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Characterization of the thermophysiological comfort of duvets in consideration of the bed cave

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ABSTRACT

Sleep is a fundamental need for humans. On average 1/3 of the lifetime is spent in bed. Important for a healthy sleep is the duvet. This should have sufficient heat insulation and should ensure a dry bed climate at the same time. The thermophysiological comfort of classic duvets can be rated via skin model and thermal manikin. The simultaneous detection of dry and moist heat flux of duvets is now not possible.

The lecture presents results of the German funded project AiF 19522 N "Bed Cave and Comfort". Within the project the interaction of thermophysiological comfort during sleeping and the bed cave was investigated. Duvets with different filling materials (down and feathers, polyester, animal hair as well as new developments) were examined according the classical, thermophysiological evaluation method for sleep comfort. Furthermore, a new evaluation method for duvets with the sweating, thermal manikin Sherlock (Newton type, Thermetrics) was developed. During the measurement, a realistic sleep situation can be reconstructed with the sweating, thermal manikin. All measured data were validated by monitored sleep test within a climatic chamber.

Keywords
duvets,
bed cave,
sweating, thermal manikin,
thermophysiological comfort,

1 Introduction

Sleep is a fundamental an underestimated basic need of humans. On average 1/3 of the lifetime is spent in bed. After 48 hours without sleep the concentration for simplest tasks is lost [1]. Restful sleep is very important for human regeneration and health maintenance [2].

During sleep a comfortable warm bed climate, night movements and a lowering of body temperature of 0.5 °C with subsequent rise should be possible. Therefore, produced body heat is dissipated by the skin by radiation, conduction, and convection. Further sweating can occur to cool down the human body. To avoid moisture in the bed system sweat should be transported through the system during sleep [1]. Studies show that about one fifth of the produced heat and moisture produced during sleep is released to the mattress. The majority of 80 % is released to the duvet [3]. Other components like mattress, linen or nightwear play a tangential role. So, the duvet should be able to transport the produced sweat to the ambient. Further the human body should not cool down during sleeping. Duvets must therefore have adequate thermal insulation.

Nowadays there are traditional filling of duvets like down and feathers, animal hair (e. g. sheep, camel) and nonwovens. In addition, new filling and insulation materials are used for duvets, e. g. nonwovens made from hemp fibers, microfine fiber structures, 3D knitted fabrics, polyester fiber balls, mixtures of different materials as well as new assemblies like zoned duvets with higher filling levels on the feed zone or open ventilation zones.

In the 1990s a method and model to characterize the comfort of duvets was invented at Hohenstein, which is still used today [4]. This evaluation system is based on two methods: dry heat insulation of ready-made duvets measured with the thermal manikin and the material-specific characteristics of heat and moisture transport determined with the Hohenstein skin model. The measurement of dry and wet heat flow of ready-made duvets in consideration of the bed cave is until now not possible.

Further, the insulation of the duvet depends on the draping of the duvet and the so formed bed cave between human and duvet. This draping ability of the blanket depends on the material, the rigidity, the filling quantity, and the packaging. However, so far there are no scientific studies dealing with the ideal bed cavity for thermal insulation. With the 3D scanner technology, a powerful tool is available, with which a quantitative, exact 3D measurement of the bed cavity and draping of the duvet is possible.

Within a German funded research project AiF 19522 N a new measuring and evaluation method for traditional and new ready-made duvets in consideration of the bed cave was investigated. In addition, the bed cavity geometry is measured using 3D scanner technology and the influence of the bed cave and the enclosed air layer on the thermal insulation and sleeping comfort was researched.

2 Materials and Methods

Within the project more than 40 duvets with different cover materials and fillings e. g. polyester (PES), down and feathers, wool (WO), camel hair, cotton (CO) were investigated. Screening tests showed that 18 duvets represent state of the art of German duvets. These duvets were used for further investigation. Table 1 shows these duvets with the available product information.

Table 1. Duvet materials.

Sample	Cover material	Filling	Stitching	Size [m²]	Weight [kg]	Thickness [mm]
M3	100% CO	100% PES	lengthwise	2,91	1,282	28
M4	100% CO	100% PES	lengthwise	2,68	1,662	51
M5	100% CO	90% down, 10% feather	square	2,75	1,176	22/13
M6	100% CO	100% down	lengthwise	2,77	1,774	25/14
M7	-	100% down	square	2,90	1,746	19/14
M8	100% Lyocell	60% Lyocell, 40% PES	square	2,77	1,894	41/24
M11	50% CO, 50% Lyocell	100% PES-hollow fiber	dots	2,73	1,775	53/40
M12	100% PES	100% PES-hollow fiber	flower shaped	2,75	0,804	15
M13	100% CO	100% Polylactide	body fit	2,80	1,855	42/26
M14	100% CO	100% PES	body fit	2,82	1,315	29/20
M17	100% CO	100% PES-nonwoven	lengthwise	2,63	1,197	21/14
M18	100% CO	100% PES	lengthwise	2,7	1,286	19/14
M20	-	100% WO	lengthwise	2,68	1,843	27/25
M21	100% CO	100% WO	square	2,68	1,288	15/9
M25	80% micromodal, 20% CO	100% camel hair	body fit	2,74	1,982	42
M28	100% CO	60% linen, 40% CO	lengthwise with circles	2,90	1,142	9/8
M29	70% micromodal, 30% CO	100% PES	Beads stitching with ventilation system	2,76	1,715	41/36
M32	100% CO, climate zone: 100% PES	100% down	cross with air chambers	2,91	1,121	-

2.1 Sweating, thermal manikin

The Hohenstein evaluation system for duvets is based on two methods: dry heat insulation of ready-made duvets measured with the thermal manikin and the material-specific characteristics of heat and moisture transport determined with the Hohenstein skin model. The measurement of dry and wet heat flow of ready-made duvets in consideration of the bed cave is until now not possible. Therefore, a new method was invented to characterize the thermophysiological comfort of duvets in consideration of surface coverage, snugness and the microclimate within the bed cave using the sweating, thermal manikin Sherlock (type Newton, Thermetrics).

The sweating, thermal manikin Sherlock has the anatomical shape of a human standard man (height 1.75 m, body surface 1.85 m², clothing size 50). The skin surface of the manikin was regulated to a constant temperature T_s of 31 ° C. The required electrical heating power H_c for the constant surface temperature was the measured value, for the determination of the thermal resistance R_c of duvets. The measurement was set in a climate chamber at temperature of T_a = 15 ° C and relative humidity of RH_a = 50% rh.

To create a realistic sleeping condition, the measurement took place with the sweating, thermal manikin Sherlock lying down, wearing a two-piece pajamas (CO). The head rest on a pillow. The duvet itself was measured without a cover. To record the microclimate of the bed cave, ten additional temperature and humidity sensors were attached to the sweating, thermal Manikin Sherlock, and the duvet (figure 1, middle). The duvet was draped uniformly around the manikin, which was covered up to the neck. Care was taken to ensure that the duvet lies loosely so that there is enough air volume in the bed cave". A standard bed construction consisting of a tubular steel bed frame with a one-piece foam mattress (180 mm thick), which is covered with a cotton sheet, was chosen for the investigation. Figure 1 shows the measurement setup for evaluating duvets with the sweating, thermal Manikin Sherlock.

Fig. 1 Measurement setup to characterize the thermophysiological parameters of duvets with the sweating, thermal manikin Sherlock (type Newton, Thermetrics); left: dressed Sherlock equipped with temperature and humidity sensors lying on mattress and bed frame, right: complete measurement setup.

In addition to these investigations of the thermal resistance R_c, realistic sweating during sleep was simulated with Sherlock to determine the water vapor resistance R_e of duvets. The same measurement setup was used for this. Sweating is achieved with the help of a tight sweat suit and sweat nozzles, which are distributed over the body. The sweat suit has the function of distributing the sweat (water) from the sweat nozzles evenly over the body. The sweat nozzles can be controlled individually, so different sweating rates can be set. Table 2 shows the used sweating rate, which are based on Park et al. [5]. The sweating nozzles on the back side were switched off because the measurements focus on the duvet and the microclimate within the bed cave. These sweating rates reproduce a realistic sleeping situation and leads to reproducible measurement results for duvets.

Table 2. Sweating rates during measurement of duvets with the sweating, thermal manikin Sherlock (type Newton, Thermetrics).

Manikin zone	**Sweating rate [ml/hr m²]**	**Manikin zone**	**Sweating rate [ml/hr m²]**
face	0	lower back	0
head	0	right upper thigh front	15
right upper arm front	58	right upper thigh guard	0
right upper arm back	0	right upper thigh back	0
left upper arm front	58	left upper thigh front	15
left upper arm back	0	left upper thigh guard	0
right forearm front	18	left upper thigh back	0
right forearm back	10	right lower thigh front	18
left forearm front	18	right lower thigh back	0
left forearm back	10	left lower thigh front	18
right hand	72	left lower thigh back	0
left hand	72	right calf front	17
upper chest	16	right calf back	0
shoulders	0	left calf front	17
stomach	17	left calf back	0
mid back	0	right foot	65
waist	15	left foot	65

2.2 Subject trial

To validate the results with the thermal, sweating manikin subject trials with selected duvets M5, M14 and M32 were done. Five male subjects (table 2) performed monitored sleep experiments in the climate chamber. The subjects were healthy men. Before the study, the participating subjects were given detailed information about the schedule of the test series after a medical check, were informed about possible risks, gave their consent to the tests, and confirmed their voluntary participation.

Table 3. Sample of subjects.

Subject	Age [years]	Height [cm]	Weight [kg]	BMI [ ]	Body Surface DuBois [cm²]
TP1	28	184	79	23	2,02
TP2	33	186	82	24	2,06
TP3	30	172	65	22	1,77
TP4	24	170	73	25	1,84
TP5	29	182	81	24	2,02
MW	28,8	178,8	76	23,6	1,94
Stdev	3,2	7,3	7,1	1,1	0,1

The monitored sleeping experiments were performed at 20 °C, 50% RH in a climatic chamber with air movement 0.3 m / s. To create comparable conditions to the experiments with the sweating, thermal manikin Sherlock the subjects slept in the climatic chamber for at least 6 hours, wearing a pair of cotton underpants and a two-piece pajama out of cotton. The head rested on a pillow. The duvet itself was tested without a cover, using five temperature and humidity sensors to record the microclimate of the bed cave. The test bed was draped loosely by the test subjects, so that they formed a “sleeping cave”. A "standard bed construction" was chosen for the present study. It consists of a tubular steel bed frame with a one-piece foam mattress (180 mm thick), which is covered with a cotton sheet. Figure 2 shows the experimental test setup during the monitored sleeping experiment with subjects.

Fig. 2 Measurement setup “Sleeping trial” in climatic chamber with subject (left), position of temperature and humidity sensors (right, duvet turned for visualization).

The objective body data were recorded using various sensors. The heart rate was recorded using a chest strap (Polar WearLink). Temperature sensors (T) for the skin temperature as well as combined temperature-humidity sensors (T, RH; MSR Electronics GmbH) for recording the microclimate were distributed on the body surface in accordance with ISO 9886. To create a distance to the skin and thus to record the moisture in the microclimate between textile and skin, the sensor was attached to a spacer (thickness 3 mm). In addition to the objectively recorded measured values, the subject's subjective sensations after the sleep were queried and recorded using a questionnaire.

Before sleeping experiments, the test subjects were equipped with the sensors and get dressed. This process took at least 30 minutes to also acclimatize the subjects. The individual experiments each lasted at least 6 hours, during which the test subjects slept in a bed under the respective duvet.

Furthermore, the change in weight of the test subjects and the sweat absorption of the individual items of clothing and the duvet were determined by weighing before and after the sleep experiment. For this purpose, the test subjects and the clothing were weighed before and after the experiment.

3 Results and Discussion

3.1 Sweating, thermal manikin

The investigations with the sweating, thermal manikin Sherlock indicate that it is possible to determine the thermal resistance R_c and water vapor permeability R_e of duvets. Table 4 shows the results of these characterizations. Regarding the thermal resistance R_c the values are in the rage 0.56 – 1.00 m²K/W. M28 shows the lowest thermal resistance with 0.56 m²K/W (table 4). Therefore, this duvet is less insulating and should be used as summer duvet. Duvets M5, M8, M17, M18, M20 and M32 have R_c-values in the middle range between 0.61 – 0.72 m²K/W. The residual duvets M3, M4, M6, M7, M11, M12, M13, M14, M21, M25, M29 show high thermal resistance values in the range 0.75 – 1.00 m²K/W (table 4). So, the thermal insulation of these duvets can be rated as high and they should be used in winter when the ambient temperature in bedrooms is low.

Table 4. Thermal resistance R_c and water vapor resistance R_e of different duvets measured with sweating, thermal manikin Sherlock.

Sample	Thermal resistance R_c [m²K/W]	Water vapor resistance R_e [m²Pa/W]
M3	0.77	98.78
M4	0.76	82.93
M5	0.61	64.86
M6	0.96	104.84
M7	1.00	102.54
M8	0.72	73.98
M11	0.87	100.09
M12	-	54.09
M13	0.77	83.13
M14	0.75	73.33
M17	0.65	66.85
M18	0.69	68.23
M20	0.71	84.74
M21	-	61.54
M25	0.95	92.48
M28	0.56	51.89
M29	0.87	84.69
M32	0.62	60.15

The results of water vapor resistance R_e are in the range 51.89 – 104.84 m²Pa/W. Especially duvet M28 and M12 has low R_e-values, which means these duvets have a good breathability and during sleep produced sweat can be transported through the duvet to the ambient. The highest water vapor permeabilities have the duvets M6 and M7 with values in the range 102.54 – 104.84 m²Pa/W. This can be explained, among other things, by the high thickness of the duvet. The by human produced sweat (water vapor) must pass through more material before it can be released into the ambient. The results show no correlation between the R_e-value and the filling or stitching design of the duvets.

In addition, the microclimate in the bed cave was determined during the measurements of the water vapor resistance by ten temperature and humidity sensors. Figure 4 shows the average temperature (orange, left) and relative humidity (blue, right) in the bed cave during the measurements of the water vapor resistance R_e using the sweating, thermal manikin Sherlock. There are slight differences in the microclimate of the bed cave for different duvets. The temperature is between 25.67 - 28.89 °C. The lowest temperatures in the bed cave were achieved for duvet M3 and M28, for duvets M11, 21 the highest. In the case of relative humidity in the bed cave, the values are in the range of 54.43 - 67.43% RH. From a clothing physiological point of view, the relative humidity should be below 60% RH, because at higher relative humidity's no differentiation can be made by humans and it is sensed as unpleasant wet. The duvets M14 and M28 have the lowest relative humidity in the bed cave during the determination of the water vapor resistance. The duvets M7 and M11 the highest relative air humidity in the bed cave.

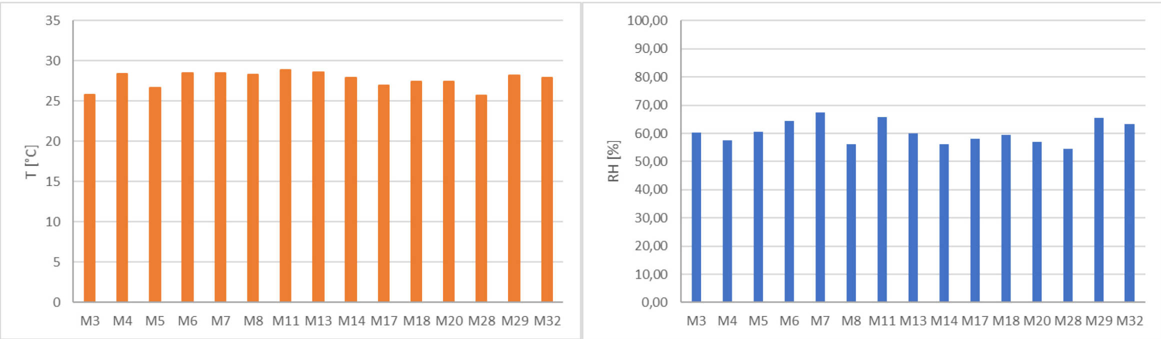

Fig. 4 Temperature T (left) and relative humidity RH (right) in the bed cave during the measurements of the water vapor resistance R_e using sweating, thermal manikin Sherlock

There are no apparent correlations between water vapor resistance R_e measured with the sweating, thermal Manikin Sherlock and the climate in the bed cave.

3.2 Subject Trial

During the monitored sleeping experiments the test subjects produced a small amount of sweat between 275 g and 490 g (table 5). Most of the produced sweat P evaporates, i.e. 95.54% (M32) - 97.27% (M14) (ratio evaporated sweat E/produced sweat P) were transported through the duvet and released into the environment. In the duvets themselves, 1.31 g (M5), 1.62 g (M14) and 3.91 g (M32) remain over the entire monitored sleeping experiment (table 5). This means that only very small amounts of sweat remain in the duvets. The results show clearly that while sleeping under the duvet M32, which has climatic zones, the subjects produces less sweat. Simultaneous duvet M32 absorbs the highest amount of sweat.

The results of the individual monitored sleeping experiments were evaluated. The data was analyzed subject-specific and product-specific. The mean values across all subjects were calculated. Due to the large number of data, the following results are limited to mean values of the recorded objective data (skin temperature, temperature in the microclimate, humidity in the microclimate) for all duvets on lower back right position.

Table 5. Produced and evaporated sweat amount during subject trial.

Clothing	**Amount of sweat [g]**		
	M5	**M14**	**M32**
Subject	490.00	461.11	275.00
Underpants	1.17	0.89	1.18
Pajama shirt	1.80	4.76	2.44
Pajama trousers	7.59	2.59	1.24
Duvet	1.31	1.62	3.91
Cushion	0.98	2.07	2.23
Bed sheet	0.70	0.68	1.26
Produced Sweat P [g]	490.00	461.11	275.00
Evaporated sweat E [g]	476.46	448.50	262.74
E/P [%]	97.24	97.27	95.54

Figure 5 shows the relative humidity (right) in the microclimate above the skin of the subject on lower back right position. All three duvets M5 (grey curve), M14 (orange curve) and M32 (blue curve) show the same curve progression with minor differences for the individual duvets. Towards the end of the sleep period of six hours, however, trends can be seen. M32 tends to have the lowest moisture in the microclimate above the skin, M14 the highest. This confirms the measurements with the sweating, thermal Manikin Sherlock.

Here M14 has the highest water vapor resistance R_e compared to the duvets M5 and M32. Low water vapor resistance R_e means produced sweat is transported through the duvet to the ambient. In case of higher values this transport is less efficient and the relative humidity in the microclimate above the skin rises.

By comparing the temperature in the microclimate (figure 5, right) above the skin of the subject on lower back right position of the three duvets similar curve progression can be seen, too. This is not surprising considering that these duvets have slightly differences in the thermal resistance R_c (table 4). The measurement fluctuations within curve M14 on the lower back right can be explained by averaging over all subjects. M14 has the highest thermal resistance, which means thermal insulation, of these three samples. It is therefore not surprising that the temperature in the microclimate of the bed cave is higher in the case of M14 than in the other duvets. Duvet M14 has the higher R_e-value compared to M5 and M32, but the relative humidity in the microclimate is almost the same for these three duvets during the subject trail. Furthermore, the subject produced 461.11 g of sweat in case of M14, which is greater than M32 and a little bit lower than M5. That implies that M14 puffers more sweat than M5 and M32.

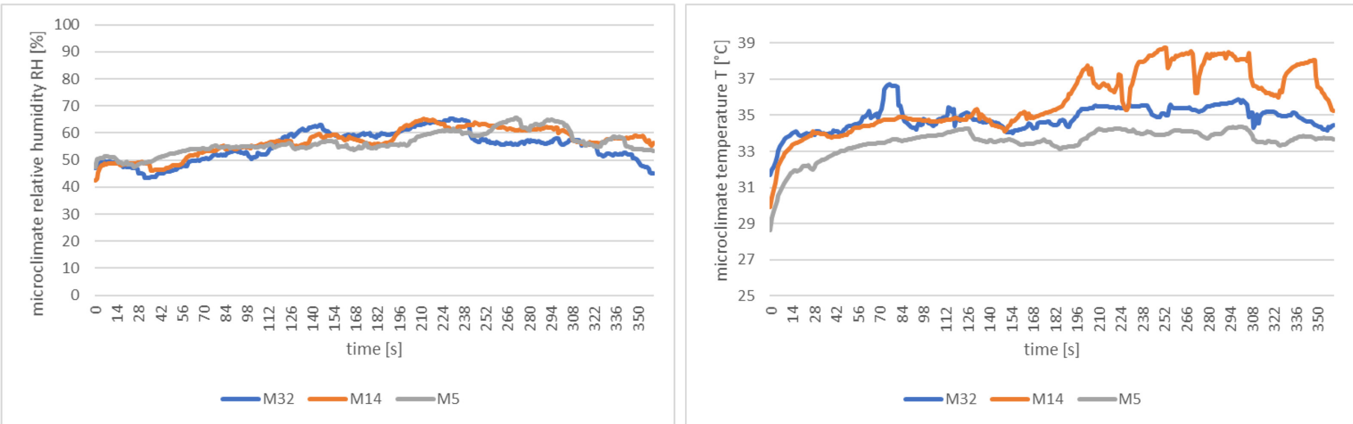

Fig. 5 Relative humidity RH (left) and Temperature T (right) in the microclimate above the skin on lower back right position during monitored sleeping experiment with subjects.

Figure 6 shows the skin temperature on lower back right position during the monitored sleeping experiment. The values show, as before the temperature in the microclimate, that the three duvets slightly differ in their thermal resistance. It can be said that the lowest skin temperatures occur while sleeping under the duvet M32. Compared to M5 and M14, this duvet also has the lowest thermal resistance (Table 4).

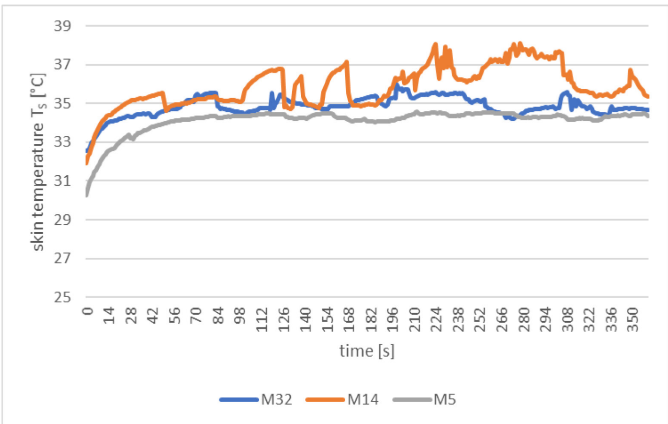

Fig. 6 Skin temperature T_s on lower back right position during monitored sleeping experiment with subjects.

After each individual sleeping experiments, the subjects filled out a detailed standardized questionnaire for the duvets M5, M14 and M32. This questionnaire includes questions about the feeling and comfort of the duvets, as well as the overall comfort. These detailed questions are relevant for the overall assessment, to be able to classify the thermophysiological properties of duvets and the measurements with the sweating, thermal manikin Sherlock.

The examined duvets differ in terms of their stitching: M5 square, M14 body fit and M32 cross- with air chambers (table 1). The subjects did not notice any of these stitching negatively. They were consistently rated with grade 2 (good).

The evaluation of the temperature shows only slight differences between the samples. Duvets M5 and M32 are classified as comfortable (grade 2, good), M14 as comfortable-warm (grade 2.7, satisfactory) and thus as a little bit warmer and uncomfortable. This reflects the measurement data of the skin temperature on the lower back right (figure 6).

The moisture sensation of the three duvets differ slightly, too. While duvet M5 is described as dry, M14 and M32 is classified as slightly damp. The perception of moisture by the subjects is still described as good (grade 2). In addition, no humidity accumulation is felt in all duvets.

Overall, the thermophysiological comfort of duvet M5 is rated with a grade of 1.7, followed by M32 with 2.2 and M14 with 2.6. This shows clearly that there are only slight differences between the individual perception of these three duvets.

4 Conclusions

Within the German funded IGF research project AiF 19522 N “Bed Cave and Comfort”, a new system for characterizing the thermophysiological comfort of duvets should be developed, which can objectively assess the heat and moisture management of duvets considering the shape and size of the bed cave. For this purpose, a suitable measuring method was developed to characterize the thermal resistance R_c (thermal insulation) and the water vapor resistance R_e (breathability) with the sweating, thermal manikin Sherlock. It became apparent that in manikin measurements by considering the bed cave a higher information content for characterizing the clothing-physiological comfort of duvets is obtained. Based on sleep tests with subjects, these thermophysiological indicators as well as the measurement method for the sweating, thermal manikin Sherlock could be validated. The new measurement method with the sweating, thermal manikin Sherlock is suitable for characterization of the thermophysiological comfort of duvets. Here, classic as well as innovative duvets can be assessed regardless of the filling used, and the construction and manufacture of the duvets. Conventional clothing physiological characterizations with the Hohenstein skin model do not have to be carried out and there is no loss of information in accuracy and significance.

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