Acta Astronautica 104 (2014) 260–265

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Self-perspiration garment for extravehicular activity improves skin cooling effects without raising humidity

Kunihiko Tanaka [a,*], Koji Nakamura [b], Tetsuro Katafuchi [a]

[a] Gifu University of Medical Science, Department of Radiological Technology, 795-1 Ichihiraga Seki, Gifu 501-1194, Japan
[b] Gifu University of Medical Science, Department of Medical Technology, Seki, Gifu 501-3892, Japan

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form
7 August 2014
Accepted 10 August 2014
Available online 17 August 2014

Keywords:
Extravehicular mobility unit
Liquid cooling and ventilation garment
Perspiration
Heat conduction
Humidity

ABSTRACT

Introduction: The current U.S. extravehicular activity (EVA) suit in space includes liquid cooling and ventilation garment (LCVG) to control thermal condition. Tubes knitted in LCVG for flowing water interrupt evaporation of perspiration, and astronauts feel discomfort. In the present study, we hypothesized that a self-perspiration garment would effectively lower the skin temperature without raising humidity in the garment. Thus, we developed and examined the effects of the garment.

Methods: Eight healthy subjects were studied with a cyclic ergometer of 30, 60 90 and 120 W loading for 3 min each. Skin temperature and humidity on the back were measured continuously. Subjects wore and tested three types of garments i.e., a spandex wear without any cooling device (Normal), a simulated LCVG (s-LCVG) or the spandex wear knitted a vinyl tube for flowing water, and the spandex wear with a tube, which flows water and self-perspiration with oozing water for evaporative cooling (SPEC).

Results: All measurements were reached to steady state 2–3 min after the setting. The s-LCVG decreased skin temperature 0.39 ± 0.14 °C during 12 min of cooling. With SPEC, skin temperature did not decrease significantly until 6–9 min after starting the cooling. However, the temperature decreased rapidly and significantly after that, and finally decreased 1.59 ± 0.32 °C. Humidity in the SPEC was significantly lower than that in s-LCVG.

Discussion: SPEC was effective for lowering skin temperature without raising humidity in the garment. The concept is expected to use as a better cooling system during EVA.

1. Introduction

A space suit for extravehicular activity (EVA) is pressurized to protect the human body from the vacuum of space. The current U.S. space suit, extravehicular mobility unit (EMU) is pressurized with 100% oxygen at 0.29 atm (220 mmHg or 29.6 kPa) during EVA [1,2]. According to the pressure differential between the inside and outside of EMU, the flexibility of the suit and therefore mobility is lowered, and the activity must be hard exercise [3]. Thus, working in EMU generates heat from the human body, and the heat can go nowhere in the enclosed insulated suit. Without any effective way to remove heat from the suit, the astronauts would become uncomfortably hot, leading to head exhaustion [4]

In order to keep the inside EMU at a constant temperature of 300 K (27 °C), liquid cooling and ventilation garment (LCVG) is currently worn by all astronauts performing EVA. LCVG is consisted of two major components, i.e., liquid cooling garment and ventilation unit [5,6]. The liquid cooling garment is constructed of elastic Spandex and vinyl tubes knitted into the garment. The tubes for cool water to flow is fitted for the

Abbreviations: EVA, extravehicular activity; EMU, extravehicular mobility unit; LCVG, liquid cooling and ventilation garment; SPEC, self-perspiration for evaporative cooling

* Corresponding author. Tel.: +81 575 22 9401; fax: +81 575 23 0884.
E-mail addresses: ktanaka@u-gifu-ms.ac.jp (K. Tanaka), nakamura@u-gifu-ms.ac.jp (K. Nakamura), katafuchi@u-gifu-ms.ac.jp (T. Katafuchi).

http://dx.doi.org/10.1016/j.actaastro.2014.08.009
0094-5765/

body by the elastic garment. The ventilation unit or airflow duct is sutured over the garment, and it helps in thermal absorption especially from the head, where it is not covered by any garment. However, the effect of the ventilation garment is modest, and is not effective except the head because of poor water-vapor transportation properties of Spandex and vinyl tubes. Water vapor is condensed and perspiration is accumulated in the layer near the skin. The accumulation lowers cooling efficiency and provides discomfort to the astronaut [7]. If the liquid cooling garment is not worn, and the ventilation unit is effective, our own cooling system such as heat dissipation via the dilated cutaneous blood vessels and evaporation of the perspiration might be effective. However, it is paradoxical since the astronauts have to be heated to induce vasodilation and perspiration. Conversely, if the garment itself induces perspiration, and it is evaporated by the ventilation system, the body of astronauts would be cooled, and they might be more comfortable. The liquid flowing tube, which is restricting mobility of the astronauts, should be decreased [6].

In the present study, we hypothesized that a cooling garment which has vaporing function with oozing cold water from the tubes would cool the body without raising humidity in the garment. To test this hypothesis, we develop and examine the effect of the garment during exercise.

2. Methods

Eight healthy subjects comprising 8 males (mean ± standard error (SE) of age, height, and weight were 21 ± 0.3 years, 168.3 ± 3.3 cm, and 58.0 ± 2.9 kg, respectively) were recruited for the study. Subjects had no medication and no past history of cardiovascular disease. This study was approved by the Institutional Review Board at Gifu University of Medical Science and an informed written consent was obtained from all subjects.

The subjects wore and examined three types of garments. All the garments were based on an elastic underwear made with Spandex and were tightly fitting the upper body. One was the Spandex garment without any additional cooling device (Normal). Second was a simulated LCVG (s-LCVG) (Fig. 1A). A vinyl tube of the same structure with the current LCVG for flowing water (an inside diameter of 1.6 mm, an outside 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 [6,8,9]. Cooled water for rigorous cooling at 14 °C was circulated at a speed of 1.8 L/min (240 lb/h) during exercise [10,11]. Third was also the same underwear of Spandex with a tube on the back. However, the tube was not designed only for cooling with cold water, but also self-perspiration for evaporative cooling (SPEC). For this SPEC garment, self-perspiration is induced by oozing water from 20 pores in the tube for cooling with heat loss by evaporation (Fig. 1B). The material of the tube was similar to s-LCVG, but it was wider and shorter (an inside diameter of 4 mm, an outside diameter of 6 mm, and length of 3.2 m). The tube was sutured over the outside surface of the garment to avoid the garment floating from the skin and to enhance moisture absorption unlike LCVG, in which tubes are knitted in the garment. The tube of s-LCVG was running straight mostly, but the direction of the tube was rounded to improve the

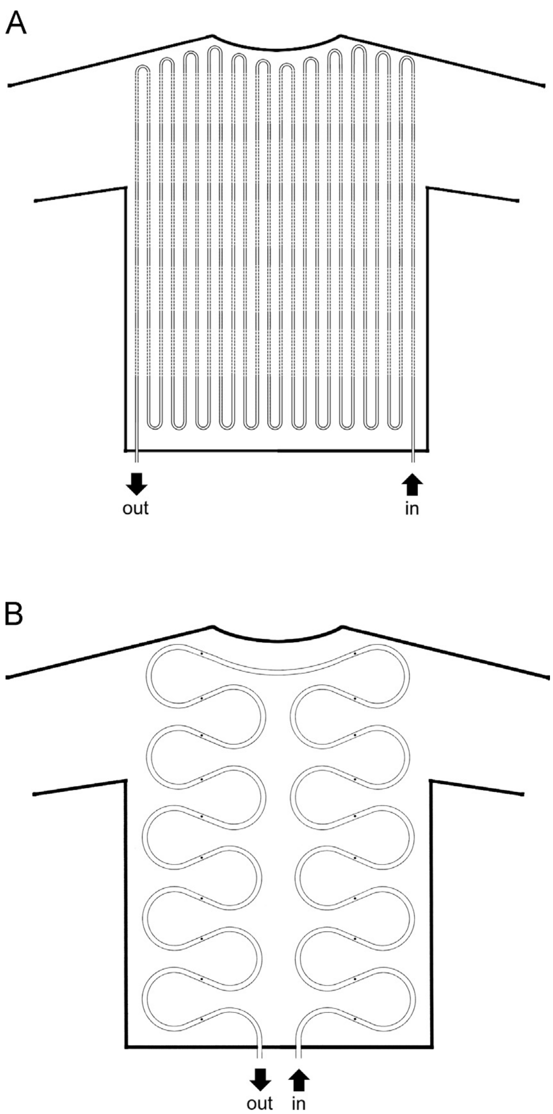

Fig. 1. (A) A schema of a garment with a knitted tube in the simulated liquid cooling and ventilation garment (s-LCVG). Dotted lines show parts of the tubes inside the garment that touch the skin directly. Solid lines show parts of the tubes outside the garment. The “in” and the “out” are the portions through which water flows into the tubes and out from the tubes, respectively. (B) A schema of a garment with a sutured tube through which cooling water flows for heat exchange, and self-perspiration for evaporative cooling (SPEC). Dots in the tubes show the portions of oozing water. The “in” and the “out” are the portions through which water flows into the tubes and out from the tubes, respectively.

ability of stretch, i.e., mobility. Cooled water at the similar temperature and speed to that for s-LCVG was also circulated, and the water oozed through the pores made in the tube at a rate of 2 mL/min over the back. Water started to circulate when the subjects started the exercise. All subjects tested all wears, but each test was performed on a different day. The order of the test with the suit was randomized. For all tests, airflow was started during the setup in advance and provided to the back of the subjects at a speed of 1 m/s throughout the measurement (Fig. 2). In the present study, we focused and evaluated the cooling effects for the back of