APPLICATION OF A THERMAL MANNEQUIN TO THE ASSESSMENT OF THE HEAT INSULATING POWER OF PROTECTIVE GARMENTS FOR PREMATURE BABIES

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Abstract:

In this study, the new tool for measuring thermal insulating power of garments for premature babies under coupled heat and moisture transport was developed. The thermal mannequin corresponds to the body weight and size of a premature baby born in the thirty fourth week of pregnancy. The mannequin surface temperature can be set at various levels, while the heat loss is measured in W/m². The mannequin is divided into eleven independent heating zones and seven independent zones of moisture evolution. The study also presents the test results of heat insulating power obtained for the newly developed garment set with commercially available garment set for babies, conducted under different climatic conditions. The results exhibit the advantage of the new material construction of the garment over the commercially available one.

Keywords:

model, thermal mannequin, newborn, heat insulating capability

INTRODUCTION

World statistics show a constantly growing level of premature births. American researchers have observed that the percentage of babies born before the thirty second week of pregnancy does not increase, whereas the number of babies born between the 34th and 36th week of pregnancy increases with each year. The newborn babies born within this group constitute over 70% of all the premature babies.[1,2] In Poland, every year about 40 thousand of premature infants are born, that is, about 10% of deliveries. Therefore, in recent years, the subgroup of newborns defined above has become the subject of increasing interest.

For many years, studies have been carried out on the thermal resistance of hospital bed-clothes with the use of children thermal mannequins.[3,4] This is connected with the fact that premature babies are very susceptible to heat loss on account of their large external surface in relation to body weight, thin immature skin, corneal layer absence, panniculus adiposus lack, brown fatty tissue absence, inefficient mechanism of "chills" and a weak vasomotor response. It has been found that in the case of premature babies with a low birth weight, in the first 24 h of their life, the water loss amounts to 150 ml per 1 kg of body weight, which can lead to disturbances in electrolyte equilibrium. For comparison, in the case of babies born after the 30th week of pregnancy, the loss of water amounts to 12 ml/kg/day.[5] For a normal premature baby's development, it is essential to provide a stable temperature and humidity of the microenvironment. The maintenance of thermally neutral environment within a very narrow temperature range from 36.5°C to 37.5°C is necessary to minimize the consumption of oxygen and calories by a newborn baby.[6] The maintenance of a constant temperature is also necessary to keep the thermal balance.

The stabilization of newborn thermal environment and avoidance of thermal stress is of importance for short- and long-term effects.[7] One third of infants with birth weight ≤ 1000 g had hypothermia after being transported from one hospital to another, despite active warming.[8] Newborns lose great amounts of heat through head due to the large skin surface, which can result in hypothermia. This in turn can lead to high consumption of oxygen and glucose (hypoglycemia), high energy expenditure connected with the body weight reduction, lethargy or hypotonia, blood vessel spasm and even thermal shock.[9,10]

Researchers of the Picardie Jules Verne University have performed tests connected with the assessment of differences in the heat insulating power of naked and dressed (including caps) newborns, using a thermal mannequin (Fig. 1) that simulated a newborn with a low birth weight. The experimental tests were carried out in a closed incubator at three different temperatures (29°C, 32°C and 34°C). The tests show that the cap put on the thermal mannequin causes a decrease in heat loss on an average by 18.9%.

Fig. 1. Thermal mannequin simulating a newborn with a low birth weight[11]

The researchers have concluded that this phenomenon can be a reason for over warming of newborn babies' brains. They suggest that babies left in an incubator should have their body covered and cap taken off. Exceptions are babies with hypothermia who should be provided with thermal balance.[11]

Global heat transport in the macro-scale can be determined by means of balance formulation with the term describing sweat evaporation.[11,12] Analyzing these equations,[17] it can be concluded that the experimental determination of the heat insulating power of protective garments for premature babies seems to be legitimate. This is possible through constructing a thermal mannequin that makes it possible to assess the heat insulating power of particular garment parts of the newborn garment. The thermal mannequins known so far were suitable only to measure the thermal insulating power.[3,4,13–15] Researchers of the Université de Picardie Jules Verne have assessed the body heat losses between mannequins with small and large body dimensions of premature infants, using two anthropomorphic thermal mannequins of newborns weighing 900 g and 1800 g (Fig. 2).[18]

A successive technologically advanced solution is the thermal mannequin worked out by the Silesian University of Technology. It is a copper anthropomorphic thermal mannequin of a newborn (Fig. 3) for testing the convectional and radiation heat exchange with environment in an air-conditioning chamber. It makes it possible to measure the stream of lost heat at selected average skin temperatures and surrounding air.[19]

Any presented mannequin has not simulated the conditions of the coupled heat and moisture transfer between the body of a newborn and the surroundings. Therefore, the basic aim of the study was to construct a measurement tool reproducing the newborn skin in the form of a mannequin that would allow one to assess the heat insulating capability of various parts of the newborn garment and the resistance of water vapor and heat insulation under conditions of simulated sweat secretion.

The maintenance of proper body temperature and humidity of premature babies is of paramount importance for their survival. Literature data and information obtained in the Neonatology Clinic of the Polish Mother's Memorial Hospital Institute show that a higher surrounding temperature and higher humidity contribute to a lower mortality of newborns with a low birth weight. These parameters influence the maintenance of proper thermo-regulation that is a key element of the premature newborn care. The loss of heat by evaporation is a process absorbing energy, evoked by water evaporation from skin or mucous membranes. The evaporation of each gram of water results in a loss of about 0.58 kcal, which equals about 20 W of heat. A premature infant skin has an underdeveloped horny layer, which causes an essential increase in the trans-epidermal water loss and a decrease in its protective possibilities. The optimal environment temperature for newborns is well defined for various body weights and maturation stages. On the other hand, it seems that there is no information regarding the effect of the composition and garment structure of the fabric's raw material on the maintenance of a premature baby's thermal balance in various development phases.

Fig. 2. Thermal mannequins corresponding to the infant weight of 1800g and 900g[18]

Fig. 3. Copper anthropomorphic thermal mannequin of a newborn[19]

Another essential aim of the study was to examine 18 different variants of knitted fabrics, specially made to provide premature babies with physiological comfort and to select an optimal structure of knitted fabric guaranteeing the warmth retention for premature babies under conditions of intensive moisture secretion and blocking moisture transport from the premature infant skin to the environment. Investigations were carried out with the use of conventional two-layer knitted fabrics to provide physiological comfort as well as knitted fabrics with on-conventional structure protected by a patent. Moreover, the authors analyzed the influence of the sweat secreted on the heat insulating power of a commercial cotton garment set for babies under conditions outside incubator. Author's solution of a garment made of two-layer bamboo viscose-polyester knitted fabric was also tested in the study.

Test methods

Characteristics of measurement tool for the assessment of biophysical properties of garments for infants

The assessment of the thermo-insulating properties of garments for premature babies was performed with the use of the premature baby thermal mannequin with a function of moisture secretion in its particular anatomic zones (Fig. 4). This mannequin was made by the ATT Wladyslaw Tarnowski Company.

The mannequin model corresponds to the size and proportions of a baby's body with birth weight of 1500 g. The mannequin dimensions have been established on the basis of real dimensions of premature babies born in the Baby Health Center in the Department of Neonatology in 2012. The most essential feature of the solution proposed is the possibility of a full continuous controlling of the moisture emission within the range of physiological values. The total mannequin surface amounts to 1100 cm². 450 miniature moisture emission points (Fig. 5) are located in the external polymeric coating imitating the skin and controlled in 7 independent zones (head center, head back, face, torso, back, hands, and legs).

The water emission rate is regulated within the range from 1 to 80 µl/h/cm².

This mannequin also consists of 11 independent heating zones: face, head, occiput, chest, abdomen, back, bottom, left hand, right hand, left leg, right leg, positioned by means of computer software, which is shown in Fig. 6. Each of the zones can be separately controlled, which makes it possible to set different temperatures and levels of moisture emission in particular measurement zones. This relates to the fact that an infant as an adult person secretes different amounts of sweat in different body parts.

Additionally, the mannequin is equipped with the function of mixing since it was accepted that the urination by a baby can also influence its biophysical comfort and thermo-regulation.

The mannequin can operate at ambient temperature from 10°C to 44°C and humidity from 20% to 90%. On account of the necessity of simulating the environment conditions as well as incubatory conditions, the mannequin was located in a large-size chamber to control climatic conditions within the temperature range from -20°C to +50°C, relative humidity from 10% to 90% (for temperatures of dew-point from +5 to +50°C) and air flow rate from 0.15 to 1.0 m/s.

The verification of the mannequin reading correctness was carried out by multiple measurements of total heat insulating power of air gap close to the mannequin's skin under the same

Fig. 4. Thermal mannequin of premature infant with the function of moisture secretion in its particular anatomic zones

Moisture emission points

Fig. 5. Emission points of water located on the mannequin head

climatic conditions (20°C, 25°C) and their comparison with those obtained for the commercially available mannequin called Newton produced by the Measurement Technology Northwest, USA. For that end, both mannequins were dismantled and located in a lying position in the large-size chamber to set the thermal conditions. The comparison of results is listed in Table 1. Moreover, the mannequin's surface temperature readings were checked in a computer and verified by means of external siliceous temperature sensors and Optris pyrometer to calibrate the measurement system.

The results of the total heat insulating power obtained were subjected to statistic assessment according to the standard PN-EN ISO 5725-2:2002 "Correctness of measuring method and measurement results – Part 2: Basic method for the determination of repeatability and reproducibility of the standard measurement method".

Fig. 6. Window of measurement parameters

Table 1. Verification results of the readings correctness on the thermal mannequin together with evaluation of uncertainty

Climatic conditions	Thermal mannequin of premature baby	Newton thermal mannequin	Temperature readings in the computer program of mannequin	Temperature readings on Optris pyrometer	Temperature readings on a siliceous sensor
	Total heat insulating power	Total heat insulating power			
	$\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$	$\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$
20°C/50%	0.093 ± 0.0005	0.095 ± 0.0006	35.00	35.02	35.00
25 °C/50%	0.098 ± 0.0008	0.099 ± 0.0007	35.00	34.98	35.01

Table 2. List of statistics W

Climatic conditions	Thermal mannequin of premature baby	Newton thermal mannequin
	Total heat insulating power	Total heat insulating power
20oC/50%	0.872	0.826
25oC/50%	0.860	0.920

Using Shapiro-Wilk's test, the conformity of distribution of total heat insulating power with the normal distribution was tested at a significance level of $\alpha = 0.02$. Hypothesis H0 was put forward, confirming that the distribution of the feature tested is a normal distribution, compared with alternative hypothesis H1, stating that the distribution of the feature tested is different from the normal distribution. The value of statistics W was compared with the values of range between quantiles that in these tests amounted to $< W(1/2\alpha, n); W(1-1/2\alpha, n) >$, that is, $< 0.743; 0.986 >$. The values of statistics for the data are listed in Table 2.

The value of statistics W in all the cases belongs to the range $< W(1/2\alpha, n); W(1-1/2\alpha, n) >$, which allows one to state that there is no basis at the significance level of $\alpha = 0.02$ to reject the hypothesis H0, and the results obtained correspond to the normal distribution.

The differences between mean values obtained during the tests using both manikins were assessed using the Cochran – Cox test. This test assumes the null hypothesis H0 that there are no statistically significant differences between the mean values of the total heat insulating power. This hypothesis was verified against the H1 hypothesis, which predicates that the mean values are statistically different. If the calculated value of statistic C does not belong to critical interval, the H0 must be accepted. This test was carried out for the significance level of 0.02. The critical interval is equal to $(-\infty; -4.0321 \text{ and } 4.0321; \infty)$. The value of statistics C was equal to 3.8508 for the tests performed under thermal conditions at 20oC/50% and -1.3383 for the tests performed under thermal conditions at 25oC/50%. As the results obtained do not belongs to the critical interval, it should be concluded that there are no statistically important differences between the results obtained on both thermal mannequins with significance level of 0.02.

Characteristics of the test fabrics

The analysis of knitted fabrics used for the premature baby garments has shown that they are made of cotton yarns. Cotton knitted fabrics presently used as protective garments for premature babies can contribute to thermal discomfort,

as with the evaporation of water absorbed from the baby's body and surroundings, the baby's body temperature goes down. Moreover, the moisture content decreases the heat insulating capability of the knitted fabric due to an increase in the coefficient of heat penetration. This discomfort increases when the premature baby is brought out from an incubator, where the ambient temperature is lower. The opinions about natural fibers, as particularly predestined for premature baby garments, can be undermined due to the following reasons. A high moisture (sweat) absorption causes excessive fiber swelling, adversely decreasing the size of skin pores. In extreme cases, these can be totally blocked, which results in unpleasant feelings connected with the garment sticking to body. At too high moisture absorption, as mentioned above, the garment heat insulating capability gets upset, which under unfavorable conditions, when organism itself produces little heat, causes unpleasant and in some circumstances "unhealthy" chill in the covered body part. With swollen fibers and consequently blocked air pores, the organism cannot take up more oxygen through skin. Supplying oxygen through skin plays a very important role in the organism physiology. Too much moisture directly under the garment can create favorable conditions for the development of microorganisms – bacteria and fungi, which is particularly dangerous for premature infants with a reduced resistance to the effect of microorganisms.

By using a two-layer structure of knitted fabric made with fibers with different affinities to moisture, it is possible to impart knitted fabrics with properties that would eliminate the above mentioned unfavorable phenomena. A typical two-layer structure of knitted fabrics consists of [20–27] (Fig.7):

- a layer of knitted fabric made of conductive-diffusive yarns that directly adhere to body. This layer takes off and transfers moisture from the body, in the form of both liquid and vapor phases.
- a layer of knitted fabric made of yarns with absorption properties. It does not directly come in contact with the skin. Its function is to keep moisture away from the body and evaporate it to surroundings.

Fig. 7. Model of two-layer knitted fabric with required properties, made on the basis of a picture taken under an optical stereoscopic microscope[30]

Table 3. Yarns used to make the conductive-diffusive fabric layer[30]

No.	Yarn type	Denotation
1.	Polypropylene 100%, 84 dtex f 25x2	PP 84 dtex /f 25x2
2.	Polyamide 66 100%, 78/68, looped, doubling number D=2	PA66 78dtex/f68x2
3.	Polyamide 66 100%, 140 dtex f 102, (Taslan)	PA66 140dtex/f102 (TASLAN)
4.	Polyester 100%, 167 dtex f 96, (Torlen)	PES 167dtex/f96 (TORLEN)
5.	Polyester 100%, microfibers, 150 dtex f 256 (Trewira)	PESTREVIRA 150dtex/f256x1

Table 4. Yarns used to make the absorptive fabric layer[30]

No.	Yarn types	Denotation
1.	Conventional cotton 100%, 20 tex, $\alpha_m = 90$	CO 20 tex
2.	Conventional cotton 100%, 20 tex, $\alpha_m = 100$	CO 20 tex
3.	Conventional cotton 100%, 20 tex, $\alpha_m = 121$	CO 20 tex
4.	Organic cotton, combed 100%, 20 tex, $\alpha_m = 107$	CO 20 tex
5.	Conventional cotton, combed 100%, 20 tex, $\alpha_m = 109$	CO 20 tex
6.	Cotton 24 tex,	CO 24tex
7.	Conventional cotton, combed bleached 100%, 20 tex, $\alpha_m = 111$	CO BI 20tex
8.	Conventional Cotton, combed bleached 100%, 15 tex, $\alpha_m = 100$	CO BI 15 tex
9.	Fibers made of wooden pulp 100%, 20tex, $\alpha_m = 110$	Viscose 20 tex
10.	Fibers made of bamboo pulp 100%, 20tex, $\alpha_m = 129$	Bamboo20tex

To fulfill the requirements of a two-layer knitted fabric, the following types of yarns with conductive-diffusive properties (described in [30]) were proposed:

The following types of yarns were used as yarns with absorptive properties:

The textile raw materials mentioned above were used to produce two-layer knitted fabrics composed of two plain stitches joined by the tucking technique with a polyamide textured thread with a low linear density PA 22dtex7. The stitch structure is shown in Fig. 8.

For comparative purposes, two-layer knitted fabrics were also designed and produced with both layers made of the same raw materials. These fabrics are mentioned in Table 5 as variant 16 and 17 consisting of cotton yarns and variant 18 made of two layers of viscose yarn.

The two-layered knitted fabrics were made with the use of a cylindrical rib knitting machine from Mayer & Cie Company, Type Oval 36, with the following characteristics: needle gauge 20 E, number of cam boxes $z = 36$, number of needles $I = 1872$, cylinder diameter $\varphi = 30$ inches. During the production of two-layer knitted fabrics, the pretension value was $F_0 = 0.1$ cN/tex, and the value of take-off power $F_A = 0.2$ cN/wale.

Each of the produced knitted fabrics was tested to determine its surface weight according to the standard PN-EN 12127:2000, thickness according to the standard PN-EN ISO 5084:1999 and air permeability according to the standard PN-EN ISO 9237:1998. The tests results obtained are listed in Table 5.

For comparison purposes, the tests also included a commercial set of premature baby garment made of cotton knitted fabric with a surface weight of 277.17 g/m².

Fig. 8. Structure of two-layer knitted fabric and the view of conventional two-layer knitted fabric with its cross-section along the course
Table 5. Test results of two-layer knitted fabrics[30]

Nr	Type of fabric	Surface weight	Thickness	Apparent density	Air permeability
		$\text{g}\cdot\text{m}^{-2}$	mm	$\text{kg}\cdot\text{m}^{-3}$	$\text{mm}\cdot\text{s}^{-1}$
1	COBI20tex PP84dtex/ f 25x2/PA66 22dtex/f7	225.05	1.42	158.49	491
2	CO20tex PP84dtex/ f 25x2/PA66 22dtex/f7	205.98	1.44	143.04	568
3	CO24tex PP84dtex/ f 25x2/PA66 22dtex/f7	235.22	1.61	146.10	403
4	Bamboo 20tex PP84dtex/ f 25x2/PA 66 22 dtex/f7 white	235.86	1.36	173.43	570
5	Viscose 20tex PP84dtex/f25x2/PA66 22dtex/f7	236.49	1.40	168.92	537
6	CO20tex PES 167dtex/f96/PA66 22dtex/f7	207.88	1.34	155.13	679
7	CO BI 20tex PES167dtex/ f 96/PA66 22dtex/f7	221.23	1.20	184.36	801
8	CO BI 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7	199.62	1.32	151.23	498
9	CO24tex PES167dtex/ f 96/PA66 22dtex/f7	219.96	1.27	173.20	675
10	Bamboo 20tex PES167dtex/f 96/PA6622dtex/f7	232.04	1.14	203.54	834
11	Bamboo 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7	221.87	1.29	171.99	527
12	Viscose 20tex PES 167dtex/f96/PA66 22dtex/f7	221.23	1.20	184.36	963
13	CO 20tex PA66 78dtex/f68x2/PA66 22dtex /f7	220.6	1.24	177.90	342
14	CO BI 20tex PA66 140dtex/f102 (TASLAN)/PA 66 22dtex/f7	181.82	1.26	144.30	1130
15	Bamboo 20 tex PA 140 dtex/ f102 TASLAN/ \ PA66 22 dtex/ f7	194.53	1.15	169.16	1550
16	CO BI 20tex CO BI 15tex/ PA66 22dtex/f7	191.35	1.18	162.16	992
17	CO24texCO 24tex/PA66 22dtex/f7	215.51	1.36	158.46	499
18	Viscose 20tex Viscose 20tex/ PA66 22dtex/f7	238.40	1.12	212.86	1080

The tests were carried out at ambient temperature (20°C) and a humidity of 50% with an air flow of 0.1 m/s, as it was established that these climatic conditions most often occur outside the incubator, under which a baby is most exposed to heat loss. For comparison, tests were also performed at a temperature of 35°C, humidity of 65% and air flow of 0.1 m/s to verify how a baby can feel in the incubator under set conditions in the standard garment set.

A computer program controlled the heat stream value to maintain a constant temperature of 34°C in each mannequin zones. During measurements, the external conditions and the temperature of each zone were monitored. After establishing the set constant external conditions (temperature, humidity and air low rate) and the constant temperature values of each zone, there was always a constant value of heat stream. The assessment of the thermo-insulating properties of the garment was performed based on the analysis of the thermal parameters of the external environment, under-garment microclimate and parameters connected with the amount of emitted moisture, temperature and energy expenditure of the mannequin.

Results and discussion

On the basis of the parameters collected during measurements from the particular mannequin anatomic zones, the value of heat insulating capability of the infant garment set was calculated according to equation 1:

$$I_a = \frac{\left[\left(\sum_{i=1}^n f_i \cdot T_{si} \right) - T_a \right] \cdot A}{\sum_{i=1}^n H_{ci}}, \quad \frac{m^2 \cdot K}{W} \quad (1)$$

where:

f_i – part of the total area constituting the area of i zone,
 T_{si} – temperature of the surface of i mannequin zone, °C,
 T_a – ambient temperature °C,
 A – total mannequin area, m²,
 H_{ci} – heating power supplied to i mannequin zones, W.[14]

Then, the effective heat insulating power was calculated from equation 2:

$$I_{cle} = I_{ao} - I_{am}, \quad \frac{m^2 \cdot K}{W} \quad (2)$$

where:

I_{ao} – heat insulating capability of dressed mannequin,
 I_{am} – heat insulating power of nude mannequin.

On the basis of the parameters collected during measurements from the particular mannequin anatomic zones, the water vapor resistance value of the baby garment was calculated according to equation 3:

$$R_{ct} = \frac{[P_{si} - P_a]}{Q/A - [(T_{si} - T_a)/R_{ct}]}, \quad \frac{m^2 \cdot Pa}{W} \quad (3)$$

where:

P_{si} – water vapor pressure of i mannequin zone, Pa,
 P_a – water vapor pressure of environment, Pa,

Q/A – area weighted heat flux, W/m²,
 R_{ct} – area weighted heat flux, (W/m²)²,
 T_{si} – zone average temperature, °C,
 T_a – ambient temperature, °C [31].

Then, the effective water vapor resistance was calculated from equation 4:

$$R_{ef} = R_{ct} - R_{et0}, \quad \frac{m^2 \cdot Pa}{W} \quad (4)$$

where:

R_{et} – water vapor resistance of the dressed mannequin,
 R_{et0} – water vapor resistance of nude mannequin.

The effective heat insulating power and effective water vapor resistance were calculated with and without simulations of sweat secretion. The test results are presented in Table 6.

By means of Shapiro-Wilk's test, the conformity of the distribution of effective heat insulating power with simulation of sweat secretion to the normal distribution was confirmed.

Then, the single-factor analysis of variance ANOVA was performed, which showed that there are statistical differences between the mean values of the effective heat insulating power calculated with the sweat simulation of tested samples. For $\alpha = 0.05$, the value of test statistics calculated falls into the critical range defined by specified limits [3.47; ∞). The successive stage of variance analysis was to find which averages differ between themselves (post-hoc tests). To that end, Tukey's test was carried out ($\alpha = 0.05$), making multiple comparisons by pairs, testing the difference between each pair of averages and generating a matrix where "+" indicated the acceptance of zero hypothesis, whereas "-" indicated its rejection in relation to alternative hypothesis. The results of Tukey's test are presented in Table 7.

The analysis of test results presented in Table 6 and in Figure 9 indicates that from the point of view of the final application, that is, protection premature babies before the hypothermia, the best effectiveness was obtained for the material variant of the garment called Bamboo 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7. The garment made of this kind of knitted fabric is characterized by the highest value of effective heat insulating power keeping the highest value of effective resistance of water vapor.

The next series of tests was oriented towards the evaluation of behavior of the selected material composition under different environmental conditions and the comparison of the biophysical properties of the newly developed fabrics with the commercial cotton baby garment. Ambient temperature was changed in the range of 20–35°C and the relative humidity in a range of 50–65%. Average values of the effective heat insulating power, calculated from 3 measurement repetitions are listed in Table 8 and shown in Figures 9 and 10. The results for dry mannequin (without sweat secretion) and for mannequin sweating with various intensities are also listed below.

Table 6. Test results of heat insulating properties with the use of thermal mannequin together with evaluation of uncertainty

No.	Fabric type	Effective heat insulating power	Effective heat insulating power	Effective resistance of water vapor
		No simulation of sweat secretion	With simulation of sweat secretion – 3.2 ml·h ⁻¹ ·cm ⁻²	
		m ² ·K·W ⁻¹	m ² ·K·W ⁻¹	m ² ·Pa·W ⁻¹
1	CO BI 20tex PP84dtex/ f 25x2/PA66 22dtex/f7	0.099 ± 0.0012	0.060 ± 0.0012	15.987 ± 0.5707
2	CO 20tex PP84dtex/ f 25x2/PA66 22dtex/f7	0.093 ± 0.0032	0.059 ± 0.0027	19.411 ± 0.2133
3	CO 24tex PP84dtex/ f 25x2/PA66 22dtex/f7	0.102 ± 0.0017	0.055 ± 0.0014	21.099 ± 0.5508
4	Bamboo 20tex PP84dtex/ f25x2/ PA 66 22 dtex/f7 white	0.096 ± 0.0012	0.056 ± 0.0008	16.455 ± 0.2021
5	Viscose 20tex PP84dtex/f25x2/ PA66 22dtex/f7	0.101 ± 0.0017	0.059 ± 0.0012	16.911 ± 0.1221
6	CO 20tex PES 167dtex/f96/ PA66 22dtex/f7	0.088 ± 0.0017	0.037 ± 0.0049	16.002 ± 0.1339
7	CO BI 20tex PES167dtex/ f96/PA66 22dtex/f7	0.092 ± 0.0024	0.047 ± 0.0044	15.596 ± 0.1712
8	CO BI 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7	0.095 ± 0.0012	0.061 ± 0.0017	20.081 ± 0.0491
9	CO 24tex PES167dtex/ f96/PA66 22dtex/f7	0.092 ± 0.0017	0.061 ± 0.0014	18.226 ± 0.0672
10	Bamboo 20tex PES167dtex/ f96/PA6622dtex/f7	0.089 ± 0.0012	0.059 ± 0.0032	18.501 ± 0.2315
11	Bamboo 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7	0.094 ± 0.0027	0.065 ± 0.0014	22.769 ± 0.7047
12	Viscose 20tex PES 167dtex/f96/ PA66 22dtex/f7	0.108 ± 0.0008	0.058 ± 0.0038	18.614 ± 0.2156
13	CO 20tex PA66 78dtex/f68x2/ PA66 22dtex /f7	0.080 ± 0.0019	0.065 ± 0.0022	19.463 ± 0.3256
14	CO BI20tex PA66 140dtex/f102 (TASLAN)/PA 66 22dtex/f7	0.085 ± 0.0030	0.044 ± 0.0017	19.442 ± 0.2629
15	Bamboo 20 tex PA 140 dtex/f102 TASLAN/ \ PA66 22 dtex/ f7	0.101 ± 0.0022	0.059 ± 0.0055	16.133 ± 0.0768
16	CO BI20tex CO BI 15tex/PA66 22dtex/f7	0.086 ± 0.0038	0.047 ± 0.0008	15.170 ± 0.1059
17	CO24texCO24tex/PA66 22dtex/f7	0.081 ± 0.0012	0.040 ± 0.0012	17.999 ± 0.5713
18	Viscose 20texViscose 20tex/ PA66 22dtex/f7	0.096 ± 0.0019	0.053 ± 0.032	16.049 ± 0.0222

Table 7. Matrix of the comparison results of effective heat insulating power with simulation of sweat secretion by Tukey's test (the numeric denotation of samples is compatible with those in Table 6)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		+	+	+	+	-	+	+	+	+	+	+	-	-	+	-	-	+
2	+		+	+	+	+	+	+	+	+	+	-	-	+	+	+	-	+
3	+	+		+	+	-	+	+	+	-	+	+	-	-	+	-	-	+
4	+	+	+		+	+	+	+	+	+	+	-	-	-	+	+	-	+
5	+	+	+	+		-	+	+	+	-	+	+	-	-	+	-	-	+
6	-	+	-	+	-		+	+	+	+	+	-	+	+	-	+	+	+
7	+	+	+	+	+	+		+	+	+	+	-	-	+	+	+	-	+
8	+	+	+	+	+	+	+		+	+	+	-	-	+	+	+	-	+
9	+	+	+	+	+	+	+	+		+	+	-	-	+	+	+	-	+
10	+	+	-	+	-	+	+	+	+		+	-	+	+	-	+	+	+
11	+	+	+	+	+	+	+	+	+	+		-	-	+	+	+	-	+
12	+	-	+	-	+	-	-	-	-	-	-		-	-	+	-	-	-
13	-	-	-	-	-	+	-	-	-	+	-	-		+	-	+	+	-
14	-	+	-	-	-	+	+	+	+	+	+	-	+		-	+	+	-
15	+	+	+	+	+	-	+	+	+	-	+	+	-	-		-	-	+
16	-	+	-	+	-	+	+	+	+	+	+	-	+	+	-		+	+
17	-	-	-	-	-	+	-	-	-	+	-	-	+	+	-	+		-
18	+	+	+	+	+	+	+	+	+	+	+	-	-	-	+	+	-

Fig. 9. List of test results of total heat insulating power measured on thermal mannequin

Table 8. Average values of effective heat insulating power of baby garment and author's solution of garment made of two-layered bamboo-polyester knitted fabric, tested under set climatic conditions together with evaluation

Material	Garment set	Ambient temperature	Relative humidity	Air flow rate	Mannequin surface temperature	Sweat secretion rate	Total heat insulating power	Effective heat insulating power
Naked mannequin		°C	%	m/s	°C	µl/h/cm ²	m ² · K · W ⁻¹	m ² · K · W ⁻¹
Commercial cotton baby garment	Creepers, cap, gloves	20	50	0,1	34	0	0.093 ± 0.0024	
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7							0.159 ± 0.0039	0.066 ± 0.0018
Naked mannequin		20	50	0,1	34	2	0.184 ± 0.0045	0.094 ± 0.0024
Commercial cotton baby garment	Creepers, cap, gloves						0.091 ± 0.0023	
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7		20	50	0,1	34	5	0.146 ± 0.0036	0.055 ± 0.0016
Naked mannequin							0.17 ± 0.0042	0.079 ± 0.0021
Commercial cotton baby garment	Creepers, cap, gloves	20	50	0,1	34	10	0.089 ± 0.0023	
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7							0.138 ± 0.0034	0.049 ± 0.0014
Naked mannequin		20	50	0,1	34	20	0.16 ± 0.0039	0.071 ± 0.0019
Commercial cotton baby garment	Creepers, cap, gloves						0.085 ± 0.0022	
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7		20	50	0,1	34	20	0.121 ± 0.0030	0.036 ± 0.0011
Naked mannequin							0.146 ± 0.0036	0.061 ± 0.0017
Commercial cotton baby garment	Creepers, cap, gloves	20	50	0,1	34	20	0.073 ± 0.0019	
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7							0.096 ± 0.0025	0.023 ± 0.0010
Naked mannequin		20	50	0,1	34	20	0.111 ± 0.0028	0.038 ± 0.0012
Commercial cotton baby garment	Creepers, cap, gloves							

Material	Garment set	Ambient temperature °C	Relative humidity %	Air flow rate m/s	Mannequin surface temperature °C	Sweat secretion rate μl/h/cm ²	Total heat insulating power m ² · K · W ⁻¹	Effective heat insulating power m ² · K · W ⁻¹
Naked mannequin							0.064 ± 0.016	
Commercial baby garment Commercial baby garment	Creepers, cap, gloves	20	50	0.1	34	30	0.078 ± 0.0021	0.014 ± 0.0009
Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7							0.092 ± 0.0024	0.028 ± 0.0010
Naked mannequin							0.054 ± 0.0015	
Commercial cotton baby garment Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7	Creepers, cap, gloves	20	50	0.1	34	40	0.061 ± 0.0017	0.007 ± 0.0008
							0.080 ± 0.0021	0.026 ± 0.0010
Naked mannequin							-0.009 ± 0.0008	
Commercial cotton baby garment Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7	Creepers, cap, gloves	35	65	0.1	34	2	-0.021 ± 0.0009	-0.012 ± 0.0009
							-0.024 ± 0.0010	-0.015 ± 0.0009
Naked mannequin							-0.021 ± 0.0009	
Commercial cotton baby garment Bamboo 20tex PES TREVIRA 150dtex/f256x1/ PA66 22dtex/f7	Creepers, cap, gloves	35	65	0.1	34	5	-0.091 ± 0.0023	-0.070 ± 0.0019
							-0.093 ± 0.0024	-0.072 ± 0.0019

Fig.10. List of test results of effective heat insulating power measured on thermal mannequin

From the analysis of the data presented in Fig. 10, it follows that the effective heat insulating power of the baby garment made of bamboo/PES knitted fabric (Bamboo 20tex PES TREVIRA 150dtex/f256x1/PA66 22dtex/f7/) is higher by 42.4% from that of the commercial baby garment made of cotton knitted fabric, when tested without sweat simulation. When the simulated sweating is at a level of $10 \mu\text{l/h/cm}^2$, the difference between the garments tested increases to 69.44%, while with the intensity of sweating at a level of $40 \mu\text{l/h/cm}^2$, this difference increases to 271.42%.

The sweating intensity of mannequin refers to the literature reports that describe that babies born at the proper time secrete about $2 \mu\text{l/h/cm}^2$ of sweat, babies born after 34 weeks of pregnancy secrete from 5 to $20 \mu\text{l/h/cm}^2$ of sweat and babies born before the 30th week of pregnancy had water loss even at a level of $32 \mu\text{l/h/cm}^2$. [26,27]

Analyzing the test results, it can be observed that an increase in the moisture/sweat secretion rate causes a decrease in the heat insulating power of the baby garment set tested. As shown in Figs 9 and 10, the rate of decreasing effective heat insulating power is similar for both types of materials used. The tangent of trend line for cotton clothing is equal to -0.010 and for newly developed material composition takes the value of -0.012. Based on the tests performed, it was observed that the author's solution of baby garments better protects the baby's body against heat loss than the commercial garments.

In the case of the two final measurements, the result of heat insulating power was negative as the heat flux was supplied from outside to the baby mannequin. One can believe that a baby staying under such conditions would be overheated. Consequently, there can occur a dilation of fine peripheral

vessels located in the skin. Through dilated vessels, the excess heat is then given back to the environment by convection or with sweat.

Summarizing

The neonate mannequin with the function of moisture secretion in its particular anatomic zones allows one to determine the heat insulating power parameters of infantile clothing under the simulation of the real conditions of use. It is the only phantom worldwide making it possible to provide such a wide measurement range, allowing better understanding of the heat losses in the premature baby's body through convection, conduction, evaporation and radiation.

The premature baby mannequin presented in this paper makes it possible in future to optimize thermal conditions in incubators department of neonatology and to analyze the clothing used for infants. Owing to this mannequin, it was possible to conduct studies connected with the development of the new generation of protective clothing for premature babies characterized by a much higher value of effective heat insulating power at different rate of sweat secretion comparing to the commercially available cotton garment.

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