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Thermal management in closed incubators: New software for assessing the impact of humidity on the optimal incubator air temperature

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ABSTRACT

Background: Low-birth-weight (LBW) neonates are nursed in closed incubators to prevent transcutaneous water loss. The RH's impact on the optimal incubator air temperature setting has not been studied.
Methods: On the basis of a clinical cohort study, we modelled all the ambient parameters influencing body heat losses and gains. The algorithm quantifies the change in RH on the air temperature, to maintain optimal thermal conditions in the incubator.
Results: Twenty-three neonates (gestational age (GA): 30.0 [28.9–31.6] weeks) were included. A 20% increase and a 20% decrease in the RH induced a change in air temperature of between −1.51 and +1.85 °C for a simulated 650 g neonate (GA: 26 weeks), between −1.66 and +1.87 °C for a 1000 g neonate (GA: 31 weeks), and between −1.77 and +1.97 °C for a 2000 g neonate (GA: 33 weeks) ($p < 0.001$). According to regression analyses, the optimal incubator air temperature = $a + b$ relative humidity $+c$ age $+d$ weight ($p < 0.001$).
Conclusions: We have developed new mathematical equations for calculating the optimal temperature for the incubator air as a function of the latter's relative humidity. The software constitutes a decision support tool for improving patient care in routine clinical practice.

Abbreviations

A_c	skin surface area involved in convective exchanges (%)
A_e	skin surface involved in evaporative exchanges = A_c (%)
A_{cov}	percentage of skin covered by clothing (%)
A_r	effectively radiating surface area (%)
C	convective heat exchange over the skin (kJ.h^{-1}.m^{-2})
C_p	heat capacity of the air (1.044 kJ.°C^{-1}.kg^{-1}).
C_{resp}	convective heat exchange in the respiratory tract (kJ.h^{-1}.m^{-2})
δ	latent heat of water vapour (2.406 kJ.g^{-1})
E_{resp}	evaporative heat loss in the respiratory tract (kJ.h^{-1}.m^{-2})
E_{sk}	skin evaporative heat loss (kJ.h^{-1}.m^{-2})
εsk	skin emissivity (0.97)
fcl	clothing surface thickness (dimensionless)
Fpcl	coefficient for the reduction in evaporative heat loss due to clothing (dimensionless)
Fcl	reduction factor for dry heat exchange due to clothing insulation (dimensionless)
GA	gestational age (weeks)
H	thickness of the fabric (m)
h_r	radiant heat transfer coefficient (kJ.h^{-1}.m^{-2}. °C^{-1}):
h_c	convective heat transfer coefficient (kJ.h^{-1}.m^{-2}. °C^{-1}),
h_e	evaporative heat transfer coefficient (kJ.h^{-1}.kPa^{-1}.m^{-2})
Icl	thermal clothing insulation (m².°C.W-1)
K	conductive heat exchange (kJ.h^{-1}.m^{-2})
LBW	low-birth-weight (g)
PNA	postnatal age (days)
R	radiant heat loss (kJ.h^{-1}.m^{-2})
RH	relative air humidity (%)
SD	standard deviation
σ	Stephan-Boltzmann constant (5.57.10^{-8} W m^{-2}.°K^{-4} or 20.45.10^{-8} kJ.h^{-1}.m^{-2}.°K^{-4})
M	minimal metabolic heat production (kJ.h^{-1}.m^{-2})
m_e	mass of water vapour contained in the expired air (kg water.kg dry air^{-1})
m_i	mass of water vapour contained in the inspired (kg water.kg dry air^{-1})

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M_r metabolic heat production required to maintain homeothermia ($kJ.h^{-1}.m^{-2}$)
Pa_{H2O} water vapour partial pressure of the air (kPa)
P_B barometric pressure (kPa)
Ps_{H2O} water vapour partial pressure of the skin (kPa)
P_{H2O} water vapour partial pressure for the inspired or expired air (kPa)
T_{Body} body temperature (°C)
T_e temperature of the expired air (°C)
T_i temperature of the inspired air (°C)
T_{inc} incubator air temperature (°C)
$\bar{T}_r$ mean radiant temperature
$\bar{T}_{sk}$ mean skin temperature (°C)
T temperature of the expired air (Te,°C) or inspired air (Ti,°C)
V_E volume of expired air ($kg.h^{-1}$)
ω wetness of the skin (%)

1. Introduction

Premature and low-birth-weight (LBW) neonates are nursed in closed incubators. Ideally, the air temperature and relative humidity (RH) must enable the maintenance of thermoneutral conditions. Thermoneutrality is defined as the range of air temperatures within which metabolic heat production is minimal and the body temperature can be regulated solely by autonomic and behavioural responses (peripheral vasomotricity, postural changes, etc.) [1,2]. When thermal conditions are outside the thermoneutral zone, the energy needed to maintain body temperature is no longer used for body growth and optimal physiological functioning [1,2].

In a closed incubator, the thermoneutral temperature is defined not only by the incubator's air temperature but also by other factors that affect body heat losses (such as the incubator wall temperatures, and the air velocity and RH inside the incubator). Thermal exchanges between the neonate and its environment occur via conduction, convection, radiation and transepidermal water loss. The latter heat loss mode is important in premature neonates (particularly during the first 10 days of life) because their skin is immature and thus permeable [1,2]. To reduce the risks of dehydration and excessive body cooling, the relative humidity of the air in the incubator is often artificially increased in routine clinical practice [3–5]. However, the value of this procedure remains subject to debate because of the potential for bacterial proliferation [5–7] and delayed maturation of the skin layers [8]. Thus, RH control remains a challenge in the clinical management of preterm neonates.

A few researchers have tried to correct the thermoneutral temperature by taking account of ambient RH levels. Thus, Hey and Katz [9] defined temperature tables for neonates weighing between 1000 g and 2000 g at a RH of 50%; they recommended increasing or decreasing the air temperature values by 0.5 °C when the RH falls to 25% or rises to 75%. Hammarlund and Sedin [10] suggested increasing the RH (during in the first days of life) only for premature infants born before 31 weeks of gestation. Sauer et al. [11] performed experiments in a metabolic chamber at two different water vapour partial pressures. On that basis, they recommended reducing the neutral temperature by 0.05 °C for every mmHg increase in vapour pressure. The latter researchers stated that for infants born after 30 weeks, the effect of humidity on the neutral temperature was small enough to be neglected.

The objective of the present study was to: (i) clinically validate a newly developed software package called PRETHERM® (based on analytical calorimetry and which takes into account all the ambient parameters which modify the body heat balance: anthropomorphic data, clothing insulation, ventilatory support and the shape of the incubator); and (ii) use our mathematical model to simulate the impact of changes in RH on the thermoneutral temperature. We expected that these data would constitute a decision support tool for improved patient care in routine clinical practice.

2. Methods

2.1. Theory: analytical calorimetry

When homeothermia is maintained, body heat storage is nil; metabolic heat production compensates for the heat losses to the environment. In this situation, the internal body temperature (in humans) stabilizes at between 36.5 and 37.5 °C.

$$M_r = -(R + C + K + E_{resp} + C_{resp} + E_{sk}) \quad (1)$$

where M_r is the level of metabolic heat production required to maintain homeothermia; R is the radiant heat loss, C is the convective heat loss, K is the conductive heat loss, E_{resp} is the heat loss due to evaporation of water from the respiratory tract, C_{resp} is the heat loss through respiratory convection, and E is the heat loss due to evaporation of water from the skin. The heat exchange calculation includes heat exchanges coefficients that have been specifically determined for very LBW infants (900 g–1500 g) through the use of an anthropomorphically accurate manikin [12,13].

Radiative losses (R) characterize the heat exchanges between the neonate and the surrounding surfaces, and are calculated using the Stephan–Boltzmann equation:

$$R = h_r(\bar{T}_{sk} - \bar{T}_r)F_{cl} \quad (2)$$

where h_r is the radiant heat transfer coefficient ($kJ.h^{-1}.m^{-2}.°C^{-1}$):

$$hr = \sigma \varepsilon_{sk} A_r \left[\left(\bar{T}_{sk} + 273\right)^4 - \left(\bar{T}_r + 273\right)^4 \right] (\bar{T}_{sk} - \bar{T}_r)^{-1} \quad (3)$$

σ is the Stephan–Boltzmann constant ($20.45.10^{-8}$ $kJ.h^{-1}.m^{-2}.°K^{-4}$), ε_{sk} is the emissivity of the skin (0.97, dimensionless), A_r is the skin surface area involved in radiantheat exchanges (57%, $\bar{T}_r$ is the mean radiant temperature (°C) [14], $\bar{T}_{SK}$ is the mean skin temperature (°C), and F_{cl} is the coefficient for heat exchange reduction due to clothing (dimensionless). F_{cl} is evaluated as recommended by ISO 9920 [14]:

$$F_{cl} = [(h_r + h_c)\,Icl + 1/f_{cl}]^{-1} \quad (4)$$

where h_r and h_c are respectively the radiant and convective heat transfer coefficients (described below), I_{cl} is the thermal insulation afforded by clothing ($m^2.°C.W^{-1}$) and f_{cl} is the clothing surface thickness factor (because the thickness of the clothing increases the body surface area):

$$f_{cl} = 1 + 1.97 I_{cl} \quad (5)$$

The thermal insulation afforded by clothing depends on the percentage of the skin surface area that is covered (A_{cov},%) and the thickness of the fabric (H, m):

$$I_{cl} = 0.067.10^{-2} A_{cov} + 0.217\,H\,A_{cov} \quad (6)$$

Convective losses are heat exchanges between the neonate and the air circulating in the respiratory tract (C_{resp}) or over the skin (C):

$$C_{resp} = \dot{V}_E(T_e - T_i)\,C_p \quad (7)$$

where $\dot{V}_E$ is the volume of expired air ($kg.h^{-1}$), which is calculated from the equation defined in [16], T_e – T_i is the difference between the temperature of the expired air (T_e, equivalent to the internal body temperature) and the temperature of the inspired air (T_i, equivalent to the incubator air temperature if the preterm newborn is spontaneously breathing, or 37.0 °C with 100% RH if ventilatory support is provided) (°C), and C_p is the air's heat capacity ($1.044\ kJ.°C^{-1}.kg^{-1}$).

$$C = h_c A_c (T_{sk} - \bar{T}_a)\,F_{cl} \quad (8)$$