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

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OPTIS PRO FT

PROBLEM FORMULATION

- Neonate skin is not fully formed.
- Skin requires proper temperature and humidity which may vary within very narrow limits; thermal comfort is is extremely important.
- It is necessary to place the newborn within the incubator, which can adjust both temperature and humidity of air contacting the skin.

http://moms.popsugar.com/Cedars-Sinai-Using-iPads-Help-Moms-Infants-Bond-29247949

PROBLEM FORMULATION

- We introduce the heat balance for the newborn baby, *kJ / (h·kg mass).*
- Balance formulation according to:

  - EN ISO 7933 Ergonomic of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain;

  - Agourram, Bach, Tourneux, Krim, Delnaud, Libert, Why wrapping premature neonates to prevent hypothermia can predispose to overheating, Journal of Applied Physiology, 108, 1674–1681, 2010.

  - G. Sedin, Physics and physiology of human neonatal incubation, chapt. 59 in Fetal and Neonatal Physiology, 2004.
- Heat balance is determined for the whole body of newborn.

  Effect of clothing, coats and environmental factors is modeled by the coefficients in the balance.

PROBLEM FORMULATION

Advantages

•Global description of heat transfer for the whole body (in macro-scale), it can cause the overheating (hyperthermia) or body cooling (hypothermia).

•All heat loss phenomena are included, i.e. the convection + evaporation from the muscosa in the respiratory tract of marginal importance.

•Coupled heat and mass transport is introduced, i.e. the part of heat is transported with the mass (the sweat).

Disadvantages

•Distribution of moisture (sweat) can not be determined.

•It is impossible to determine the temperature map (i.e. distribution of state variable) and the local scale of description (cf. impact of PCM, complex clothing structure, different environmental conditions etc.).

•The description uses a significant number of empirical relationships, it is not universal.

GLOBAL FORMULATION OF HEAT BALANCE

Heat supplied by:
- Metabolic heat production

Heat lost and absorbed by:
- Conduction on contact surface K_i
- Radiation on external surfaces R_i,
- Convection on external surfaces C_i,
- Skin evaporation E_i (the only component that describes the moisture)

Heat losses are determined for the six parts of the body:
- Head $i=1$;
- Trunk $i=2$;
- Arms $i=3,4$;
- Legs $i=5,6$.

http://www.superstock.com/stock-photos-images/1527R-1158617

GLOBAL FORMULATION OF HEAT BALANCE

Heat losses are determined for *i-th* part of the body as the sum:

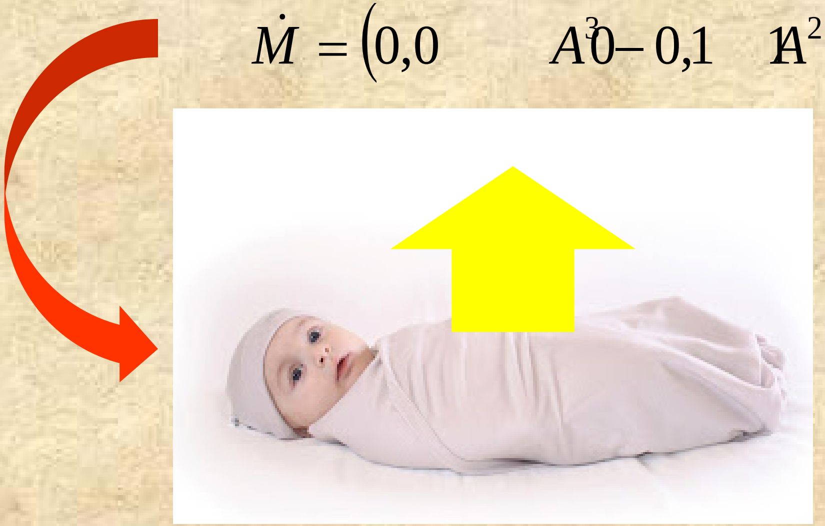
$K_i + R_i + C_i + E_i$

Global heat loss from the muscosa within the respiratory tract by:

- Convection C_{resp},
- Evaporation E_{resp}.

Metabolism (metabolic change over time) is determined as an empirical relationship and the function of postnatal age *A*, in $kJ \cdot h^{-1} \cdot kg^{-1}$

$$\dot{M} = \left(0,0\;A^3 0 - 0,1\;1A^2 + 33,56A + 836,54\right)4,15\;/\;2$$



http://gettinggreenwithbaby.blogspot.com/2013_03_01_archive.html

GLOBAL FORMULATION OF HEAT BALANCE

$$\dot{M} - \left[\sum_{\text{i a ,b l p d a d r y t s}} \left(R_i + C_i + K_i + E_i \right) + C_r \; {}_e + E_{rs} \; {}_{ep} \right] = S_s$$

Body heat storage rate *S*=0, i.e. metabolism is balanced by heat losses; thermal equilibrium determines constant temperature distribution on the skin.
***S*>0**, i.e. metabolism is greater than heat losses to surrounding; heat storage rate is accumulated; temperature increase which cause <u>the hyperthermia</u>.
***S*<0**, i.e. metabolism is less than heat losses; there is the heat deficit, temperature decrease which can cause <u>the hypothermia</u>.

http://pl.wikipedia.org/wiki/Plik:Incubator-tahrir.jpg

http://www.ciazowy.pl/artykul,maluszek-pod-kontrola-do-czego-podlaczony-jest-wczesniak-w-szpitalu,2419,1.html

GLOBAL FORMULATION OF HEAT BALANCE

Heat loss by conduction exists only at the interface skin – mattress.
It depends on:

- Contact surface of the skin with a mattress A_{ki} *in* m^2,
- Conductive heat transfer coefficient; $h_k = 0{,}84\ kJ \cdot h^{-1} \cdot m^{2}$,
- Temperature difference between the surface of the skin T_i and the mattress T_m, measured in ℃ by infrared thermometer,
- Neonate body mass W_t in *kg.*

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

http://gettinggreenwithbaby.blogspot.com/2013_03_01_archive.html

GLOBAL FORMULATION OF HEAT BALANCE

Heat loss by radiation to surrounding exists from the skin and clothing to incubator space. There is the function of:

- Stefan-Boltzmann constant $\sigma = 5{,}666667 \cdot 10^{-8}\ kJ\ h^{-1} m^{-2} K^{-1}$,
- Skin emissivity $\varepsilon_{sk} = 0{,}97$;
- Effective surface area of skin segment subjected to radiation A_{ri}, in m^2
- Mean temperature of skin segment T_i measured in ℃,
- Mean temperature of radiation T_r measured by infrared thermometer in ℃
- 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.

$$R_i = \sigma\,\varepsilon_s\,A_{kr}\left[(T_{ii}+2\quad)^4 - 7(T_r+23\quad)^4\right]F7_c\,W_{tl}^{-1}$$

http://gettinggreenwithbaby.blogspot.com/2013_03_01_archive.html

GLOBAL FORMULATION OF HEAT BALANCE

Heat loss by convection to surrounding exists from the skin and clothing to incubator space. There is the function of:

- Convection coefficient of the specified body part h_{ci} in $kJ \cdot h^{-1} \cdot m^{-2} \cdot {}^{\circ}C^{-1}$,
- Temperature of particular part of the skin surface T_i in °C,
- Temperature of surrounding air T_a in °C,
- Effective surface area of skin segment subjected to convection A_{ci}, in m^2,
- Dimensionless reduction factor of thermal radiation and convection by clothing, F_{cl}

$$C_i = h_{c}\left(T_{i} - T_{a}\right) A_{c} F_{ic} W_{t}^{-1}$$

http://gettinggreenwithbaby.blogspot.com/2013_03_01_archive.html

GLOBAL FORMULATION OF HEAT BALANCE

- Heat flow by evaporation at skin surface is the only possibility to transport the mass (i.e. sweat) from skin to surrounding. The coupled heat and mass transport is now described.
- Maximal evaporative heat flow is caused by sweat evaporation from the whole skin surface.

http://gettinggreenwithbaby.blogspot.com/2013_03_01_archive.html

GLOBAL FORMULATION OF HEAT BALANCE

Heat loss by evaporation at skin surface to surrounding exists from the skin and clothing to incubator. There is the function of:

- Difference of water vapor partial pressure between skin $P_{s,H20}$ and surrounding $P_{a,H20}$;
- Dynamic total evaporative resistance of clothing and boundary layer of air R_{dyn} in $m^2\,kPa\,W^{-1}$;
- Evaporative heat transfer coefficient of specified body segment $h_{ei}=1,67\,h_{ci}$ in $kJ\,h^{-1}mb^{-1}m^{-2;}$
- Relative humidity of skin, $w=0,06$ for moderate temperature and dry skin, this parameter describe influence of clothing;
- Effective surface area of skin part subjected to evaporation $A_{ei}=A_{ci}$ in m^2;
- Dimensionless reduction factor of mass transport by clothing, the range is $F_{pcl}=1$ for completely permeable clothing $F_{pcl}=0$ for impermeable textiles.

$$E_i = \left(P_{s,H_2O} - P_{a,H_2O}\right) R_d^{-1} = h_{ye}\, w \left(P_{his,H_2O} - P_{a,H_2O}\right) A_e\, F_p\, {}_i W_t{}_c^{-1}$$

GLOBAL FORMULATION OF HEAT BALANCE

There are two components determined in muscosa of respiratory tract i.e. segmental heat losses by convection C_{resp} and evaporation E_{resp}.

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

There is the function of:

- Pulmonary ventilation rate V_E in $kg\ h^{-1}$;
- Heat capacity of air in normal conditions $C_p = 1{,}044\ kJ\ kg^{-1}\ ℃^{-1}$;
- Temperature of exhaled air according to Hanson T_E in ℃;
- Temperature of inhaled air equal to surrounding temperature $T_l = T_a$ in ℃;
- Denotes latent heat of vaporization $\delta = 243\ kJ/g\ H_20$,
- Absolute humidity of exhaled air M_E in $kg\ H_20/kg$ *of dry air*;
- Absolute humidity of inhaled air M_l in $kg\ H_20/kg$ *of dry air*;
- Partial pressure of water vapor in exhaled air P_E in *kPa;*

SOLUTION OF PRESENTED PROBLEM

Parameters to solve the above model are the following,
cf. Agourram, Bach, Tourneux, Krim, Delnaud, Libert, Why wrapping premature neonates to prevent hypothermia can predispose to overheating, Journal of Applied Physiology, 2010.

- The front part and upper section of incubator are open to surrounding.
- Air temperature within incubator changes from initial $T_{a0}=33,2^{o}C$ to final $T_{ak}=31,8^{o}C$ in time $t=30min$; speed of change is negative $-0,04^{o}C/min$.
- Temperature of surrounding air within nurse room is $T_a=(23,2\pm0,2)^{o}C$,
- Mean radiation temperature is $T_r=(19,9\pm0,2)^{o}C$; moisture of surrounding air is $w=(44\pm1,9)\%$.
- Conditions within incubator: temperature for mixed air between interior and surrounding $T_a=(23,2\pm0,2)^{o}C$; speed of air $v=0,06ms^{-1}$; relative air humidity $w=(35\pm4)\%$.
- Parameters of neonate: body mass $W_t=(1,060\pm0,026)kg$; postnatal age $(4,5\pm0,4)days$; body surface $(0,100\pm0,010)m^2$; mean radiation temperature $T_r=30,6^{o}C$.
- Surface temperature of mattress is equal to $T_m=(31,4\pm0,1)^{o}C$.

SOLUTION OF PRESENTED PROBLEM

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

Areas of particular parts of neonate body

Particular part of neonate body	Area $\cdot 10^{-3}$ 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

SOLUTION OF PRESENTED PROBLEM

Head is covered by the bonnet.

Thermal insulation of bonnet I_{cl} is described in $m^2 \cdot {}^{\circ}C \cdot W^{-1}$

$$I_{cl} = 0{,}0 \cdot 16^{-2} A_{co} T + 0{,}2 \; T1 \; A_{c} l$$

A_{co} is dimensionless proportional area of head covered by bonnet;

Th is material thickness in *m*.

Heat reduction factor for radiation and convection acc. to Nishi and Gagge

$$F_{cl-he} = \left[\left(h_{a-hd} + h_{r-hd}\right) I_{acl} + \left(1 + 1{,}9 \; I_{cl}\right)^{-1} 7\right]^{-1}$$

Heat reduction factor for evaporation according to Nishi and Gagge

$$F_{pcl-he} = \left\{\left(1 + 2{,}2 \; h_{c-hd}\right)\left[I_{cle} - \left[1 - \left(1{,}9 \; I_{cl}\right)^{-1}\left(h_{c-h} 7 + h_{r-h} 1\right)^{-1}\right]\right]\right\}^{-1}$$

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

SOLUTION OF PRESENTED PROBLEM

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

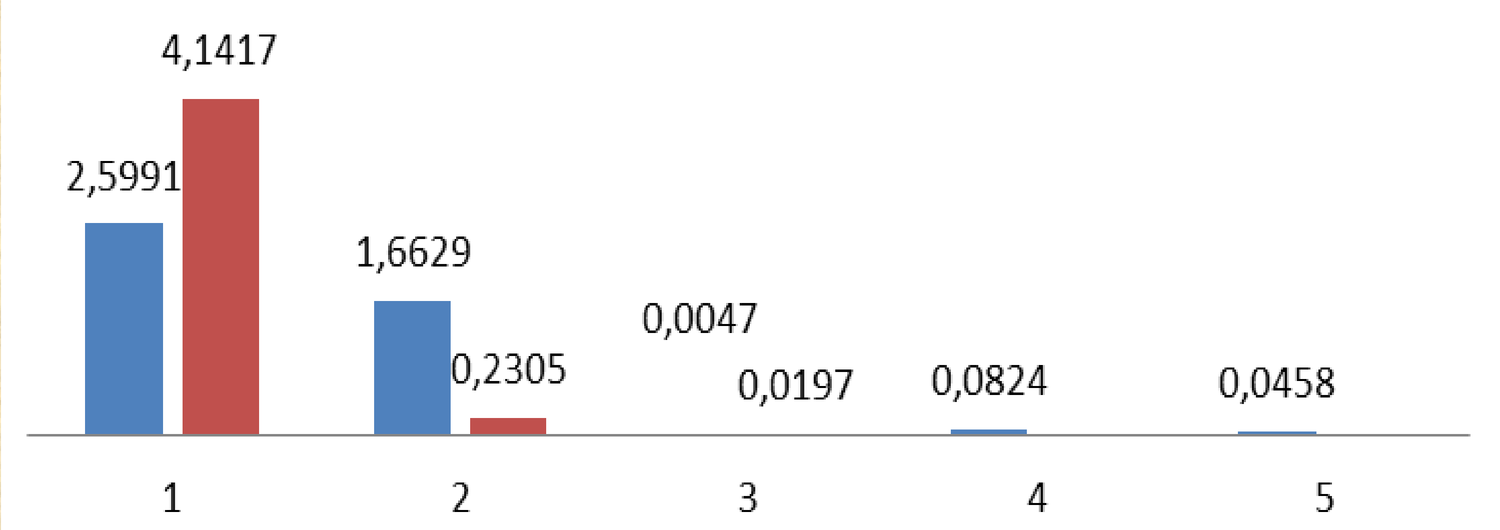
Heat loss by radiation for other body parts

Particular part of neonate body	Heat loss by radiation	
	F_{cl}=0,98	F_{cl}=0,86
Head	0,588482716	0,516423608
Trunk	0,293127285	0,257234148
Arm (one)	0,799882707	0,701937885
Leg (one)	4,379545427	3,843274558

SOLUTION OF PRESENTED PROBLEM

The most adverse physiological case for neonate:

- special medical clothing made of PVC foil, 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%*.



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

SOLUTION OF PRESENTED PROBLEM

Introducing now *A=4,5 days;*

$$S = \dot{M} - \left[\sum_{i\,a\,b,\;p\,l\;\;o\,l\;\;a\;\;d\;\;r\;\;t\,y\;\;s} \left(R_i + C_i + K_i + E_i \right) + C_r + E_{e\,r} \right] =_{se} 8,5_{\;p\,s} - 8,7_{p}\;\; 0 = -0,28\;\; 5$$

- Body heat storage rate is negative.
- Heat production is less than the heat lost by the body, temperature decrease which can cause hypothermia.

CONCLUSIONS

- The heat source is the metabolism, the heat is lost by a few mechanisms.
- There is coupled heat and mass transport because the evaporation describes a part of heat transported with the sweat. The skin temperature is determined but is impossible to define the moisture distribution.
- The obtained results are approximate because:
  - Each newborn baby has the individual heat transport parameters;
  - Input parameters are wide tolerated, its range is extended;
  - Some correlations are empirical for the limited number of neonates;
  - Some assumptions are introduced to simplify the solution.
- The most critical body part is head characterized by the maximal heat loss
- We can influence this loss using the bonnet: by means of the structure, material thickness and area of covering. The main reducing factor is area of covering, material thickness is of less significance.
- Heat loss can be reduced by application of different textiles (F_{cl} ; F_{pcl}).
- All these parameters help to control the hyperthermia and hypothermia of newborn baby by the times to reach the temperatures *38˚C*; *40˚C*; *43˚C*.