Ryszard Korycki

Sensitivity of the Heat and Mass Transport System Within Neonate Clothing

**Lodz University of Technology,
Faculty of Material Technologies
and Textile Design,
Department of Technical Mechanics
and Computer Science,**
ul. Żeromskiego 116, 90-924 Łódź, Poland
E-mail: ryszard.korycki@p.lodz.pl

Abstract
The global model of heat and mass transport is determined by means of the heat balance with a term describing evaporation of sweat. Heat is supplied by metabolic heat production and lost by means of different phenomena within all body portions. The global correlation can be solved for prescribed parameters of the bonnet and external clothing. Different clothing materials, covering area and thickness of the bonnet, as well as characteristic times are discussed to prevent hyperthermia and hypothermia.

Key words: *heat and mass transport, composite clothing, neonate.*

Nomenclature

A	*postnatal age of newborn baby, days.*
A_{body}	*total surface of newborn body,* m^2
A_{co}	*proportional area of head covered by bonnet, -.*
B_T	*conversion factor of units for experimental temperature rise equation,* $1\ °C\ kg^2\ s^{-1}$.
B_t	*conversion factor of units for characteristic times equations,* $1\ W\ kg^{-2}\ s$.
C	*heat loss by convection on external surfaces,* $W\ kg^{-1}$.
C_{resp}	*heat loss by convection from muscosa in respiratory tract,* $W\ kg^{-1}$.
C_p	*heat capacity of air in normal conditions;* $C_p = 1.044\ kJ\ kg^{-1}K^{-1}$.
C_b	*heat capacity of soft tissues;* $C_b = 9.78 \cdot 10^{-4}\ kJ\ s^{-1}$.
E	*heat loss by evaporation,* $W\ kg^{-1}$.
E_{resp}	*heat loss by evaporation from muscosa in respiratory tract,* $W\ kg^{-1}$.
F_{cl}	*reduction factor of thermal radiation and convection by clothing, -.*
F_{pcl}	*reduction factor of mass transport by clothing, -.*
h_{ci}	*convectional heat transfer coefficient;* $W\ m^{-2}K^{-4}$.
h_{ei}	*evaporative heat transfer coefficient,* $h_{ei} = 0.46\ h_{ci}\ W\ hPa^{-1}m^{-2}$.
h_k	*conductive heat transfer coefficient;* $h_k = 0.23\ Wm^{-2}$.
I_{cl}	*thermal insulation of bonnet,* $m^2K\ W^{-1}$.
K	*heat loss by conduction,* $W\ kg^{-1}$.
$\dot{M}$	*metabolic heat production,* $W\ kg^{-1}$.
M_E	*absolute humidity of exhaled air,* $kg\ H_20/kg$ *of dry air.*
M_l	*absolute humidity of inhaled air,* $kg\ H_20/kg$ *of dry air.*
p_{s,H_20}	*water vapour partial pressure on skin, hPa.*
p_{a,H_20}	*water vapour partial pressure in atmosphere,* $p_{a,H_20} = 1 \cdot 10^5\ hPa$.
p_E	*partial pressure of water vapor in exhaled air, kPa.*
R	*heat loss by radiation on external surfaces,* $W\ kg^{-1}$.
R_{dyn}	*dynamic total evaporative resistance of clothing and boundary layer of air,* $m^2\ kPa\ W^{-1}$.
S	*heat stored in body,* $W\ kg^{-1}$.
$t_{38°C}$	*time required to reach warning body temperature 38 °C, 3600 s.*
$t_{40°C}$	*time required to reach heat stroke 40 °C, 3600 s.*
$t_{43°C}$	*time required to reach extreme value of temperature 43 °C, 3600 s.*
T	*temperature, °C.*
T_a	*temperature of surrounding air, °C.*
T_E	*temperature of exhaled air according to Hanson, °C.*
Th	*material thickness of bonnet, m.*
T_l	*temperature of inhalted air equal to surrounding temperature,* $T_l = T_a$ *°C.*
T_m	*temperature of mattress, °C.*
T_r	*mean temperature of radiation measured by infrared thermometer, °C.*
$\dot{V}_E$	*pulmonary ventilation rate:* $0.00028\ kg\ s^{-1}$.
w	*relative humidity of skin segment, -.*
W_t	*body mass of neonate, kg.*
δ	*latent heat of vaporisation;* $\delta = 243 \cdot 10^{-3}\ kJ/kg\ H_20$.
ε_{sk}	*skin emissivity;* $\varepsilon_{sk} = 0.97$.
ξ_c	*area coefficient of body portion subjected to convection* A_c/A_{body}, -.
ξ_e	*area coefficient of body portion subjected to evaporation* A_e/A_{body}, -.
ξ_k	*area coefficient of body portion contacting mattress during conduction* A_k/A_{body}, -.
ξ_r	*area coefficient of body portion subjected to radiation* A_r/A_{body}, -.
σ	*Stefan-Boltzmann constant;* $\sigma = 5.67 \cdot 10^{-8}\ W\ m^{-2}K^{-4}$.

Introduction

Appropriate medical support for a newborn baby is to ensure an adequate microclimate of the baby's skin, i.e. temperature and humidity. A newborn infant if requiring special medical care is situated in a closed incubator with a specific microclimate inside. The exact parameters of the the incubator are adjusted so that it is not necessary to have any clothing for the child. The newborn baby is located just on the bottom plate of the incubator, on a commercially available medical structure/mattress covered by a textile diaper, cf. ***Figures 1.a*** & ***1.b***. A completely different solution is to locate the newborn in an open incubator, but dressed in clothing that provides adequate conditions of heat and moisture on the skin. The structure of clothing can be diverse. This may be a medical garment made of PVC-foil, which provides almost complete absence of moisture transport from the skin to the outside of clothing. The clothing can be alternatively a typical infant garment made of a textile structure (knitted fabric) with an optional additional layer of PVC-foil. The textile component provides the necessary thermal protection, whereas the PVC layer serves as a membrane blocking moisture transfer, ***Figure 1.c***. The bonnet is always of a typical knitwear structure, ***Figure 1.d***.

Newborn skin is covered by amniotic fluid and vernix cascosa. Heat is lost by evaporation of amniotic fluid and water of amniotic fluid from the skin surface [1]. The body temperature will be lowered and the organism exposed to hypothermia. The main difficulty is to secure optimal heat and mass losses from the skin by clothing. An ideal incubator should maintain a uniform and constant thermal environment. The effectiveness of a supplemental heating blanket to improve the heating characteristics

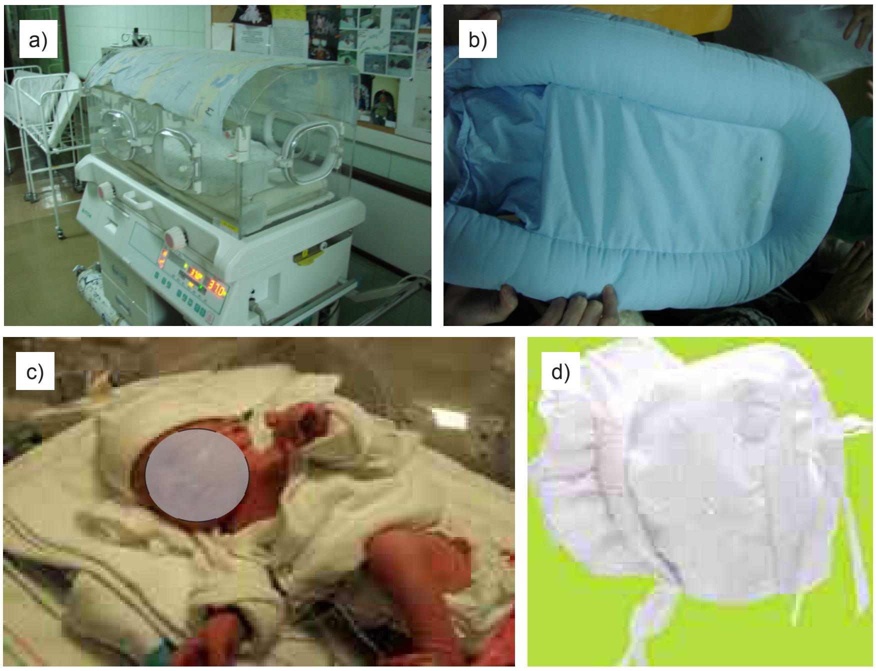

***Figure 1.** Medical support of newborn's baby; a) – closed incubator; b) – commercially available medical mattress; c) – newborn baby dressed in infant clothing within open incubator (**source** http://www.ciazowy.pl/artykul,maluszek-pod-kontrola-do-czego-podlaczony-jest-wczesniak-w-szpitalu,2419,1.html); d) – newborn's knitwear bonnet.*

of two incubator warming devices was discussed by Hubert et al [2]. Optimizing the thermal environment can improve the survival chances of newborn babies. Understanding the basic psychological principles and current methodology of thermoregulation is essential in clinical care, cf. Sherman et al [3]. The authors determine principles and technological advances providing optimal thermal support. Helder, Mulder & Goudoever [4] compare effects on premature infants' weight gain of a computer-generated and nurse-determined incubator humidity strategy. The general conclusion is that, the computer-generated strategy does not significantly reduce the time needed to regain birthweight. Intentional induction of elevated body temperature to treat malignant lesions has its origins in whole-body hyperthermia. Some therapeutic values of heat, characteristics of hyperthermia, its beneficial effects, determination of characteristic temperatures, etc. were discussed by Vertrees et al [5]. Thermography is a technique used to measure body surface temperature in the study of thermoregulation. Knobel, Guenther & Rice [6] used this technology to examine the relationship between body temperature and the development of enterocolitis in premature infants. This non-invasive, inexpensive measurement tool can be used to study the temperature differentials present in pathological conditions. Application of semipermeable membranes on the skin of premature newborns can aid in protecting the skin, reduce disturbances in fluid and electrolyte levels and decrease neonatal mortality. Gurgel et al [7] verify the effect of semipermeable membranes in low-birth-weight preterm newborns.

According to Agourram et al. [8], wrapping low-birth-weight neonates in a plastic bag prevents body heat loss. A bonnet can be applied, since large amounts of heat can be lost through the head. On the other hand, a bonnet may provide too much thermal insulation, thereby increasing the risk of hyperthermia. The authors determine characteristic times $t_{38^\circ C}$, $t_{40^\circ C}$ & $t_{43^\circ C}$ in a mathematical model that involved calculating various local body heat ($t_{38^\circ C}$) sources. A plastic bag combined with a bonnet does not cause a critical situation as long as metabolic heat production does not increase.

Exposure to cold may give rise to thermogenic responses that will increase heat production, and skin circulation may decrease to lower the heat losses, cf. Sedin [1]. Heat balance does not only depend on the ambient temperature and radiant energy but also on many factors that determine the heat transfer between the infant and the environment. The estimation of water loss from the skin and different routes of heat exchange are discussed.

Important observations concerning the basic responses to cold – increased heat production and decreased heat loss, the timing of these events and their development pattern, can change our understanding of care for neonates, cf. Sahni and Schulze [9].

The main goal of the paper is to analyse the sensitivity of heat and mass transport to the parameters of clothing and a bonnet. A global physical model is formulated using metabolic heat production and different heat loss phenomena. Mathematically speaking, heat balance with the term of evaporative mass exchange is introduced. The global model is next solved and its sensitivity analysed for the parameters of the bonnet and clothing prescribed. Different cases leading to hyperthermia and hypothermia are compared by means of characteristic times and temperature changes. Initial parameters are determined by other authors and the paper does not apply a rigorous, extensive program of measurement and evaluation. The paper is a continuation of a previous description concerning the heat balance of neonates [10]. The novelty element is the sensitivity approach of heat transfer within composite clothing. Additionally the impact of different clothing materials accompanied by abonnet was determined and characteristic times described with respect to hypothermia and hyperthermia.

Heat balance model

To secure the constant body temperature of a newborn infant, heat production and exchange with the environment should be balanced [1]. It is difficult to create a theoretical model of newborn skin - clothing - different environmental conditions, particularly for a number of individual organisms in various conditions. Therefore the model is only approximate. Physically speaking, the system above is introduced to describe coupled heat and mass transport from the skin,through combined textile clothing treated as a composite structure to the environment. Newborn skin has prescribed values of temperature and moisture concentration, which are described by boundary conditions. The state variable is the temperature during heat transfer and moisture concentration in mass/moisture transport. Environmental conditions are defined for the microclimate in an incubator open to the surroundings.

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

The first one is the physiology of the newborn baby i.e. metabolism and different mechanisms of heat loss by the body. The main subject is newborn skin, whereas different heat losses are modelled by empirical correlations.

The advantages of this approach are the following: (i) Heat and mass transport is determined globally, with all phenomena specified at the macro level. The final differences between metabolic heat production and heat losses can cause hyperthermia or hypothermia. (ii) The model discussed introduces all heat loss mechanisms, including marginal heat loss through mucosa in the respiratory tract. (iii) There is coupled heat and mass transport because the evaporation describes a part of heat transported with moisture.

Disadvantages can be defined as follows: (i) The moisture distribution on the skin is defined as a function of the heat transfer. (ii) It is impossible to determine the temperature distribution for a particular part of the body, because the model does not introduce a local description for some phenomena such as pcm-materials, the composite structure of clothing etc. (iii) A mathematical description is not universal with respect to some empirical relationships.

The alternative is an analysis of clothing, i.e. determination of heat and mass transport within the textile composite. Dominant is the composite clothing, whereas the neonate body and surroundings are modelled by boundary and initial conditions, with clear physiological interpretations. Coupled heat and mass transport is described by second-order differential equations with a set of conditions. Advantages/disadvantages are contrary to that-specified above.

Let us apply the first approach, i.e. global heat and mass transport through clothing to the surroundings. Fundamental aspects are defined as follows. (i) The multiparametric model is based on the heat balance, and moisture is transported by sweat evaporation. (ii) The balance approach is determined universally according to EN ISO 7933 [11]. Therefore the selection of parameters for the newborn is not always representative. Other sources are introduced, e.g. Agourram et al. [8] & Sedin [1]. (iii) Heat balance is formulated for the body. Impacts of clothing and environmental conditions are determined by appropriate coefficients in balance components.

Moisture diffusion is described separately only by Sedin [1], and the global transport defined by two separate balances of heat and moisture. Unidirectional mass transport is described by the first-order differential equation with respect to evaporated mass and pressure.

The global heat balance is formulated for a neonate within an incubator [8, 11]. Heat is supplied by metabolic heat production, that which is lost by conduction, dry heat loss on external surfaces by radiation and convection as well as by sweat evaporation. Global segmental heat is lost by convection and evaporation in the respiratory tract. Heat is lost through six body parts: the head, trunk, two arms, two legs. The metabolism as the 1empirical relationship [8] and balance correlation have the form in ***Equation 1.***

The difference between the metabolism and heat losses determines heat stored in body. Let us consider three basic cases: (i) $S = 0$ i.e. metabolic heat production is balanced by global heat loses. Thermal equilibrium is described by the constant temperature on the skin. (ii) Metabolic heat production is greater than that lost to the surroundings ($S > 0$). Heat is accumulated within the body, and the temperature increase, which can cause hyperthermia. (iii) Metabolic heat production is less than heat losses ($S < 0$). The heat deficit causes that the temperature decreases and the organism is exposed to hypothermia.

Let us next analyse heat losses for the body parts [8, 10, 11]. Heat loss by conduction is determined through contact between the skin and mattress in ***Equation 2.***

The dry heat loss consists of radiation and convection. Radiation at the skin surface is described as the fourth power of temperatures, whereas convection as the temperature difference between the skin and surroundings in the following form in ***Equation 3.***

The reduction factor can change from $F_{cl} = 1$ for the total impermeable textiles to $F_{cl} = 0$ for completely permeable clothing. Typical structures are characterised by $F_{cl} = 0.86$ for a combined medical structure made of PE-foil and fabric, and $F_{cl} = 0.98$ for special newborn clothing made of PE-foil. The mean temperatures of particular body segments and convection coefficients h_{ci} are determined according to [8, 10]. About a half of the skin's surface is subjected to radiation and convection whereas less than 10% is to conduction.

Evaporative heat flow determines moisture/sweat transport from the skin. Let us introduce maximal heat flow from the skin surface. We denote mathematically in ***Equation 4.***

The evaporative heat transfer coefficient h_{ei} can be determined from Levis equation. The relative humidity of the skin segment can be assumed as $w = 0.06$ for moderate temperature and dry skin; this parameter describe the influence of clothing. The reduction factor of moisture

$$\dot{M} = (0.00165A^3 - 0.138A^2 + 3.56A + 35.4)4.185/24$$

$$\dot{M} - \left[\sum_{\text{i, body parts}} \left(R_i + C_i + K_i + E_i \right) + C_{resp} + E_{resp} \right] = S \qquad (1)$$

$$K = \sum_{\text{i,body parts}} K_i = h_k A_{body} W_t^{-1} \cdot \sum_{\text{i,body parts}} \left(T_i - T_m \right) \xi_{ki} \qquad (2)$$

$$R + C = \sum_{\text{i,body parts}} \left(R_i + C_i \right) = A_{body} F_{cl} W_t^{-1} \cdot \sum_{\text{i,body parts}} \left[\sigma\, \varepsilon_{sk}\, \xi_{ri} \left[\left(T_i + 273 \right)^4 - \left(T_r + 273 \right)^4 \right] + h_{ci} \left(T_i - T_a \right) \xi_{ci} \right] \qquad (3)$$

$$E = \sum_{\text{i,body parts}} E_i = w A_{body} F_{pcl} W_t^{-1} \cdot \sum_{\text{i,body parts}} h_{ei} \left(p_{s,H_2O} - p_{a,H_2O} \right) \xi_{ei} \qquad (4)$$

Equations 1 - 4.

Table 1. *Dry (radiational and convectional) heat loss through head in W kg-1.*

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.001	2.599	2.204	1.904
0.003	2.492	1.976	1.624
0.005	2.391	1.787	1.411

Table 2. *Evaporative heat loss through head in W kg-1.*

Material thickness, m	Covering area of bonnet, %		
	20	60	100
0.001	1.663	1.410	1.218
0.003	1.594	1.264	1.039
0.005	1.530	1.143	0.903

Table 3. *Convectional heat loss through all body portions in W kg-1.*

Body portion	Convectional heat loss
Head	0.0047
Trunk	0.0105
Arm (one)	0.0002
Leg (one)	0.0021
Whole body	0.0182

Table 4. *Radiational heat loss for other body parts in W kg-1.*

Body portion	Heat loss by radiation	
	F_{cl} = 0.98	F_{cl} = 0.86
Trunk	0.588	0.516
Arm (one)	0.293	0.257
Leg (one)	0.800	0.702
Whole body	4.380	3.843

Table 5. *Convectional heat loss for other body parts in W kg-1.*

Body portion	Heat loss by convection	
	F_{cl} = 0.98	F_{cl} = 0.86
Trunk	0.061	0.053
Arm (one)	0.177	0.157
Leg (one)	0.475	0.417
Whole body	2.128	1.867

Table 6. *Evaporative heat loss for other body parts in W kg-1.*

Body portion	Heat loss by evaporation
Trunk	0.009
Arm (one)	0.035
Leg (one)	0.075
Whole body	0.337

Table 7. *Heat loss in respiratory tract in W kg-1*

Heat loss by	
convection C_{resp}	evaporation E_{resp}
0.082	0.046

transport changes from $F_{pcl} = 1$ for completely permeable clothing to $F_{pcl} = 0$ for impermeable textiles.

Two components are determined globally in the muscosa of the respiratory tract, the segmental heat losses by convection $C_{resp,}$ and the evaporation E_{resp} are described as follows [1, 8, 11].

$$C_{resp} = \dot{V}_E C_P (T_E - T_l) W_t^{-1}$$
$$E_{resp} = \dot{V}_E \delta (M_E - M_l) W_t^{-1} \qquad (5)$$

Temperature of exhaled air according to Hanson T_E as well as the partial pressure of water vapour in exhaled air p_E can be described according to [8, 11].

Heat loss through the head can be reduced by a bonnet and described mathematically by thermal insulation $I_{cl\ head}$ according to Nishi & Gagge [12].

$$I_{cl\ head} = 0.067 \cdot 10^{-2} A_{co} + 0.217\ ThA_{co} \qquad (6)$$

Heat reduction factors for radiation and convection as well as the evaporation of the bonnet are described according to [12]. We additionally assume $h_{c\text{-}head} = h_{r\text{-}head}$ in ***Equation** 7*.

The time to reach a temperature hazardous to the health is a function of the thermal insulation provided by the bonnet. However, increasing the metabolism at a constant skin temperature can cause hyperthermia. In this case the temperature reduction rate is determined according to [8].

$$\Delta T_b = B_T S (W_t C_b)^{-1} \qquad (8)$$

In the case of hypothermia, the essential criterions are the effective times of the increase in temperature [1, 8] from 37 to 38 °C ($t_{38\ °C}$), 40 °C ($t_{40\ °C}$) & 43 °C ($t_{43\ °C}$). The first one is the warning time to balance the heat transport, whereas the other is the mortality rate.

$$t_{38\ °C} = 3.49 B_t W_t S^{-1}$$
$$t_{40\ °C} = 3 \cdot 3.49 B_t W_t S^{-1} \qquad (9)$$
$$t_{43\ °C} = 6 \cdot 3.49 B_t W_t S^{-1}$$

General solution and sensitivity of balance model

The main problem of heat balance for the neonate is to introduce appropriate calculation parameters to solve all above equations. Let us introduce the input parameters according to Agourram et al. [8], determined by the means of separate thermographic experiments concerning the appropriate sample size of 30 low-birth-weight neonates. The temperature of the mattress surface as well as air temperature were measured continuously by means of thermistors (accuracy of ±0.10 *°C*). Air humidity was determined using a hygrometer, with an error range less than 5% over the humidity range 20 – 90%. The moisture / humidity was recorded 0.1 m above the central point of the mattress. The mean radiation temperature of the neonate body was measured by a black-globe thermometer. Air velocity within the incubator is determined by means of a hot-wire anemometer, with an accuracy equal to ± 0.05 ms^{-1}. The local skin temperatures were measured by infrared camera with a sensitivity of ± 0.10 °C at temperature 30 °C and accuracy equal to ± 2% in the range of temperatures 20 – 250 °C.

The front part and upper section of the incubator are open to the surroundings, which is a nurse room. The air temperature within the incubator changes from T_{a0} = 33.2 °C to T_{ak} = 31.8 °C in time *t=30min, with* the speed of change being negative: $-6.67 \cdot 10^{-4}$ $°Cs^{-1}$. The temperature of the surrounding air in the nurse room is T_a = 23.2 ± 0.2 °C, the mean radiation temperature of the neonate body T_r = 19.9 ± 0.2 °C, *and the* relative humidity w = 44 ± 1.9%. The temperature of mixed air between the incubator and the surroundings is equal to T_a = 23.2 ± 0.2 °C, with the speed of air within the incubator v = 0.06 ms^{-1} and relative air humidity w = 35 ± 4%. The body mass of the neonate is W_t = 1.060 ± 0.026 kg, the postnatal age 4.5 ± 0.4 days*,* the body surface 0.100 ± 0.010 m^2, and the mean radiation temperature T_r = 30.6 °C. The surface temperature of the mattress is T_m = 31.4 ± 0.1 °C. Neonate cloth-

$$F_{cl-head} = \left[(h_{c-head} + h_{r-head}) I_{cl\ head} + (1 + 1.971 I_{cl\ head})^{-1} \right]^{-1}$$
$$F_{pcl-head} = \left\{ (1 + 2.22 h_{c-head}) \left[I_{cl\ head} - \left[1 - (1.971 I_{cl\ head})^{-1} (h_{c-head} + h_{r-head})^{-1} \right] \right] \right\}^{-1} \qquad (7)$$

***Equation** 7.*

ing is a bag made of thin, impermeable plastic (PE) of average thickness 50 µm and total mass $5 \cdot 10^{-3}$ kg. The material is characterised by the heat reduction factor $F_{cl} = 0.98$.

Some input data were adopted from other sources and are partly original, as indicated earlier in relevent places in the text. However, all calculations are original and have not been cited in the literature.

The main problem is to determine the impact of the bonnet on the thermal insulation of the head as well as the consequent risk of hyperthermia and hypothermia. The dry heat loss versus the material thickness of the bonnet is shown in ***Table 1***, whereas the heat loss by evaporation is in ***Table 2***. Heat conduction during immediate contact with mattress is presented in ***Table 3***. Let us next determine the sensitivity of heat exchange with respect to clothing applied, cf. ***Table 4***. Convectional heat loss for other body parts is shown in ***Table 5***, whereas evaporative loss is in ***Table 6***. Global components are determined in the respiratory tract as segmental heat losses by convection C_{resp} and evaporation E_{resp}, see ***Table 7***. These values are marginal.

Thus the most sensitive body part is the head and the most significant heat losses are radiation, convection and evaporation. Hence we can compare heat loss mechanisms for the head and other parts, cf. ***Figure 2***. Let us analyse the worst physiological case: special medical clothing made of PE-foil with the reduction factor $F_{cl} = 0.98$, thickness of the bonnet 0.001 m, and relative area of covering 20%. Introducing $A = 4.5$ days in ***Equation 1***, the heat storage rate can be determined in ***Equation 10.***

The heat storage rate is negative i.e. metabolic heat production is less than heat lost by the body. Consequently the body temperature decreases, which can cause hypothermia.

Temperature increase according to ***Equation 8*** $\Delta T_b = -2.112 \cdot 10^{-5}$ °Cs^{-1} is negative i.e. medical clothing made of PE can cause hypothermia for small thickness and minimal covering area. Results of numerical simulations are presented in ***Table 8*** for PE clothing (heat reduction factor $F_{cl} = 0.98$) and ***Table 9*** for combined clothing PE + fabric ($F_{cl} = 0.86$).

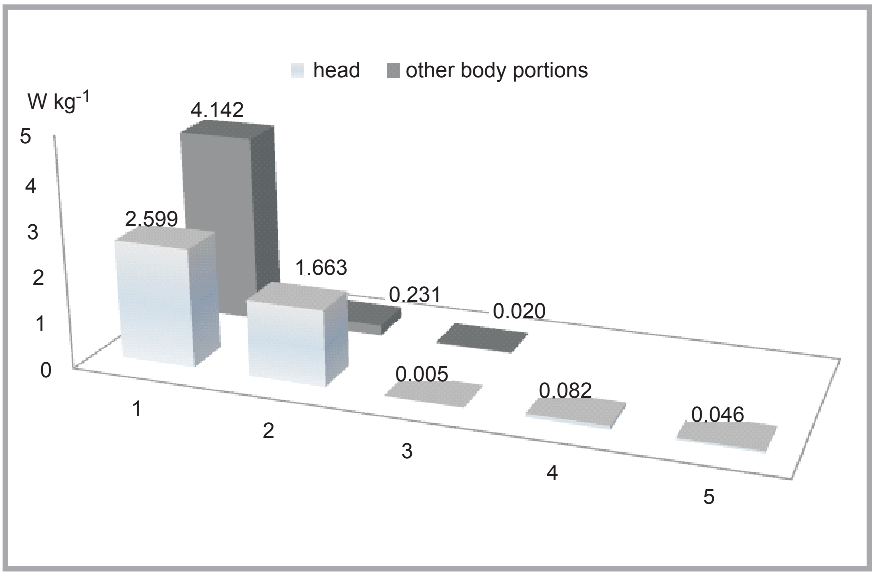

***Figure 2**. Visualization of heat losses for head and other body parts covered by plastic bag ($F_{cl} = 0.98$); 1 – radiation + convection; 2 – evaporation; 3 – conduction; 4 – convection in respiratory tract; 5 – evaporation in respiratory tract.*

Conclusions

The formulation presented contains simplifications in physical and mathematical models, e.g. constant skin temperature for increased metabolism, description of some components in physical correlations etc. The aim of this is the personal physiology of heat losses within organism. Some approximated equations are determined empirically. Additionally input parameters are accompanied by tolerances, and their differences can be significant.

***Table 8.** Characteristic parameters for reduction factor $F_{cl} = 0.98$.*

	Material thickness, m	Covering area of bonnet, %		
		20	60	100
Increase in temperature 0.00028 °C s^{-1}	0.001	-0.076	0.099	0.232
	0.003	-0.028	0.200	0.356
	0.005	0.016	0.284	0.450
Time $t_{38\,°C}$ 3600 s	0.001	0	10.090	4.306
	0.003	0	4.998	2.808
	0.005	62.71	3.523	2.220
Time $t_{40\,°C}$ 3600 s	0.001	0	30.269	12.919
	0.003	0	14.994	8.424
	0.005	188.1	10.569	6.659
Time $t_{43\,°C}$ 3600 s	0.001	0	60.538	25.839
	0.003	0	29.988	16.849
	0.005	376.3	21.139	13.317

***Table 9.** Characteristic parameters for reduction factor $F_{cl} = 0.86$.*

	Material thickness, m	Covering area of bonnet, %		
		20	60	100
Increase in temperature 0.00028 °C s^{-1}	0.001	0.061	0.236	0.369
	0.003	0.108	0.337	0.495
	0.005	0.153	0.420	0.587
Time $t_{38\,°C}$ 3600 s	0.001	16.437	4.236	2.709
	0.003	9.212	2.967	2.028
	0.005	6.540	2.376	1.702
Time $t_{40\,°C}$ 3600 s	0.001	49.309	12.708	8.126
	0.003	27.637	8.901	6.084
	0.005	19.619	7.129	5.106
Time $t_{43\,°C}$ 3600 s	0.001	98.619	25.415	16.252
	0.003	55.274	17.801	12.169
	0.005	39.238	14.258	10.212

$$S = \dot{M} - \left[\sum_{i,\ \text{all body parts}} \left(R_i + C_i + K_i + E_i \right) + C_{resp} + E_{resp} \right] = 8.505 - 8.787 = -0.282 \tag{10}$$

Equation 10.

According to ***Table 1*** and ***Equation 6***, thermal insulation depends on two parameters: Heat loss by radiation and convection can change significantly, and the maximal difference is *84%* in relation to the minimal value. Thus the dry heat loss of the head can change the global balance diametrically. Controlling the two parameters: material thickness and relative covering area, we can thus prevent hypo- or hyperthermia.

According to ***Table 2***, evaporative loss can change over a wide range in relation to the initial value. Controlling the same parameters, we change the evaporative heat loss by 45%, which is also a significant component of heat loss through a newborn's head.

The values of heat loss obtained during immediate contact (***Table 3***) are considerably less than the other heat exchange mechanisms. It follows that the thermal insulation of the bonnet does not influence the heat loss by conduction.

The type of clothing can affect the radiative heat loss, with the difference being about 13%, cf. ***Table 4***. Radiation is reduced by a medical structure made of PE-foil with reduction factor $F_{cl} = 0.98$. An alternative is complex clothing made of PE-foil combined with fabric of reduction factor $F_{cl} = 0.86$. In view of heat transport reduction, the foil is not optimal enough to secure the organism against hyperthermia. It is necessary to apply an additional textile layer to optimise heat transfer to the surroundings and improve the negative feel of the foil.

Differences in convectional and evaporative heat losses are significantly less than those obtained for radiation (***Tables 5***, ***6***).

The heat storage rate is determined by means of the metabolism and heat losses of particular body portions. A metabolism greater than heat losses can cause hyperthermia; otherwise the organism is exposed to hypothermia. Risk of hyperthermia can be estimated using empirical correlations to determine characteristic times. The most important is the temperature safety limit $t_{38\,°C}$. There is a limit to the risk of self-regulation of the heat balance, although times of heat stroke and the lethal threshold $t_{40\,°C}$; $t_{43\,°C}$ are also important.

Assuming a constant metabolism, heat loss should be optimised to secure the correct temperature by the following: (i) increasing the area of the covering bonnet, (ii) increasing the thickness of the bonnet,0 and (iii) application of a combined structure made of PE and fabric of reduction factor $F_{cl} = 0.86$ instead of simple PE foil of reduction factor $F_{cl} = 0.98$.

The bonnet can cause hypothermia for small material thickness and minimal covering area, whereas clothing material of a prescribed reduction factor is not so important, see the blue colour of the cells in ***Tables 7*** & ***8***. In most cases the metabolism is greater than heat losses, which can cause hyperthermia. However, there is no risk of hyperthermia because the characteristic times, $t_{38\,°C}$, $t_{40\,°C}$ & $t_{43\,°C}$, are relatively long. Thus these times are more sensitive to the covering area than a change in the thickness of the bonnet.

According to calculations, the most critical body portion is the head, being subject to the greatest heat loss. The heat storage rate is the most sensitive to change in the covering level of the bonnet as well as material thickness. Less significant is material used in a special medical structure defined by the reduction factor of infrared radiation.

The approach of heat and mass transport presented is complementary. However, it is possible to continue its expansion into other materials and description methods. The new goal can be numerical optimisation of heat and mass transfer parameters to secure a correct balance. To describe balance universally, it is necessary to introduce non-empirical correlations.

The existing heat balance does not introduce the local description i.e. local heat losses in the system newborn body – clothing – surrounding. Local description can introduce some heat transfer phenomena in the physical and mathematical model as well as appropriate coefficients in heat and transfer equations as well as boundary and initial conditions. State variables can be determined on a local scale within a complex structure of clothing. Thus additional effects and structures can be analysed, for example, phase change materials, textile composites made of different materials, the membrane effect etc. [13 - 15]. The state fields obtained can be additionally visualised, which help to create new areas of analysis and interpretation.

Of course, the theoretical model requires practical verification. This problem has already been partially discussed in literature [8]. However, the implementation of further comprehensive research is necessary, which is beyond the scope of this theoretical paper.

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