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ORIGINAL ARTICLE

Design and performance of personal cooling garments based on three-layer laminates

M. Rothmaier · M. Weder · A. Meyer-Heim · J. Kesselring

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Abstract Personal cooling systems are mainly based on cold air or liquids circulating through a tubing system. They are weighty, bulky and depend on an external power source. In contrast, the laminate-based technology presented here offers new flexible and light weight cooling garments integrated into textiles. It is based on a three-layer composite assembled from two waterproof, but water vapor permeable membranes and a hydrophilic fabric in between. Water absorbed in the fabric will be evaporated by the body temperature resulting in cooling energy. The laminate's high adaptiveness makes it possible to produce cooling garments even for difficult anatomic topologies. The determined cooling energy of the laminate depends mainly on the environmental conditions (temperature, relative humidity, wind): heat flux at standard climatic conditions (20°C, 65% R.H., wind 5 km/h) has measured 423.2 ± 52.6 W/m^2, water vapor transmission resistance, R_{et}, 10.83 ± 0.38 m^2 Pa/W and thermal resistance, R_{ct}, 0.010 ± 0.002 m^2 K/W. Thermal conductivity, k, changed from 0.048 ± 0.003 (dry) to 0.244 ± 0.018 W/m K (water added). The maximum fall in skin temperature, ΔT_{max}, under the laminate was 5.7 ± 1.2°C, taken from a 12 subject study with a thigh cooling garment during treadmill walking (23°C, 50% R.H., no wind) and a significant linear correlation ($R = 0.85$, $P = 0.01$) between body mass index and time to reach 67% of ΔT_{max} could be determined.

Keywords Evaporative cooling · Heat flux · Skin temperature · Personal cooling system

1 Introduction

Cooling systems have found many applications in daily life for deliberate lowering of skin and body temperature. Vests and garments have been developed to serve personnel working in hot environments [21], to assist human sweating (astronautics [4, 22] and military [3, 14]) or to enhance athletes' performance [1, 6, 23]. Medical applications cover the field of patients suffering from multiple sclerosis (MS) [11, 16, 20], treatment of fever [13] and others with disorders that impair the body's ability to cool itself [9, 10]. The working principle is based mainly on circulating cold air or liquids [17], phase change materials like polymer gels, paraffin waxes or ice/water mixtures [18] or liquid evaporation [5]. However, most of the devices are bulky, weighty, depend on electric power and limit the wearer's freedom of action, a potential reason for limited commercial success and availability in the market so far. Especially for patients in a community setting, a light weight, flexible system incorporated into a textile garment would make a noticeable difference compared to the systems available on the market today. By covering the human torso, head and/or upper extremities, an effective and efficient textile-based system would be possible [7, 12, 13, 15, 19, 24].

In this paper, we report the development and characterization of a new textile-based laminate that allows the making up of light weight cooling systems. The basic

M. Rothmaier (✉) · M. Weder
Empa, Swiss Federal Laboratories for Materials Testing and Research, Laboratory for Protection and Physiology,
9014 St. Gallen, Switzerland
e-mail: markus.rothmaier@empa.ch
URL: http://www.empa.ch

A. Meyer-Heim · J. Kesselring
Department of Neurology, Rehabilitation Centre,
7317 Valens, Switzerland

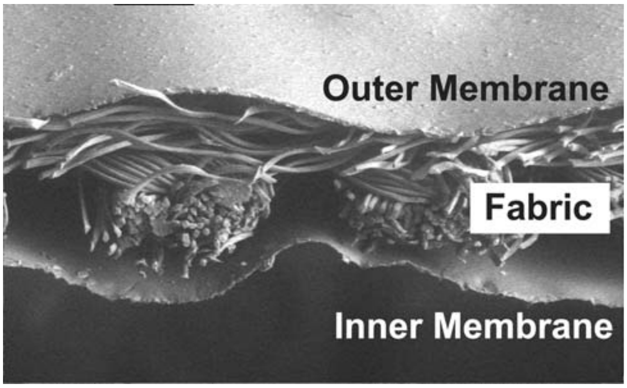
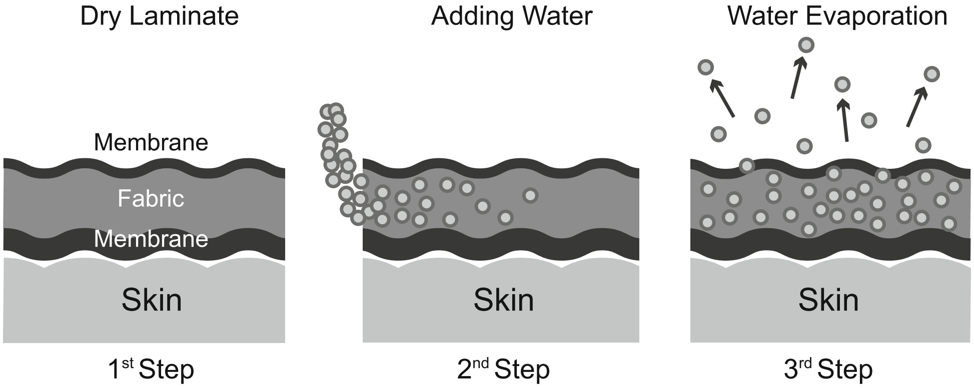


Fig. 1 Scanning electron microscope picture of the three-layer laminate; from *top to bottom* outer Sympatex membrane (thickness 10 µm), textile fabric made of polyester multifilament (100 µm), inner Sympatex membrane (15 µm)

principle of the herein presented technology is based on body temperature driven evaporation of water out of a skin-contacting reservoir. For this purpose, two thin Sympatex membranes (impermeable to air and liquid water yet permeable to water vapor) are laminated on top of a thin woven polyester fabric, resulting in a three-layer laminate (Fig. 1). Both membranes and the fabric define a confined space for storing a small quantity of liquid water. Sympatex membranes are made of polyetherester, a hydrophilic co-polymer (hydrophobic polyester units combined with hydrophilic polyether units). Opposite to micro porous membranes, where water vapor permeates through tiny pores, Sympatex membranes, made of polyetherester, are dense and allow water vapor to diffuse through the bulk polymer (driven by absorption and evaporation processes). Advantageous is the fact that dense membranes can be washed in a standard laundry process, without getting blocked by residues (dirt particles, salts from washing powder and sweat, etc.). For cooling garment production tailored and water tight sealed three-layer laminates can be integrated into pants, shirts or cuffs, respecting the anatomy of the wearer. The garment is worn in a manner such that the innermost layer is in direct contact with the wearer's skin (gaps of air between skin and membrane would lead to reduced cooling efficiency due to lower thermal conductivity). The water between the layers diffuses as vapor through the outer membrane; it removes latent heat required for evaporation, hence providing cooling to the underlying skin and tissue (Fig. 2). Since the membranes used in our approach are very thin (10–15 µm) mechanical protection and stabilization is needed, thus a thin air permeable mesh is applied on top.

After a first successful application of the technology for cooling thermosensitive MS patients during a clinical study [16] further basic specification of the three-layer laminate and quantification of environmental effects (temperature, relative humidity and wind speed) has been necessary and the results are presented herein. The investigations have been split into three parts for characterization and performance testing. First, elementary measurements of the three-layer laminate have been performed in the laboratory to determine water vapor transmission resistance (R_{et}), thermal resistance (R_{ct}) and thermal conductivity (k). R_{et} is directly responsible for the efficiency of water vapor transport out of the laminate's water reservoir, whereas R_{ct} and k determine the thermal insulation and heat flux between the skin and ambiance, respectively. The aim of our laminate design was directed towards minimum R_{et} and R_{ct} (for efficient water evaporation), minimum thermal resistance (to avoid sweating when the garment is worn without water added), and large k (mandatory for high heat flux). Second, the characterization of the evaporation performance of the three-layer laminate under stable and standardized conditions in a climatic chamber has been performed for changing environmental parameters (wind speed, relative humidity and temperature). For this purpose a tempered mini cylinder test device (MICY) wrapped with a sample has been used to determine heat flux, cooling power, time to evaporate a quantity of water and discrepancies due to design imperfections. Third, in order to study the effectiveness of skin cooling, temperature progression and allocation under standard climatic conditions, a treadmill study with 12 male

Fig. 2 Diagram of the three-layer laminate and the principle of water evaporation from the reservoir



volunteers wearing a thigh cooling garment has been conducted and correlations of body mass index (BMI) and anterior thigh skin-fold thickness versus measured temperature have been investigated.

2 Materials and methods

2.1 Production of laminates and garments

The three-layer laminates (thickness 100 μm) are assembled of a hydrophilic polyester fabric, laminated on both sides with a polyetherester membrane (Sympatex, Germany). In our experiments, we used an asymmetrical laminate composition of a 10 μm (towards the atmosphere) and a 15 μm thick membrane (towards the skin). The membranes are water tight, but water vapor permeable (water tightness = 10 m hydrostatic head according to ISO 811, water vapor permeability = 2,600 g/m^2 24 h according to a modified ASTM E 96–66 B, water vapor transmission resistance $R_{\mathrm{et}} = 1.8$ m^2 Pa/W according to ISO 11092). The utilized laminating process (VOACK, Austria) delivers a slightly elastic product ($\leq$10% elongation), which still displays the high water vapor permeability characteristics due to a minimum loss of active membrane surface ($\leq$10%). A grammage of 90.5 ± 1.9 g/m^2 has been determined with a laboratory balance (consecutive measurements of three 10 × 10 cm samples, 23 ± 0.2°C, 50 ± 2% R.H.).

The garment for thigh cooling (Fig. 3) consists of two tailored segments of three-layer laminate (each approximately 1,000 cm^2), that were sealed on the edges with a 2 cm wide hot melt sealing ribbon (Sympatex, Germany) through ultrasonic welding with a Sonotronic 35/400 using a 11 mm Sonotrode (Pfaff, Germany). For water admission a polypropylene T-connector has been placed between the two membranes connected to a small rubber tube, and an air exit has been integrated at the lower end of the laminate by covering a hole of 5 mm with a microporous Teflon membrane. The Teflon membrane and T-connector have been bonded to the outer Sympatex membrane through hot melt sealing ribbon as well. The two segments were sewed into a stretchable polyester fabric (Eschler, Switzerland) and covered with an uncongested textile mesh to protect against mechanical damage. The final garment has the shape of cycling shorts. Each segment of laminate is placed snugly around the corresponding thigh, covering the area between knee and loin. The lower abdominal and rear sections have no laminate coverage. The garment can be opened by means of an integrated broad hook and loop fastener on the inner thigh side (for dressing reasons).

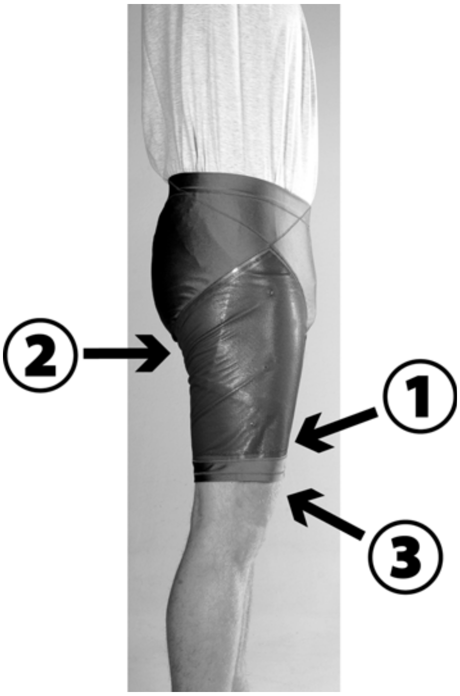


Fig. 3 Garment for thigh cooling. The three-layer laminate is part of short pants, which can be opened for easier dressing on the inner thigh side with a hook and loop fastener. Marker *1*, *2* and *3* indicate temperature sensor positions

2.2 Water vapor transmission resistance, thermal resistance and thermal conductivity

Water vapor transmission resistance, R_{et}, and thermal resistance, R_{ct}, have been determined according to EN 31092, thermal conductivity, k, according to ISO 5085, respectively (all measurements were conducted under steady-state conditions with proprietary setups; $n = 3$ for R_{et} and k, $n = 5$ for R_{ct}).

2.3 Mini cylinder test device

The MICY consists of an aluminum cylinder used to measure heat flux through membranes and textiles attached around it. Dimensions are similar to a human upper arm (surface 0.088 m^2). The cylinder is heated electrically with four heating foils; four sensors (Pt 100) are built in to measure the temperature and control the heating power. In order to avoid heat loss by conduction, the cylinder is surrounded by two heating guards on both sides. The heating power needed to keep surface temperature constant at 35°C during the experiments was recorded in 30-s intervals. MICY is placed in a climatic chamber (temperature and humidity control) facing a propeller generating variable wind speed (test conditions referenced in Table 1). Measurements are divided into different phases (Fig. 4):

Table 1 Summary of performance measurements with MICY

Sample no.	Climatic chamber conditions (temperature, R.H., wind)			Power and heat flux measured		Time needed to evaporate water	E_M	$(E_C - E_M)/E_C$
	°C	%	km/h	W	W/m^2	min	J	%
1	10	65	5	45.2 ± 6.2	513.5 ± 70.7	24.8 ± 2.0	50,445 ± 5102	4.7
2	20	65	5	37.3 ± 4.6	423.2 ± 52.6	26.6 ± 4.1	45,540 ± 4262	12.6
3	30	65	5	28.4 ± 1.4	323.1 ± 16.3	36.5 ± 2.1	44,937 ± 2041	12.3
4	20	30	5	49.3 ± 5.0	560.2 ± 56.9	23.5 ± 2.2	46,971 ± 4469	9.8
5	20	80	5	36.3 ± 3.6	412.9 ± 40.8	32.1 ± 1.8	50,340 ± 4699	3.4
6	20	65	20	70.8 ± 6.9	805.0 ± 78.0	16.3 ± 2.2	46,245 ± 4136	11.2
7	20	65	10	55.9 ± 4.7	635.4 ± 53.3	21.3 ± 3.2	46,167 ± 3962	11.4

Values in table are given as mean ± SD, number of repeated experiments = 3; E_M, energy measured to evaporate water; E_C, energy calculated to evaporate water

acclimatization phase (1 h, heating up cylinder and sample to constant temperature), activating phase (15 s, injection and distribution of 20 ml water inside the laminate, water temperature equal to climatic chamber temperature), recording phase (2 h, evaporation of water and recording of variable heating power). Samples were slightly stretched over the cylinder, to avoid the formation of an insulating air layer between sample and metal surface, and fixed with clamps on the lee side.

2.4 Skin temperature measurements

Skin temperature was measured with two MSR (Modular Signal Recorder) temperature sensors and data loggers (MSR Electronics GmbH, Switzerland) under the right leg of the thigh cooling garment (lower front side and upper back side, Fig. 3 markers 1 and 2). For referencing, an additional temperature sensor has been placed on the left thigh, not covered by the garment (Fig. 3, marker 3). Measurements were done in a climatic chamber (23 ± 0.2°C, 50 ± 2% R.H., no wind) on a mercury treadmill (h/p/cosmos sports and medical gmbh, Germany; walking speed 4 km/h) adding 40 ml of water to right leg (water temperature equal to climatic chamber temperature). The experiment was conducted with 12 healthy male volunteers; age 37.1 ± 10.0 (range 26–61); BMI 24.2 ± 3.1 (range 17.1–28.1); anterior thigh skin-fold value 12.3 ± 3.8 (range 6.3–17.5; Harpenden skinfold caliper, FysioSupplies, The Netherlands). According to the subsequent protocol the person was entering the chamber 15 min before the experiment not yet wearing the garment. Data was recorded 15 min before (now wearing the garment) and 75 min after adding water. Statistics was done with SPSS v14 (SPSS Inc., USA), alpha was set at $P < 0.05$.

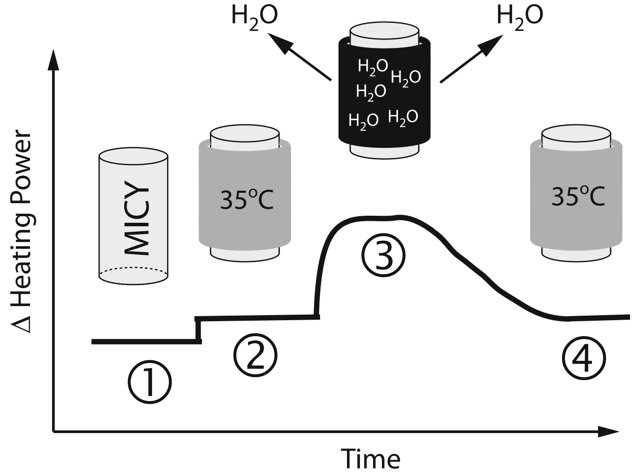


Fig. 4 Graphical scheme of experimental procedure (time progression versus Δheating power to maintain cylinder temperature at 35°C is displayed) using mini cylinder test device MICY. Labels *1* MICY only, *2* laminate sample wrapped around MICY (acclimatization phase), *3* laminate filled with water, evaporation started, *4* end of experiment, all water evaporated

3 Results

3.1 Water vapor transmission resistance, thermal resistance and thermal conductivity

R_{et} of the herein described three-layer laminate has been determined to be 10.8 ± 0.38 m^2 Pa/W ($n = 3$); $R_{et} = 1.8$ m^2 Pa/W for an individual 15 μm Sympatex membrane given in the corresponding datasheet. R_{ct} equals 0.010 ± 0.002 m^2 K/W ($n = 5$). k changed from dry to wet state (laminate reservoir filled with water) from 0.048 ± 0.003 to 0.244 ± 0.018 W/m K ($n = 3$).

3.2 Mini cylinder test device

Table 1 shows a summary of MICY measurements in a climatic chamber according to the protocol given earlier ($n = 3$, SD given in table). Changes of climatic chamber temperature at constant R.H. (Fig. 5a) showed a distinct influence in the performance of the laminate. At 10°C and 65% R.H. a maximum power of 45.2 W could be achieved (measured over the first five minutes after adding water), whereas at 20 and 30°C the power dropped 17 and 37%; the heat flux changed accordingly from 513.5 to 423.2 and 323.1 W/m^2. As a result, higher heat fluxes were leading to shorter cooling times (24.8, 26.6 and 36.5 min, measured from the addition of water until the recorded heating power equaled initial values). Changes in relative moisture in the climatic chamber at a constant temperature of 20°C (Fig. 5b) were also displaying a clear dependency of the evaporation process on water vapor present in the surrounding air. Dry (30% R.H.), moderate (65% R.H.) and humid (80% R.H.) conditions reduced the maximum power measured and heat flux (49.3 W, 560.2 W/m^2) by 24 and 26%, respectively. The time needed to evaporate all water out of the laminate rose with higher R.H. from 23.5 to 26.6 and 32.1 min. Wind speed had unquestionably the largest influence on the cooling performance of the laminate at 20°C and 65% R.H. (Fig. 5c). For a given wind speed of 5, 10 and 20 km/h the maximum power measured rose (37.3 W, heat flux 423.2 W/m^2) by nearly 50 and 90%, respectively. The time needed to evaporate all water out of the laminate dropped fast with increasing wind speed from 26.6 to 21.3 and 16.3 min. Evaporating water through the laminate did not deliver the predictable energy in any of the experiments (specific heat + heat of vaporization = 52 kJ/20 ml H_2O at 293°K). The mean differences (calculated, E_C, versus measured energy, E_M; Table 1) were between 3.4 (20°C, 80% R.H., 5 km/h) and 12.6% (20°C, 65% R.H., 5 km/h). Losses due to laminate imperfections and water residues in the tubing system (needed for filling) are responsible for this finding to some extent, as well as the fact that water evaporation does not occur directly on the metal cylinder surface, but a small distance from there (approximately 0.1 mm).

3.3 Skin temperature measurements

Maximum skin temperature drop (ΔT_{max}) was 5.7 ± 1.2°C (lower front side) and 4.7 ± 1.1°C (upper back side), respectively. The vertical position also determined the cooling duration measurably, a reduction of 25% was measured between upper (ΔT_{max} was measured after 39 ± 7 min) and lower position (51 ± 7 min); 50% of ΔT_{max} (T_{50}) was reached for the front position after 188 ± 59 and 253 ± 123 s (back), respectively. 67% of ΔT_{max} (T_{67}) was reached for the front position after 393 ± 105 and 512 ± 186 s (back), respectively. The mean reference temperature (Fig. 3, marker 3) measured during the same experiments at the left thigh increased by 0.6 ± 0.4°C, 60 min after activating the right thigh with

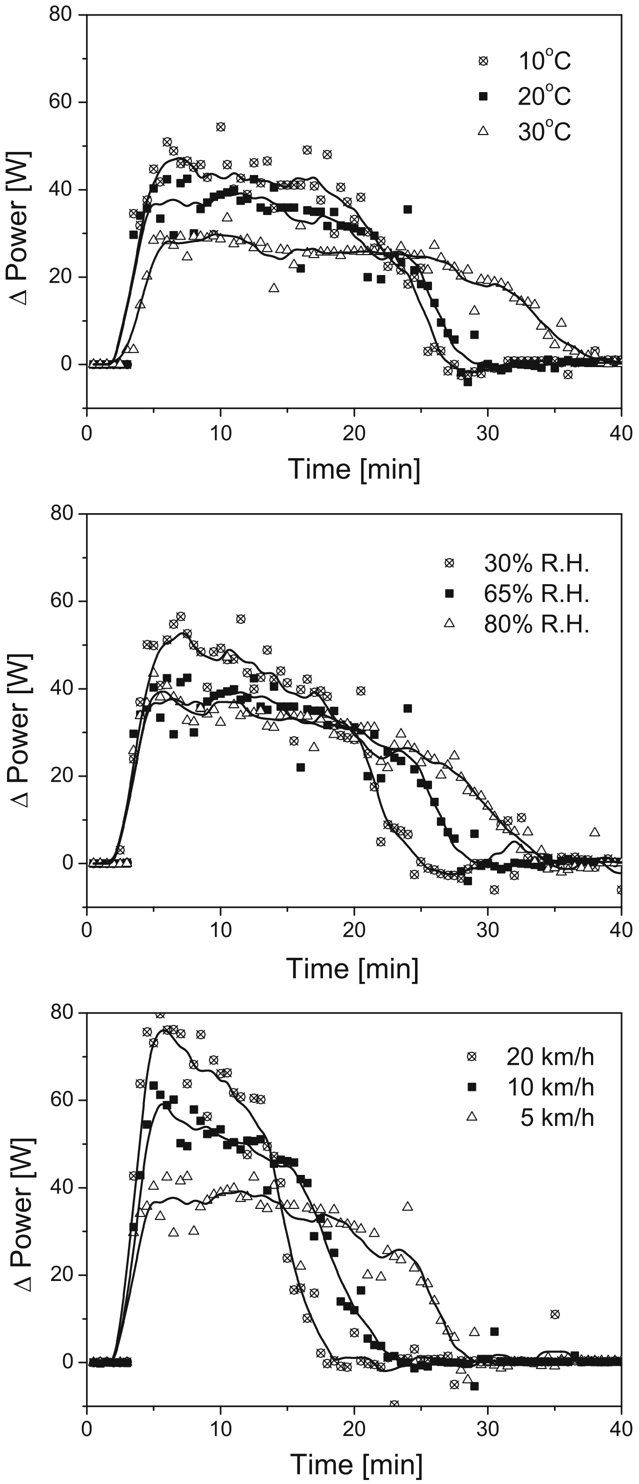


Fig. 5 Representative set of performance measurements of the three-layer laminate with MICY under different ambient conditions, shown as additional heating power needed versus time to keep cylinder surface at 35°C after water added (data points 1–3 show thermal equilibrium of laminate and cylinder, water injection at data point number 4); **a** wind speed 5 km/h, R.H. 65%, temperature 10, 20 or 30°C; **b** wind speed 5 km/h, temperature 20°C, R.H. 30, 65 and 80%; **c** R.H. 65%, temperature 20°C, wind speed 5, 10 and 20 km/h

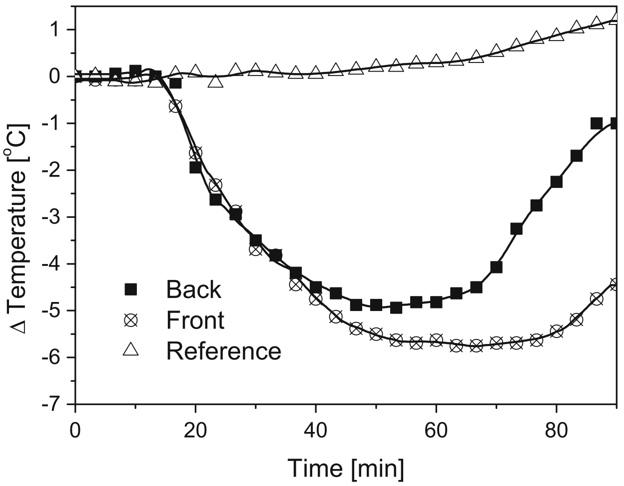


Fig. 6 Skin temperature progression plotted across time for thigh cooling garment. Male volunteer walking at 4 km/h on a treadmill (no wind, 23°C, 50% R.H; *back* temperature sensor positioned at right thigh under the garment, upper back side, *front* temperature sensor positioned at right thigh, lower front side under the garment, *reference* temperature sensor positioned at left thigh, lower front side, not covered by the garment)

water. Starting skin temperatures were 31.7 ± 0.8°C (back), 30.7 ± 0.6°C (front) and 29.5 ± 0.7°C (reference).

Fig. 6 shows a representative skin temperature progression and allocation of one male volunteer wearing a thigh cooling garment while walking on the treadmill (right thigh side activated with water, left side used as reference without water). It is obvious that for the two measurement sites (indicated with markers 1 and 2, Fig. 3) comparable temperature progression was measured as long as the temperature decreases, but finally different maximum skin temperatures and cooling durations were reached.

To detect possible correlations of temperature changes and body composition 12 statistical tests (Pearson correlation; data normally distributed according to Shapiro-Wilk) have been conducted (Table 2): BMI versus ΔT_{max}, T_{50}, and T_{67} (Fig. 7) and thigh skin-fold value versus ΔT_{max}, T_{50}, and T_{67}—in each case for lower front and upper back position. For BMI versus T_{67} (front and back) the strongest and most significant linear correlation was found ($R = 0.85$ and 0.82, $P = 0.01$), however all skin-fold measurements were not significant.

No sweating under the garment has been noticed (visual inspection, after garment removal).

4 Discussion

In this work, we illustrated a different design approach to thin and flexible personal cooling systems using our newly developed three-layer laminates. Key parameters for its employment in textile garments are given as well. Our laboratory study validated the essential functionality of filling water into the laminate based reservoir and the subsequent evaporation process for different environmental conditions. Furthermore, the presented measurements indicate the feasibility to use the resulting evaporation energy for skin cooling purposes.

R_{ct}, R_{et} and k showed the appropriateness of the new technology for clothing applications. Determination of R_{ct} demonstrated that the three-layer laminate had comparable values to cotton fabrics (0.01–0.03 m^2 K/W for summer clothes [8]). Therefore, it will not contribute to an increased thermal insulation and sweating when worn without water. In other words, garments made of the laminate can also be worn before or after cooling. R_{et} measured is representative for the sum of all three laminate layers and points towards low resistance for water vapor transmission which is advantageous for easy evaporation. Taken into consideration that water evaporates in fact through the outer Sympatex membrane only, the effective R_{et} will be even lower than measured R_{et}, most likely in the range of the original Sympatex membrane (a slight increase due to the laminating process is expected). Changes in k by a factor of approximately 5, from empty to water filled laminate, show that the air to water exchange increases the thermal conductivity noticeably, which finally improves the heat flux from the

Table 2 Summary of treadmill study; two-tailed Pearson correlations of BMI and thigh skin-fold value versus temperature data are listed

Variables (lower front position)	Correlation		Variables (upper back position)	Correlation	
BMI versus	*R*	*P*	BMI versus	*R*	*P*
ΔT_{max}	−0.67	0.02	ΔT_{max}	−0.61	0.04
T_{50}	0.65	0.02	T_{50}	0.71	0.01
T_{67}	0.85	0.01	T_{67}	0.82	0.01
Thigh skin-fold value versus			Thigh skin-fold value versus		
ΔT_{max}	−0.26	0.42	ΔT_{max}	−0.40	0.19
T_{50}	0.25	0.44	T_{50}	0.19	0.56
T_{67}	0.56	0.06	T_{67}	0.41	0.18

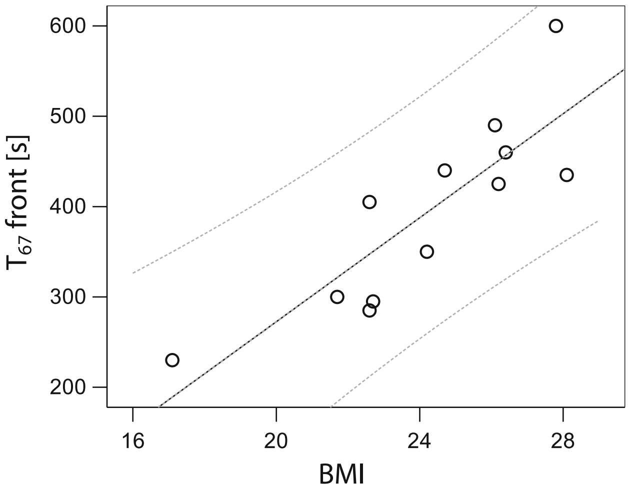


Fig. 7 Scatterplot of BMI versus T_{67} determined at lower front position (linear correlation $R = 0.85$, $P = 0.01$; linear fit and 95% confidence intervals shown)

skin surface to the effective evaporation zone (outer Sympatex membrane).

Different experimental conditions were shown to affect the cooling performance of the laminate. Foremost, the heat flux strongly depends on the environmental conditions. Ambient temperature and relative humidity are responsible for performance and duration of the evaporation process. Rising ambient temperatures will unquestionably contribute to the evaporation process, leading to a non-negligible amount of water evaporated by ambient energy sources (and not contributing to the cooling effect). The influence of low and high relative humidity was also investigated. At very low levels, dry air from the environment will support the evaporation process (leading to a loss of cooling power to the person) where at very high levels water vapor concentration in the environment obviously constrains the evaporation process substantially. Air blown against the laminate has another perceptible effect on the cooling performance. Either wind or the movement of the laminate versus air does remove water saturated air from the laminate's surface and therefore affect the speed of evaporation and the resulting heat flux. Both effects are occurrences happening on whenever personal cooling systems are operated outside a protected environment or when the wearer is moving.

The potential of a thigh cooling garment has been studied with 12 male volunteers walking on a treadmill. The progression of skin temperature after water has been added to the three-layer laminate depends on two factors. Firstly, the front side (in walking direction) leads to more wind. Comparative measurements showed that a temperature difference of up to 1°C could be achieved for the front versus back section of the thigh garment. Secondly, water will be distributed homogenously in the three-layer laminate mainly by capillary forces, but over time a concentration gradient from bottom to top will establish due to gravitation. Water evaporated completely at the most upper position first, resulting in longer cooling performance at lower positions. The two effects most probably explain the different trends of skin temperature displayed in Fig. 6.

Correlating BMI versus recorded temperature data did show only a moderate but significant negative R for $\Delta T_{\max}$, but considerable and highly significant positive correlations for T_{50}, and T_{67} (front and back). These findings are in accordance with the lower thermal conductivity of biomaterials with high fat/muscle ratio and the coupled lower blood circulation (and therefore slower energy removal from the skin) in persons with high BMI, respectively [2]. Contrariwise, all thigh skin-fold measurements were not significant, which mostly emphasizes the difficulty of the executed single location measurement. The data quality suffers basically from the error-prone measurement procedure (tricky skin-fold pinching, especially for muscular subjects) and the high variances when the caliper is shifted only a few centimeters on the subject's thigh in horizontal or vertical direction.

There are numerous advantages of the presented technology compared to other current cooling technologies. First, the three-layer laminates can be filled through an opening with water and do not have to be soaked in water completely—a simple principle for generating cooling effects used for example by athletes wearing wet headbands or t-shirts—and refilling is possible at the wearer's need; the garment does not even have to be removed. Due to the controlled filling and water distribution, the wearer does not get wet and therefore no unpleasant feeling (or embarrassment) occurs while wearing the garment. Furthermore, the low thermal resistance of the laminate does not significantly contribute to a temperature rise when the dry laminate is worn, so there is no need to undress when no cooling is needed. Disadvantages are mainly caused from performance dependence on the environmental conditions (in very hot or humid environments an insignificant cooling effect would be observed).

When cooling garments are designed for patients additional requisites about comfort (e.g. weight, maintenance) and ergonomics (e.g. self dressing) come into consideration. Owing to the laminate's light weight, the additional mass for the wearer is negligible. The main weight load is water, whose volume will depend on the preferred cooling duration and the environmental conditions. Small laminate thickness and high flexibility facilitate the product manufacturer in composing individual fitting garments that snugly contact the skin, even at difficult topologies—and help the wearer to stay free to move. For the same reason the wearer can easily dress himself without the help of additional persons. Water filled garments dry fast also when not worn on the body, so the potential for unpleasant odors and fungal or bacterial growth is low. Furthermore, the membrane material is washable and thanks to its non porous nature laundry detergents, salt residues and additives will not inhibit the water vapor transport functionality.

Future developments and applications are possible in many directions. Besides thigh cooling, other body parts will be our future focus to cover more body surface in general and to increase the effectiveness of cooling [19]. Regions where flexible laminates can be easily applied close to the skin are chest and back. Other regions like hands and feet are not suitable mainly due to their small surface area. Another feature would be an adaptive filling mechanism. Adding water from a small tank to the laminate depending on activity and/or environmental parameters would certainly increase the effectiveness and operating range for the wearer and open other application areas.

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