GLOBAL HEAT AND MASS TRANSPORT IN SYSTEM: NEWBORN BABY SKIN – TEXTILE COMPOSITE – SURROUNDING

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Abstract

Global model of heat and mass transport is defined by heat balance with term introducing mass exchange during sweat evaporation. Heat is supplied by metabolic heat production and lost by means of different phenomena. Necessary parameters of neonate body help to solve global correlation for different parameters of bonnet and external clothing. Different cases are discussed to prevent hyperthermia and hypothermia.

Introduction

Heat and mass transport can be described by different physical and mathematical methods although bounding basic rule is always balance formulation. There are two main approaches.

- Physiology of newborn baby, i.e. we introduce metabolic heat production and different heat losses of an organism. Determinant is now the children's body whereas the influence of clothing and surrounding are modelled by means of empirical correlations. Advantages of this approach are: (i) global formulation of transport mechanisms in macro-scale; (ii) description of heat loss by different phenomena; (iii) description of coupled heat and mass transport during evaporation. Disadvantages are now: (i) moisture cannot be determined because the model does not introduce mass distribution; (ii) temperatures are determined globally and there is impossible to describe locally pcm-materials, composite structure of clothing etc.; (iii) correlations are empirical, i.e. description can be not universal.
- Clothing structure, i.e. we determine heat and mass transport within textile composite. Dominant is the textile structure, whereas the children's body and surroundings are modelled by the set of boundary and initial conditions without clear physiological references. The coupled heat and mass transport is described by means of the second-order differential equations. Advantages and disadvantages are described in reverse manner as above.

Let us introduce the first approach, i.e. the global model of heat and mass transport from neonate skin through textile composite to surrounding. Main aspects are the following:

- There is the multiparametric model, i.e. heat is transported by various phenomena, whereas mass by sweat evaporation. Basic heat balance is the global correlation [1, 2], particular parameters of newborn babies are discussed in [1]. All terms are expressed in $kJ\ h^{-1}kg^{-1}$.

- Multimodal balance is discussed for the whole body, whereas the influence of clothing, covering by the bonnet and surroundings is introduced by appropriate parameters. Balance is formulated for neonate body within an incubator. Heat is supplied by metabolic heat production $\dot{M}$; lost and accumulated by conduction K, radiation on external surfaces R, convection on external surfaces C as well as skin evaporation E. Global segmental heat losses are convection C_{resp} and evaporation E_{resp} from the mucosa of respiratory tract.

1 Model description

The only heat source of neonate is metabolism which can be determined empirically as the function of postnatal age A expressed in days by following correlation.

$$\dot{M} = \left(0{,}00165A^3 - 0{,}138A^2 + 3{,}56A + 35{,}4\right)4{,}185/24 \quad (1)$$

Heat is lost in 6 parts of newborn baby: head, trunk, two arms and two legs. Global heat balance can be also defined in the general form.

$$\dot{M} - \left[\sum_{\text{i, all bodyparts}} \left(R_i + C_i + K_i + E_i\right) + C_{resp} + E_{resp}\right] = S \quad (2)$$

where S is body heat storage rate. According to balance of metabolic heat production $\dot{M}$ and heat losses, we can determine the following cases:

- $S = 0$, i.e. metabolic heat production is balanced by heat lost; thermal equilibrium determines the constant temperature distribution on skin.
- $S > 0$, i.e. metabolic heat production is greater than heat lost to surroundings; heat storage rate is accumulated within the body; the temperature increases, which causes hyperthermia.
- $S < 0$, i.e. metabolic heat production is less than heat lost; there is the heat deficit, and the temperature decreases, which can cause hypothermia.

Next, let us determine all the required terms of thermal balance. All terms are described by exact correlations and different experimental coefficients. Necessary parameters and coefficients are formulated for different heat transport conditions as well as clothing materials.

Heat is lost by conduction for the specified part of children's body K_i through skin contacting the mattress. We can describe this phenomenon by means of the following formula:

$$K_i = h_k\left(T_i - T_m\right)A_{ki}W_t^{-1} \quad (3)$$

where h_k=0.84 $kJ\ h^{-1}m^{-2}$ is conductive heat transfer coefficient; T_i–T_m denotes temperature difference between the skin surface of particular body segment and mattress in °C; A_{ki} is local skin contact area described in m^2; W_t is neonate body mass described in kg.

Heat loss by radiation at skin surface R_i can be described typically as difference of fourth power of temperatures. Thus, this term can be described in following manner.

$$R_i = \sigma\, \varepsilon_{sk}\, A_{ri}\left[\left(T_i + 273\right)^4 - \left(T_r + 273\right)^4\right]F_{cl}W_t^{-1} \quad (4)$$

where $\sigma=5.666667\cdot10^{-8}$ kJ $h^{-1}m^{-2}K^{-1}$ is the Stefan-Boltzmann constant; $\varepsilon_{sk}=0.97$ is skin emissivity; A_{ri} is effective surface area of skin segment subjected to radiation in m^2; T_r is mean temperature of radiation measured by infrared thermometer in $°C$ according to [3]; T_i is mean temperature of skin segment measured similarly in $°C$; F_{cl} is dimensionless reduction factor of thermal radiation and convection by clothing, $F_{cl}=0.86$ for combined medical clothing made of PVC foil and fabric, $F_{cl}=0.98$ for special clothing made of PVC foil, the range is from $F_{cl}=1$ for impermeable textiles to $F_{cl}=0$ for completely permeable clothing.

Heat loss by convection at skin surface C_i depends on the heat flow described by a temperature difference. It can be described mathematically as follows:

$$C_i = h_{ci}\left(T_i - T_a\right)A_{ci}F_{cl}W_t^{-1} \tag{5}$$

where h_{ci} determined in kJ $h^{-1}m^{-2}°C^{-1}$ describe convection coefficient of the specified part of neonate body; T_i–T_a denotes temperature difference between the skin surface of body segment and surrounding air in $°C$; A_{ci} defines effective surface area of skin segment subjected to convection in m^2.

Heat flow by evaporation at skin surface is the only possibility to transport the mass (i.e. sweat) from skin to surrounding. It depends on the difference of water vapor partial pressure between skin and surrounding. Maximal evaporative heat flow is caused by sweat evaporation from the whole skin surface. Now, we can denote mathematically [1, 2]:

$$E_i = \left(P_{s,H_2O} - P_{a,H_2O}\right)R_{dyn}^{-1} = h_{ei}w\left(P_{s,H_2O} - P_{a,H_2O}\right)A_{ei}F_{pcl}W_t^{-1} \tag{6}$$

where $P_{s,H20}$–$P_{a,H20}$ is difference of water vapor partial pressure between skin $P_{s,H20}$ and surrounding $P_{a,H20}$, atmospheric pressure is $P_{a,H2O}=1\cdot10^5$ hPa; R_{dyn} is dynamic total evaporative resistance of clothing and boundary layer of air in m^2 kPa W^{-1}; $h_{ei}=1.67$ h_{ci} denotes evaporative heat transfer coefficient of specified body segment in kJ $h^{-1}mb^{-1}m^{-2}$ and as it can be determined from Levis equation, w is relative humidity of skin segment, $w=0.06$ for moderate temperature and dry skin, this parameter describe influence of clothing; $A_{ei}=A_{ci}$ is an effective surface area of skin segment subjected to evaporation in m^2; F_{pcl} is dimensionless reduction factor of mass transport by clothing, the range is from $F_{pcl}=1$ for completely permeable clothing to $F_{pcl}=0$ for impermeable textiles.

Irrespective of heat losses defined for the specified body segments, there are two components determined in respiratory tract i.e. segmental heat losses by convection C_{resp} and evaporation E_{resp}. Both can be described as follows.

$$C_{resp} = \dot{V}_E C_P\left(T_E - T_l\right)W_t^{-1} \; ; \; E_{resp} = \dot{V}_E \delta\left(M_E - M_l\right)W_t^{-1} \tag{7}$$

where $\dot{V}_E$ is pulmonary ventilation rate in kg h^{-1}; $C_p=1,044$ kJ $kg^{-1}°C^{-1}$ denotes heat capacity of air in normal conditions; T_E defines temperature of exhaled air according to Hanson in $°C$

$$T_E = \frac{32{,}6 + 0{,}066T_a + 32P_{a,H_2O}}{462\left(T_a + 273\right)} \tag{8}$$

$T_l=T_a$ is temperature of inhaled air equal to surrounding temperature $°C$; $\delta=243$ kJ/g H_20 denotes latent heat of vaporization, M_E is absolute humidity of exhaled air in kg H_20/kg *of dry air* [3]; M_l is absolute humidity of inhaled air in kg H_20/kg *of dry air* [3]; P_E is partial pressure of water vapor in exhaled air in kPa described as follows

$$M_E = 0{,}622\frac{P_E}{\left(100 - P_E\right)} \; ; \; P_E = 0{,}611\,e^{\frac{17{,}27T_E}{T_E+273}} \tag{9}$$

2 Model solution

Let us introduce necessary parameters to solve the above model [1]. Surrounding conditions are typical for a nursery. Additionally, front part as well as upper section of incubator are open to the surroundings. The temperature of surrounding air within an incubator changes from initial $T_{a0}=33.2^oC$ to final $T_{ak}=31.8^oC$ in time $t=30\ min$; speed of change is negative – $0.04^oC/min$. The temperature of the surrounding air within a nursery is $T_a=(23.2\pm 0,2)^oC$, mean radiation temperature is $T_r=(19.9\pm 0,2)^oC$; moisture of the surrounding air is $w=(44\pm 1,9)\%$. Conditions within an incubator are the following: the temperature for mixed air between interior and surroundings $T_a= (23.2\pm 0.2)^oC$; speed of air $v=0.06ms^{-1}$; relative air humidity $w=(35\pm 4)\%$.

Body mass of a neonate is $W_t=(1,060\pm 0,026)kg$; postnatal age is $(4.5\pm 0.4)days$; body surface $(0.100\pm 0.010)m^2$; mean radiation temperature $T_r=30.6^oC$.

Surface temperature of mattress is equal to $T_m=(31.4\pm 0.1)^oC$.

The same source [1] helps to determine mean temperatures of body segments and convection coefficients as well as areas of the particular parts of a body, cf. Table 1, Table 2. It is immediately obvious that the only part of a body takes an active part in individual form of heat transfer, c.f. from 50% for radiation and convection to 10% for conduction. Neonate clothing is typical medical garment for newborn children transparent for infrared radiation (*98%* of transparence).

Tab. 1: *Temperatures and convection coefficients for particular parts of neonate body*

Particular part of neonate body	Covered		Uncovered	
	T_i °C	h_{ci} $kJ\cdot h^{-1}\cdot m^{-2}\cdot °C^{-1}$	T_i °C	h_{ci} $kJ\cdot h^{-1}\cdot m^{-2}\cdot °C^{-1}$
Head	35.53±0.72	3.63±0.11	32.82±1.84	3.60±0.17
Trunk	34.93±0.79	2.84±0.09	32.33±1.30	2.82±0.10
Arm (one)	32.10±0.65	4.02±0.03	29.50±1.85	3.97±0.05
Leg (one)	34.36±0.79	3.84±0.04	31.57±1.50	3.82±0.05
Whole body	34.37±0.68	3.63±0.07	31.71±1.76	3.60±0.08

Source: [1]

Tab. 2: *Table 2. Areas of particular parts of neonate body*

Particular part of neonate body	Area · 10^{-3} m^2		
	A_{ri}	A_{ci}	A_{ki}
Head	21.43±0.08	22.63±0.05	1.44±0.04
Trunk	7.10±0.08	1.97±0.07	3.75±0.05
Arm (one)	4.42±0.05	5.40±0.05	0.40±0.05
Leg (one)	10.06±0.04	11.99±0.05	0.90±0.04
Whole body	55.04±0.07	56.76±0.06	7.74±0.05

Source: [1]

Our next goal is to determine the heat loss for particular parts of a neonate body. To simulate the reduction of the heat loss, let us first assume a head is covered by the bonnet. Thus, thermal insulation of a bonnet I_{cl} can be described in $m^2 \cdot °C \cdot W^{-1}$ by the following empirical correlation.

$$I_{cl} = 0{,}067 \cdot 10^{-2} A_{co} + 0{,}217\, Th\, A_{co} \tag{10}$$

where A_{co} is dimensionless proportional area of head covered by bonnet; *Th* describe material thickness in *m*.

Bonnet can reduce both heat and mass transport to surrounding. Heat reduction factor for radiation and convection can be described according to Nishi and Gagge [4] by means of experimental correlation as follows:

$$F_{cl-head} = \left[\left(h_{c-head} + h_{r-head} \right) I_{cl} + \left(1 + 1{,}971 I_{cl} \right)^{-1} \right]^{-1} \tag{11}$$

where $h_{c-head} = h_{r-head}$.

Heat reduction factor for evaporation according to [4] is described experimentally.

$$F_{p\,cl-head} = \left\{ \left(1 + 2{,}22 h_{c-head} \right) \left[I_{cl} - \left[1 - \left(1{,}971 I_{cl} \right)^{-1} \left(h_{c-head} + h_{r-head} \right)^{-1} \right] \right] \right\}^{-1} \tag{12}$$

The main parameter is the time to reach the safety limit (*38˚C*) time of hyperthermia (*40˚C, 43˚C*) and rate of body cooling for hypothermia.

Let us first determine thermal insulation by a bonnet and general heat balance for constant metabolic heat production (Tables 3, 4, 5). We have to discuss the thermal insulation effect of a covering bonnet on hyperthermia (overheating) and hypothermia (overcooling) of an organism.

The heat loss of head by radiation is calculated for different parameters of the bonnet, Table 3. According to mathematical correlations Eq. (10) and Eq. (11), heat resistance depends on two parameters. Material composition does not influence heat insulation. Let us also assume three different material thicknesses (*1mm=0,001m*; *3mm=0,003m*; *5mm=0,005m*) as well as three relative areas of a covering bonnet (*20%, 60%* and *100%*). A fully covered head is the maximal value and determines maximal heat insulation of a bonnet.

Tab. 3: *Heat loss by radiation for head*

Material thickness [m]	Relative area of covering bonnet		
	20%	60%	100%
0.001	1.726537723	1.463927064	1.26446982
0.003	1.655039492	1.312611774	1.078808162
0.005	1.588556011	1.187095692	0.937262784

Source: Own

Heat loss by radiation can change significantly; maximal difference is about *100%*. It is evident that the most critical part of a neonate with respect to radiation is its head.

Heat loss by convection is determined for the same parameters, Table 4. Convection is a significant phenomenon and it can change considerably. Thus, radiation and convection of a head can change the global heat balance of a neonate organism and prevent hypo- and hyperthermia.

Tab. 4: *Heat loss by convection for head*

Material thickness [m]	Relative area of covering bonnet		
	20%	60%	100%
0.001	0.872631811	0.739902354	0.639092083
0.003	0.836494963	0.663424132	0.545254417
0.005	0.802892685	0.599985422	0.473714133

Source: Own

Heat loss by evaporation is shown in Table 5. Evaporative heat transport is lesser than by radiation and convection. However, it is still a significant value.

Tab. 5: *Heat loss by evaporation for head*

Material thickness [m]	Relative area of covering bonnet		
	20%	60%	100%
0.001	1.662947478	1.410009052	1.217898034
0.003	1.594082603	1.264266867	1.039074495
0.005	1.530047781	1.143373679	0.902742385

Source: Own

Heat can be transported by convection during an immediate contact between a body and a mattress. Convectional heat loss is shown in Table 6 for minimal thickness of the covering bonnet. The obtained values are considerably lower than others, cf. Tables 3, 4, and 5. Consequently, thermal insulation of a bonnet does not influence significantly heat loss by convection.

Tab. 6: *Heat loss by convection for head*

Particular part of neonate body	Heat loss by convection
Head	0.004712875
Trunk	0.010490094
Arm (one)	0.000221887
Leg (one)	0.002111094
Whole body	0.018216747

Source: Own

Heat is also radiated by other parts of a body. Radiation is reduced by special clothing which can be combined medical clothing for neonate made of PVC foil of a reduction factor of infrared radiation $F_{cl}=0,98$. Alternative is newborn baby clothing made of PVC foil and fabric of reduction factor $F_{cl}=0,86$. Calculations are demonstrated in Table 7.

Tab. 7: *Heat loss by radiation for other body parts*

Particular part of neonate body	Heat loss by radiation	
	F_{cl}=0.98	F_{cl}=0.86
Trunk	0.588482716	0.516423608
Arm (one)	0.293127285	0.257234148
Leg (one)	0.799882707	0.701937885
Whole body	4.379545427	3.843274558

Source: Own

The values shown in Table 7 are different for both structures and the same body part. We can regulate effectively heat balance by means of clothing material. In view of heat reduction, PVC-foil is not optimal enough to secure the organism against hyperthermia. It is necessary to apply the additional textile layer to optimize heat transfer from the body to the surroundings and improve the negative feel of a foil.

Heat loss by convection for other body parts is given in Table 8 for the same conditions.

Tab. 8: *Heat loss by convection for other body parts*

Particular part of neonate body	Heat loss by convection	
	F_{cl}=0.98	F_{cl}=0.86
Trunk	0.060674023	0.05324455
Arm (one)	0.178619977	0.156748143
Leg (one)	0.475045067	0.416876283
Whole body	2.1277588	1.867216906

Source: Own

Differences of obtained results are significantly lower than for radiation, cf. Table 7.

Comparison of evaporative heat loss for other body segments is shown in Table 9.

Tab. 9: *Heat loss by evaporation for other body parts*

Particular part of a neonate body	Heat loss by evaporation
Trunk	0.009141994
Arm (one)	0.035471224
Leg (one)	0.075232721
Whole body	0.336670742

Source: Own

General components are additionally determined in respiratory tract i.e. segmental heat losses by convection C_{resp} and evaporation E_{resp}, see Table 10.

Tab. 10: *Heat loss in respiratory tract*

Heat loss by	
convection C_{resp}	evaporation E_{resp}
0.082403062	0.045849057

Source: Own

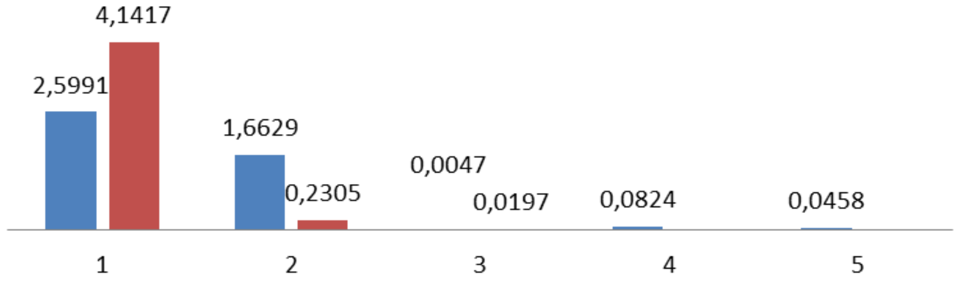
It is evident that the most critical body part is the head. The most significant heat transport is radiation and convection for the whole body as well as evaporative heat loss for the head. Hence, we compare heat losses for the head and other parts separately, cf. Table 11 and Figure 1. Moreover, we assume the most adverse physiological case for a newborn baby:

- special medical clothing made of PVC foil which reduces thermal radiation and convection by means of clothing insignificantly $F_{cl}=0,98$;
- minimal material thickness of the bonnet *1mm = 0,001m*, minimal relative area of covering by bonnet *20%*.

Tab. 11: *Heat loss in respiratory tract*

Heat loss	Body part	
	Head	Trunk + arms + legs
Dry heat loss (radiation + convection)	2.5991	4.1417
Heat and mass transport (evaporation)	1.6629	0.2305
Conduction	0.0047	0.0197
Heat losses in respiratory tract (convection + evaporation)	C_{resp}=0.0824	E_{resp}=0.0458
Sum	8.7868 kJ · h^{-1} · kg^{-1}	

Source: Own



blue – head; red – other body parts; 1 – radiation + convection ; 2 – evaporation ; 3 – conduction ; 4 – convection in respiratory tract; 5 – evaporation in respiratory tract
Source: Own
Fig. 1: *Visualization of heat losses for head and other body parts*

According to Eq. (1), metabolism is determined as the function of postnatal age *A* expressed in days. Introducing now *A=4.5 days* we obtain $\dot{M}$ = *8.505289934 kJ* $h^{-1}kg^{-1}$. We can calculate after some simple transformations the following heat storage rate.

$$S = \dot{M} - \left[\sum_{\text{i, all bodyparts}} \left(R_i + C_i + K_i + E_i \right) + C_{resp} + E_{resp} \right] = 8{,}5052 - 8{,}7868 = -0{,}2816 \tag{13}$$

It is immediately obvious that this rate is negative. It means that metabolic heat production is lower than the heat lost by the body. The temperature decreases, which can cause hypothermia.

Thus, heat transfer can be regulated by three basic parameters: surface area of a head covered by a bonnet, material thickness of a bonnet, clothing material. Thin plastic clothing can cause hypothermia for small thickness and minimal covering area. In other cases, metabolic heat production is greater than heat loss, which can cause hyperthermia but characteristic times $t_{38^\circ C}$; $t_{40^\circ C}$; $t_{43^\circ C}$ are sufficiently long.

Conclusions

The model applied is global because it introduces one heat source (i.e. metabolism) and a few different phenomena of heat transport (i.e. different heat loss mechanisms). There is coupled heat and mass transport because evaporation introduces a part of heat transported with mass (i.e. sweat). Heat transport is determined within each body part and systemically for respiratory tract. The global approach can determine skin temperature but moisture distribution is not analysed. Moisture can be determined by approximate correlations.

It is also necessary to introduce the local description which allows determining above phenomena in local scale. We can determine the local distribution of state fields i.e. temperature and moisture within a textile structure.

The obtained and discussed results are approximate. Detailed reasons are the following:

- Each newborn baby has an individual heat transport system;
- Input parameters are wide tolerated, its range of reference is extended;
- Some correlations are empirical, defined for numerically limited sample of neonates;
- Some additional assumptions are introduced to simplify the model solution.

The crucial idea is to determine the heat losses for particular body parts. The most critical part is neonate’s head characterized by the maximal heat loss. We can influence the heat transfer conditions and global heat balance by means of structure, material thickness and area of covering by a bonnet. The heat transport can be mainly limited by covering level of the bonnet; material thickness is of less significance. Heat loss can also be reduced by application of different clothing materials. All these parameters help to control the hyperthermia as well as hypothermia of newborn baby. These parameters can be determined by means of special times i.e. times to reach the specified temperatures *38˚C*; *40˚C*; *43˚C*.

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GLOBÁLNÍ TRANSPORT TEPLA A HMOTY V SYSTÉMU: POKOŽKA NOVOROZENCE – TEXTILNÍ KOMPOZITA – OKOLÍ

Globální model transportu tepla a hmoty je definován tepelnou rovnováhou při změně hmoty během odpařování potu z těla. Teplo je vytvářeno metabolickou produkcí tepla a ztrácí se vlivem různých jevů. Podmínky pro zajištění nezbytných parametrů těla novorozence jsou řešeny globálně pro různé parametry dětské čepičky a vrchního oblečení. Studie se zabývá různými možnostmi, jak zabránit hypertermii a hypotermii.

GLOBALER WÄRME- UND MASSETRANSPORT IM SYSTEM: DIE HAUT NEUGEBORENER – TEXTILKOMPONENTEN – UMGEBUNG

Das globale Modell des Transportes von Wärme und Masse wird durch das Wärmegleichgewicht beim Stoffwechsel während der Verdunstung des Schweißes aus dem Körper definiert. Wärme wird durch die metabolische Produktion von Wärme gebildet und verliert sich unter dem Einfluss verschiedener Vorgänge. Die Bedingungen für die Sicherstellung der unabdingbaren Parameter der Körper von Neugeborenen werden global für verschiedene Parameter von Kindermützen und Oberbekleidung geklärt. Diese Studie befasst sich mit verschiedenen Möglichkeiten der Vorbeugung von Hyperthermie und Hypothermie.

GLOBALNY TRANSPORT CIEPŁA I MASY W SYSTEMIE: SKÓRA NOWORODKA – SKŁADNIKI TEKSTYLNE – OTOCZENIE

Globalny model transportu ciepła i masy zdefiniowany jest jako równowaga cieplna przy zmianie masy w trakcie odparowywania potu z ciała. Ciepło produkowane jest w wyniku metabolicznej produkcji ciepła a do jego utraty dochodzi pod wpływem różnych zjawisk. Warunki mające na celu zapewnienie niezbędnych parametrów ciała noworodka są rozpatrywane w sposób globalny dla różnych parametrów dziecięcej czapeczki i ubrania wierzchniego. Opracowanie poświęcone jest różnym możliwościom zapobiegającym hipertermii i hipotermii.