2 m) was knitted into the back of the underwear, which is the same as Normal.[3,14,15] Water cooled at 14°C was circulated at a rate of 1.8 L · min^{-1} (240 lb · h^{-1}) during exercise.[5,9] The third was also based on the same spandex underwear with a tube on the back. However, the tube was designed not only for cooling with cold water, but also self-perspiration for evaporative cooling and wearer-controlled vaporization (SPEC-W). In the case of this SPEC-W garment, self-perspiration is induced by water permeation from 10 pores in the tube for cooling with heat loss by evaporation (**Fig. 1**). The material of the tube was similar to that of s-LCVG, but the tube was wider and shorter (having an inner diameter of 4 mm, an outer diameter of 6 mm, and length of 3.2 m). The tubes were sewn to the outside of the garment to avoid lifting the fabric away from the skin. This condition also enhances moisture absorption, unlike the case for the LCVG, the tubes of which are knitted into the garment. The tubes of the s-LCVG ran mostly straight, but the direction of the tube was rounded to improve the ability to stretch, i.e., mobility. Water cooled at a similar temperature and flowing at a similar rate as the water for the s-LCVG was also circulated. Water permeated through pores in the tube at a rate of 1 mL · min^{-1} over the back. The number of pores and the amount of permeating water were half those for our previous SPEC suit.[11] In addition to the permeating water function, the subject could control the vaporization of water as an additive evaporative cooling function. When a subject pressed a button at their hand, 1.8 mL of water mist is sprayed from a tip of a tube fixed at the top of the back of the garment (Fig. 1). Water for vaporizing is supplied from the same reservoir used for circulation. Wearer-controlled vaporization was also performed once at the start of the exercise and water circulation. All subjects tested all garments on different days. The order of testing was randomized. For all tests, airflow was started during the setup in advance and provided to the back of a subject at a speed of 1 m · s^{-1} throughout the measurement.

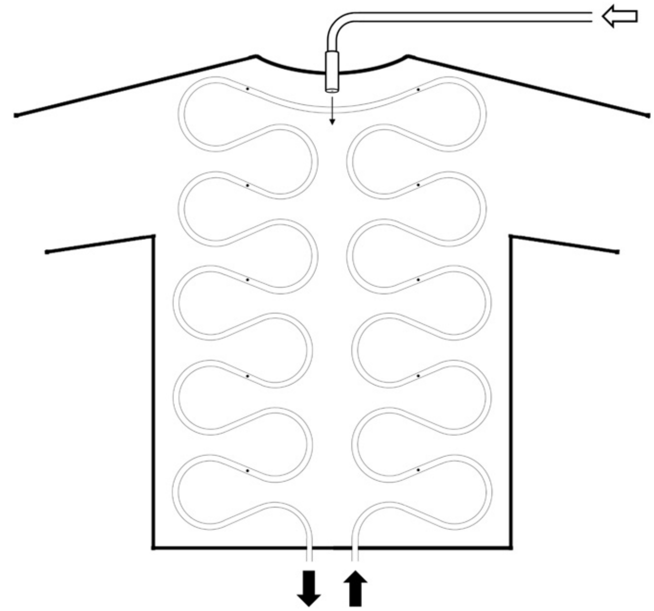

Fig. 1. Schema of self-perspiration for the evaporative cooling garment with wearer-controlled vaporization (SPEC-W). A tube through which cooling water flows for heat exchange is sutured over the garment. Dots on the tubes depict locations of water permeation. The black arrows show water flowing into and out of the tubes. Wearer-controlled vaporizing water is supplied from the same tank as that used for flowing water, as shown by the white arrow. Water mist is sprayed from the tip of a tube fixed to the top of the back of the garment.

The skin temperature over the scapula was measured using thermistors (DL-240, S&ME, Tokyo, Japan).[3] Humidity in the garment was measured using a hygrometer (CFS-GSS, TDK, Tokyo, Japan) over the vertebral column at the level of the scapular spine. These measurements were monitored and recorded continuously using an analog-to-digital converter with data acquisition and analysis software (RMT-1000, Nihon Koden, Tokyo, Japan) at a rate of 200 samples/second.

Procedure

Exercise tests were performed using an electronically braked ergometer cycle (EZ101, Combi Wellness, Tokyo, Japan). Room temperature and humidity were maintained at 27°C and 47%, respectively. After stabilization of all measurements, resting baseline data were collected for 3 min. Thereafter, exercise was performed at 30, 60, 90, and 120 W for 3 min each.[4] Time zero was set at the start of exercise. The mean skin temperature and humidity at the back during rest were considered baseline values. All measurements were performed at 3, 2, and 1 min before exercise and during the last minute of each load. These values were averaged and compared with the baseline values.

Statistical Analysis

The summarized data are represented as mean ± SE. To compare the baseline measurements, one-way analysis of variance was performed. To analyze the time course of the changes, a repeated-measure two-way analysis of variance was performed with time and conditions as factors. If statistically significant results were obtained, Scheffe's and Fisher's post hoc tests were employed for comparison within and between conditions, respectively. Statistical significance was set at $P < 0.05$.

RESULTS

Fig. 2 presents averages of baseline values of skin temperature and humidity for each garment. No significant differences were observed with one-way analysis of variance among garments during the resting periods ($P = 0.60$ and 0.77 for skin temperature and humidity, respectively).

Fig. 3 shows changes in skin temperature during exercise for the three garments. In the case of the Normal garment, skin temperature gradually but significantly decreased during exercise in spite of the increase in exercise load. The change reached significance at 90 W and skin temperature further decreased at 120 W compared with that during rest [−0.36 ± 0.14°C and −0.51 ± 0.14°C, $F(8, 24) = 10.02$, $P = 0.032$ and 0.0022 at 90 and 120 W, respectively, with Scheffe's post hoc test]. In the case of s-LCVG, skin temperature decreased linearly with time in spite of the increase in the exercise load. The change depended on the subject but reached significance at 30 W and skin temperature further decreased at 60, 90, and 120 W [−0.57 ± 0.17°C, −1.0 ± 0.15°C, −1.4 ± 0.14°C, and −1.6 ± 0.14°C, $F(8, 24) = 10.02$, $P = 0.0061$, $P < 0.0001$, $P < 0.0001$, and $P < 0.0001$ at 30, 60, 90, and 120 W, respectively, with Scheffe's post hoc test]. In the case of the SPEC-W garment, skin temperature promptly decreased significantly compared with that during rest. The change again reached significance at 30 W and skin temperature further decreased at 60, 90, and 120 W [−2.2 ± 0.52°C, −3.2 ± 0.71°C, −3.9 ± 0.83°C, and −5.2 ± 0.71°C

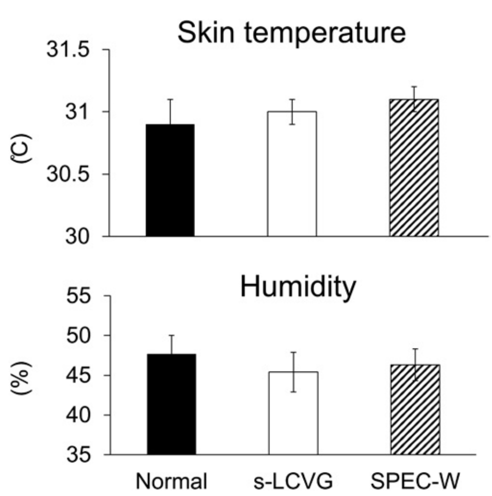

Fig. 2. Averages of baseline values of skin temperature and humidity on the back during rest and while wearing the garment without a cooling tube (Normal), the simulated liquid cooling and ventilation garment (s-LCVG), and the self-perspiration for evaporative cooling garment with wearer-controlled vaporization (SPEC-W).

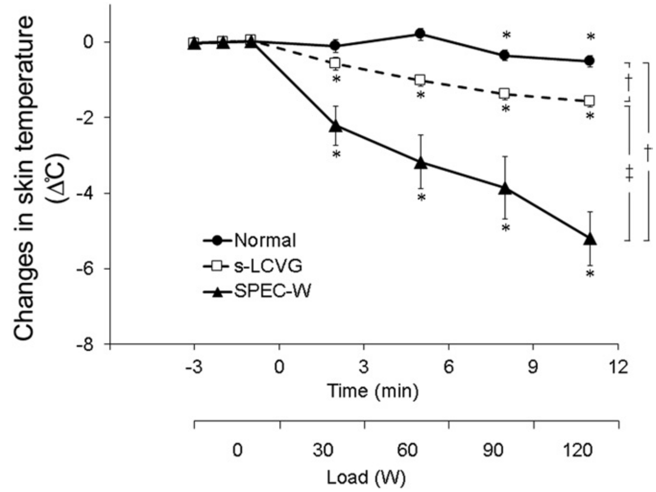

Fig. 3. Changes in skin temperature on the back during exercise using a cycle ergometer while wearing the garment without cooling tubes (Normal), the simulated liquid cooling and ventilation garment (s-LCVG), and the self-perspiration for evaporative cooling garment with wearer-controlled vaporization (SPEC-W). Values are means ± SE. *$P < 0.05$ vs. pre-exercise, †$P < 0.05$ vs. Normal, ‡$P < 0.05$ vs. s-LCVG.

$F(8, 24) = 10.02$, $P = 0.017$, $P = 0.0007$, $P < 0.0001$, and $P < 0.0001$ at 30, 60, 90, and 120 W, respectively with Scheffe's post hoc test]. The decreases were significantly larger than those in the case of the Normal and s-LCVG [$F(6, 25) = 3.78$, $P = 0.0092$ and 0.0080 vs. Normal and s-LCVG, respectively with Fisher's post hoc test].

Fig. 4 shows changes in humidity in the three garments during exercise. In the cases of the Normal and SPEC-W garments, humidity increased gradually with time and exercise load, and the change relative to the humidity before exercise was statistically significant at the end of measurements [+7.1% ± 2.4% and +7.1% ± 2.3%, $F(8, 16) = 2.20$, $P = 0.029$, 0.0022 for Normal and SPEC-W, respectively, at 120 W with Scheffe's post hoc test]. No significant difference was observed between Normal and SPEC-W despite continuously permeating water in SPEC-W. However, humidity in s-LCVG further and significantly increased at 90 and 120 W [+13.3% ± 1.1% and +13.6% ± 0.9%, $F(8, 22) = 1.82$, $P = 0.029$ and 0.027, respectively, at 90 and 120 W with Scheffe's post hoc test], and the increase was significantly greater than increases for Normal and SPEC-W [$F(48, 88) = 29$, $P < 0.0001$ vs. Normal and SPEC-W with Fisher's post hoc test].

DISCUSSION

In the present study, we clarify that: 1) the SPEC-W garment promptly and significantly decreases skin temperature; and 2) humidity in the SPEC-W garment is significantly lower than that in s-LCVG in spite of the garment being wetted directly by both vaporizing and permeating water. The Normal garment used in the present study is made of spandex similar to that used for the current LCVG. Normal has no water cooling device and yet the skin temperature tended to decrease during

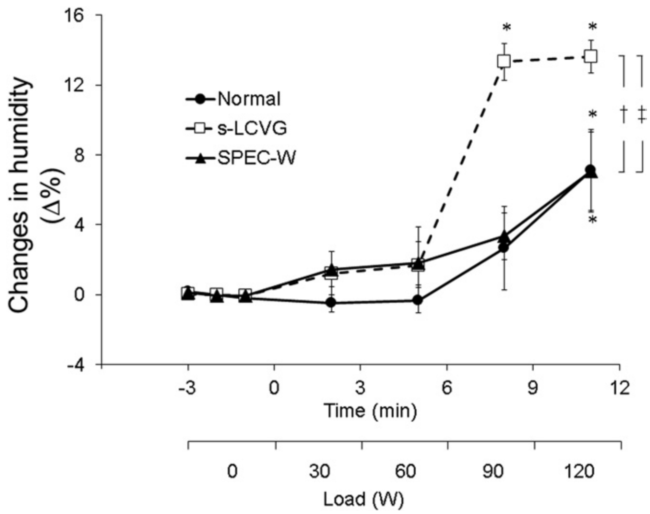

Fig. 4. Changes in humidity inside the garment during exercise using a cycle ergometer while wearing the garment without cooling tubes (Normal), the simulated liquid cooling and ventilation garment (s-LCVG), and the self-perspiration for evaporative cooling garment with wearer-controlled vaporization (SPEC-W). Values are means ± SE. **P* < 0.05 vs. pre-exercise, †*P* < 0.05 vs. Normal, ‡*P* < 0.05 vs. s-LCVG.

exercise. The change might be due to the evaporation of perspiration of the subjects themselves by airflow. The open-knit construction with Spandex provides breathability to remove moisture.[3] Thus, the effect of lowering temperature without cooling water might be observed.

In spite of the evaporative effect of the garment itself, a larger increase in humidity for s-LCVG was observed, compared with the humidity for the Normal and SPEC-W garments. The accumulation of perspiration in the layer near the skin or the impairment of evaporation is probably produced by the vinyl tubes that have a wider area of coverage in the s-LCVG. However, in the case of the s-LCVG, there is a linear and continuous decrease in skin temperature due to heat loss related to circulating cold water.[11] The results of lower skin temperature and higher humidity suggests that s-LCVG cools both skin and sweat. The wet condition is probably a cause of discomfort when wearing an LCVG.[10]

Previously, we developed and evaluated the cooling effects of the SPEC garment.[12] The SPEC garment has cooling effects associated with both cold water and evaporation. Circulating water induces heat loss similar to that in the case of s-LCVG and the evaporation of permeated water with airflow further decreases skin temperature. The area whereby cooling tubes cover the back in the case of the SPEC is 65% of that in the case of the s-LCVG. The smaller tube area, or greater evaporating area, facilitates evaporation of perspiration and permeated water. As a result, the SPEC lowers skin temperature without raising humidity during exercise. However, cooling through evaporation does not take effect until an appreciable amount of water has permeated through the pores and the cooling effect at the onset of exercise is thus less than that in the case of the s-LCVG. To address this point, a wearer-controlled vaporing function was added and tested at the onset of exercise in the present study. The function effectively decreases skin temperature from the onset of exercise. However, the effect continues throughout the exercise and the temperature is 5.2°C below baseline, which is much greater than the 2.1°C difference without the wearer-controlled function obtained in our previous study.[12] In the present study, the number of pores for permeating water is half the number in the former SPEC garment in order to employ the wearer-controlled vaporing function. However, the temperature was lower not only at the permeating time but also at the onset of exercise. The first wetting with water for vaporizing might have a water priming effect between the tube and garment, thus enhancing the permeation.[6] Skin temperature thus is further decreased, but humidity in the garment is not significantly higher than that in Normal owing to effective evaporation. Lowering skin temperature excessively with a cooling garment causes cutaneous vasoconstriction. This would prevent heat loss from the surface of the body and raise core temperature.[1] Thus, the configuration of cooling factors such as the temperature of the circulating water, airflow, speed of water permeation, and amount of wearer-controlled vaporing water may need further evaluation.

In the present study, we investigated additional effects of wearer-controlled vaporization for skin cooling. Thus, all measurements were obtained only on the back and performed in an open laboratory with the equipment of measurement and exercise. Flow speeds of air and water and water temperature are those used for the current EMU, but the vaporizing effect in the laboratory should be greater than that in the closed and tight space likely in the EMU. The evaporation of natural perspiration and insensible water loss raises humidity in the EMU. Thus, this high humidity prevents cooling by evaporation and creates condensation in the suit. The SPEC or SPEC-W garment has to be studied with a dehumidifier or any equipment for removing humidity and moisture,[7] and needs to be examined in a closed environment or in the impermeable outer garment for future practical use. The original LCVG is designed to minimize the increase in body temperature and perspiration, but if the dehumidifier is successful, the SPEC-W garment may further suppress the humidity in the garment as shown in the present study. Without any tubes, evaporation of perspiration would cool the body. Perspiration with evaporation is our effective cooling system, but astronauts must raise body temperature to perspire for cooling the body in that case. That condition conflicts with the concept that cooling garments prevent the body from overheating. To eliminate the conflict, we made and reported the cooling effects of self-perspiration of the garment in our previous study.[12] In the present study, a manual procedure was just added to compensate for the weak design point of less cooling effect during the initial period.

In conclusion, a self-perspiration garment with a wearer-controlled vaporing water function for lowering skin temperature is now developed and tested. Importantly, our new garment is effective in lowering skin temperature without raising humidity in the garment from the onset of cooling. The authors think it would be useful in the design of a future cooling system for EVA without discomfort due to the accumulation of sweat.

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