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Additional double-wall roof in single-wall, closed, convective incubators: Impact on body heat loss from premature infants and optimal adjustment of the incubator air temperature

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ABSTRACT

Radiant heat loss is high in low-birth-weight (LBW) neonates. Double-wall or single-wall incubators with an additional double-wall roof panel that can be removed during phototherapy are used to reduce Radiant heat loss. There are no data on how the incubators should be used when this second roof panel is removed. The aim of the study was to assess the heat exchanges in LBW neonates in a single-wall incubator with and without an additional roof panel. To determine the optimal thermoneutral incubator air temperature.

Influence of the additional double-wall roof was assessed by using a thermal mannequin simulating a LBW neonate. Then, we calculated the optimal incubator air temperature from a cohort of human LBW neonate in the absence of the additional roof panel.

Twenty-three LBW neonates (birth weight: 750–1800 g; gestational age: 28–32 weeks) were included. With the additional roof panel, R was lower but convective and evaporative skin heat losses were greater. This difference can be overcome by increasing the incubator air temperature by 0.15–0.20 °C.

The benefit of an additional roof panel was cancelled out by greater body heat losses through other routes. Understanding the heat transfers between the neonate and the environment is essential for optimizing incubators.

1. Introduction

When caring for low-birth-weight (LBW) neonates, the provision of an appropriate thermal environment (i.e. one that does not place excessive demands on their limited thermoregulatory abilities) is essential for survival [1,2]. Maintenance of body temperature within a narrow range (36.5–37.2 °C) involves a balance between heat production by the neonate and the heat losses from the neonate to the environment [1]. In closed incubators, heat exchange between the infant and the environment occurs by convection, evaporation, conduction and/or radiation. LBW neonates lose heat by radiation to the cool, inner surfaces of the incubator. As reported by many researchers [3,4], radiant heat loss is particularly noticeable at thermoneutrality, where it accounts for 39–58% of the body's total heat losses. Accordingly, the thermal performance of incubators can be improved by including the mean radiant temperature ($\overline{T}_r$) in a mathematical algorithm that controls the heating unit. However, this approach remains problematic because $\overline{T}_r$ cannot be measured in incubators.

In an attempt to reduce radiant heat loss, manufacturers have introduced double-wall incubators in which the two plastic panels are several centimeters apart and air can circulate between the two. However, the literature data on effectiveness of such devices are contradictory. Bell et al. [5] reported that this feature did not offer any advantage over a single-wall incubator with respect to body heat storage. The researchers showed that the lower degree of radiative heat loss in the double-wall incubator was counterbalanced by an increase in convective heat loss. In contrast, Marks et al. found that the oxygen consumption of ten premature newborns was lower in a double-wall incubator than in a single-wall incubator [6]. These disparities are difficult to explain but might be related to differences in incubator air humidity, temperature and velocity (which are not always recorded) and in the population of infants studied. Furthermore, it should be noted that the presence

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Abbreviations

A_r	Effectively radiating surface area
DW	Single-wall incubator equipped with an additional roof panel
ε_{sk}	Skin emissivity
F_{cl}	Reduction factor for dry heat exchange due to clothing insulation
h_r	Radiant heat transfer coefficient
LBW neonate	Low-birth-weight neonate
P	Heat loss
σ	Stephan–Boltzmann constant
R	Radiant heat loss
SD	Standard deviation
SW	Single-wall incubator
T_{ABD}	Abdominal skin temperature
T_{inc}	Incubator air temperature
T_{Mat}	Temperature of the mattress surface
$\overline{T}_r$	Mean radiant temperature
T_{roof}	Temperature of the inner surface of the roof wall
$\overline{T}_{sk}$	Mean skin temperature

of a second plastic wall complicates cleaning and disinfection, reduces visibility and modifies the spectrum of the light entering the incubator. Hence, single-wall incubators are still widely used [7].

In order to reduce radiant heat loss without greatly increasing the complexity of the equipment, some incubators can be fitted with an additional, removable, clear plastic roof panel. The incubator air circulates freely on both sides of this additional, inner roof panel. The additional roof panel can be easily removed when phototherapy is performed, when the roof has to be cleaned or when the nursing staff has to handle the infant. In routine practice, phototherapy is administered via an overhead light source. However, a fixed double-wall incubator roof decreases the irradiance [8,9] and consequently reduces the treatment's effectiveness. The alternative approach (an additional panel under the roof but single walls everywhere else) is based on the fact that radiant heat exchanges are proportional to (i) the projected skin surface area (relative to the wall), (ii) the solid angles with respect to the neonate and (iii) the temperature difference between the neonate's skin surface area and the incubator walls [10]. Given that the largest skin surface area is projected onto the roof directly above the reclining neonate (relative to the smaller side wall), the incubator roof is a significant source of radiant heat loss. Fitting a single-wall incubator with an additional, detachable roof panel is therefore one possible solution to the aforementioned problems. However, it has not yet been established whether the use of this additional roof panel reduces heat loss from the neonate.

The objectives of the present study were to (i) assess the influence of an additional, removable plastic roof panel in a single-wall incubator during standard care in a neonatal intensive care unit (NICU), and to (ii) determine the magnitude of the incubator air temperature adjustment required to maintain thermoneutrality when this panel is removed.

2. Methods

The incubator air temperature was determined daily by the nurse when the latter entered the neonate's gestational and postnatal ages, body mass and size, and the presence or absence of a hat, a snug or ventilator support into the software package (PRETHERM®, Tauxigny, France) based on partitional calorimetry [3,11]. Briefly, the software calculated the metabolic heat production required to compensate for (i) skin heat losses by convection, conduction, radiation and evaporation and (ii) respiratory convection and evaporation, so that the thermal exchanges between the infant and the environment reach an equilibrium. The incubator air temperature is then determined so that the difference between the required metabolic heat production and basal metabolic heat production (calculated using the equation developed by Chessex et al.) is as small as possible [7]. This corresponds to the optimal thermoneutral environment for body weight gain because the neonate does not have to expend extra energy on thermoregulation.

To reduce uncertainties related to the assessment of radiant heat loss, we first assessed the mean radiant temperature by using an anthropomorphic mannequin, as described by Décima et al. [3]. Next, we performed a prospective observational clinical study to determine whether a thermoneutral air temperature in an air-servocontrolled incubator fitted with an additional, removable plastic roof panel. Lastly, the computer program calculated the incubator air temperature required to obtain the same degree of body heat storage (i.e. a thermoneutral environment) when the additional plastic roof panel was removed (without changing any of the other environmental conditions or nursing procedures).

2.1. Assessment of radiant heat loss: the influence of an additional roof panel

In the computer program, the radiant heat loss is calculated from Stephan–Boltzmann's law:

$$R = h_r[(\overline{T}_{sk} + 273)^4 - (\overline{T}_r + 273)^4]F_{cl}$$

The radiant heat transfer coefficient (h_r) is expressed in $kJ\,h^{-1}\,m^2\,C^{-1}$ as:

$$h_r = \sigma\,\varepsilon_{sk}A_r[(\overline{T}_{sk} + 273)^4 - (\overline{T}_r + 273)^4](\overline{T}_{sk} - \overline{T}_r)^{-1}$$

where σ is the Stephan–Boltzmann constant ($20.45 \times 10.8\,kJ\,h^{-1}\,m^{-2}\,C^{-1}$), ε_{sk} is the skin emissivity (0.97, dimensionless), A_r is the skin surface area involved in radiant heat exchange (57%) [12], $\overline{T}_r$–$\overline{T}_{sk}$ is the difference between mean radiant and mean skin temperatures, and F_{cl} is the reduction factor for dry heat exchange due to clothing insulation (dimensionless).

The mean radiant temperature and h_r were assessed with a multisegment, anthropomorphic, copper-cast thermal mannequin. It was painted black (surface emissivity $\varepsilon = 0.97$) and comprised six body segments with individually controlled surface temperatures. The mannequin represents a small-for-gestational-age neonate with a body surface area of $0.086\,m^2$ and a simulated birth weight of 900 g. This physical replica has been extensively validated and is described in detail elsewhere [3,12–14].

To distinguish radiant heat exchange from convection and conduction, the radiant contribution was removed by closely covering the mannequin's surface with low emissivity ($\varepsilon_a = 0.05$) aluminum foil; this minimized the risk of increasing thermal insulation by trapping and also maintained the mannequin's body shape. The mannequin (covered with foil or not covered) was randomly exposed at incubator air temperatures ranging between 29.0 and 33.0 °C. The material's emissivity was checked with an infrared camera (Thermovision 550, AGEMA, Dangeryd, Sweden). In order to assess repeatability, each experimental situation was measured five times. For a given incubator air temperature, the mean surface temperature of the "naked" (non-covered) or foil-covered mannequin ($\overline{T}_{sk}$) was held constant at 34.4 °C to reproduce the same convective and conductive heat losses to the environment observed for preterm newborn infant of 1500 g [14]. To achieve this state, the surface temperatures of the different body segments were set as follows: upper limbs: 32.5 °C, lower limbs: 34.4, head: 35.3, trunk: 34.8 °C [3,14,15]. These values correspond to previous measurements of neonates nursed in a thermoneutral environment in