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Article

Use of a Novel Mathematical Model to Assess the Effectiveness of Skin-to-Skin Care for the Prevention of Hypothermia in Low-Birth-Weight Neonates

Stéphane Delanaud [1,*], Lisa Gossart [1,2], Maximilien Leclercq [1,3] and Jean-Pierre Libert [1]

1 Peritox (UMR_I 01, Unité Mixte UPJV/INERIS) CURS, Présidence, Chemin du Thil, Université de Picardie Jules Verne, F-80000 Amiens, France
2 Ecole de Sages Femmes Michel Vitse, Pôle Santé, 3 Rue des Louvels, F-80000 Amiens, France
3 Unilasalle-Amiens, 14 quai de la Somme, F-80000 Amiens, France
* Correspondence: stephane.delanaud@u-picardie.fr

Featured Application: diagnosis of hypothermia, assistance with care for low-birth-weight neonates.

Abstract: The effectiveness of skin-to-skin care (SSC) notably depends on the delivery room air temperature (T_a), the thermal insulation provided by the fabrics or clothes covering the mother and the neonate (I_{cl}), and the neonate's metabolism (M). The objective of the present study was to model the influence of these variables on the effectiveness of SSC for premature newborns. To this end, we used an appropriate thermal mannequin and applied a mathematical model of body heat exchanges. We performed experiments at T_a values (20.9 °C and 25.9 °C) and two I_{cl} values (sheet only and sheet + blanket). At a T_a of 25.9 °C, normothermia was estimated after one hour of SSC with the sheet (I_{cl} = 0.15 m^2 °C/W; 36.52 °C) and the sheet + blanket (I_{cl} = 0.21 m^2 °C/W; 37.09 °C) but only with the highest value of M (2.70 W/kg). With a T_a of 20.9 °C, moderate hypothermia (requiring monitoring of the neonate's thermal status) was estimated—except for M = 2.70 W/kg and I_{cl} = 0.21 m^2 °C/W. During early SSC, homeothermy can be maintained when T_a is 25 °C (the temperature recommended by the World Health Organization) but only when the neonate's tissue insulation is high ($I_{cl} \geq 0.15$ m^2 °C/W) and when the level of metabolic heat production is high.

Keywords: neonate; mannequin; mathematical model; skin-to-skin; hypothermia

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1. Introduction

Low-birth-weight and preterm neonates are particularly at risk of body cooling. Hypothermia can lead to hypoglycemia, respiratory distress, hypoxia, and metabolic acidosis and is associated with greater morbidity and mortality rates [1,2]. Thermal regulation is less effective than in adults due to the immaturity of the neonate's organs and greater body heat losses to the environment [3]. During cold exposure, the energy used to maintain homeothermy depletes that available for vital functions. These factors are especially important for premature and low-birth-weight neonates. To prevent neonatal hypothermia immediately after delivery, skin-to-skin care (SSC) is recommended by the World Health Organization (WHO) [4].

In 2017, the WHO recommended that in the absence of medical contraindications, a newborn should be dried, placed naked in the prone position on the mother's chest, covered with a clean, warm cloth and a cap, and left in contact for an hour [5]. The WHO has further stated that SSC is an effective method for preventing body heat losses in term or premature neonates [6]. Several studies of term neonates have shown that SSC is enough to warm the neonate after delivery and avoids the need for other warming methods (e.g., radiant warmers and incubators). Färdig [7] showed that early skin-to-skin contact under a warm blanket (preceded by drying of the skin) enabled neonates to maintain their internal body temperature. Christensson et al. [8] showed that axillary and skin temperatures were higher in infants placed in contact with their mothers for 90 min immediately after birth. In Christidis et al.'s infrared thermography study [9], skin surfaces in contact with the mother were warmer than those not in contact. Christensson et al. [10] claimed that SSC was equivalent to placing the neonate in a closed incubator. In a study in India, Srivastava et al. [11] showed that SSC stabilized the neonate's thermal status and increased the breastfeeding rate and the sucking reflex. Jia et al. [12] showed that in premature neonates, cold stress decreased when the delivery room air temperature (T_a) was maintained at 25 °C (i.e., the value recommended by the WHO). In a study in Croatia, Kardum et al. [13] demonstrated that when T_a was 21.7 °C, SSC was effective for maintaining homeothermy in neonates born after 38 weeks of amenorrhea but not in those born more prematurely. These research findings demonstrated the importance of the T_a and the neonate's maturity in the management of the thermal environment at birth. The effectiveness of SSC also depends on (i) the thermal insulation provided by the cloth, sheet, or clothing covering the mother and the neonate and (ii) the neonate's metabolism—the main source of heat production in response to cold stress.

The degree of thermal insulation that must be provided by the cloth placed on the neonate during SSC has not been defined, even though this is a particularly important factor in reducing body heat losses. With the exception of Karlsson [14], researchers in this field have not reported the degree of thermal insulation provided by the cloth or sheet used in SSC; they simply recommend adapting this variable to the ambient temperature. There are no guidelines on the optimal thermal properties of coverings or clothing for premature newborns during SSC. To address this problem, we used a physical model (a thermal mannequin, as recommended in the ISO 9920 standard for assessing the impact of the thermal isolation of a set of clothes on body heat exchanges) [15].

As reported by many researchers, metabolic heat production varies greatly from one individual to another. Bauer et al. [16] measured oxygen consumption in 75 premature infants (gestational age: between 26 and 28 weeks) during the first week of life: the individual values ranged from 1.11 W/kg to 2.70 W/kg (mean: 1.59 W/kg). In a now rather dated study of 33 newborns (gestational age: 25 to 38 weeks; birth weight: below 1500 g), Silverman et al. [17] showed that not all the infants were able to increase their metabolic heat production when exposed to moderate cold: indeed, heat production remained unchanged or even decreased in some cases. This finding was confirmed by Adamson et al. [18] and Pribylova et al. [19], who reported that oxygen consumption was negatively correlated with the neonate's abdominal skin temperature and rectal temperature, respectively. The results of Gandy et al.'s study [20] also showed that the neonate's metabolic heat production decreased when the internal body temperature fell, reflecting the inability to effectively counter body heat loss.

The WHO classifies the level of body cooling as cool stress for an internal body temperature below 36.5 °C, mild hypothermia for values between 36.5 and 35 °C, moderate hypothermia for values between 35 and 32 °C, and severe hypothermia for values below 32 °C. The internal body temperature is measured invasively at various sites (mainly the rectum, tympanic area, and axillary area). However, these sites are not representative of heat storage in the neonate's body and, therefore, of the neonate's overall thermal state [21–24]. In the present study, a mathematical model based on the body's heat balance was used to describe the changes over time in the mean body temperature and in body heat storage.

The objective of the present study was to determine how the effectiveness of SSC immediately after delivery was affected by T_a, the degree of thermal insulation provided by the coverings and/or clothing placed on the neonate and mother, and interindividual differences in metabolic heat production.

2. Method

2.1. The Thermal Mannequin

The anthropomorphic, multisegment thermal mannequin was designed in our laboratory (Figure 1). It corresponds to a low-birth-weight neonate (simulated weight: 1500 g; body surface area: 0.150 m^2) with a gestational age of approximately 30 weeks (according to Fenton et al.'s curves) [25]

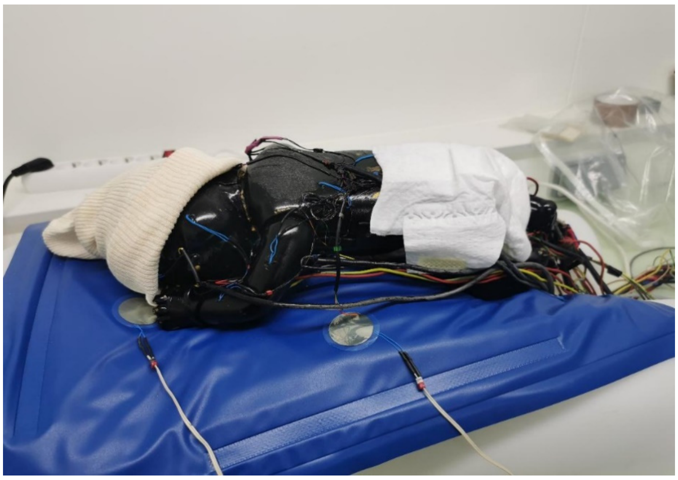

Figure 1. The 1500 g anthropomorphic mannequin wearing a head cap and a diaper. The mannequin is an anatomically faithful model of a small-for-gestational-age neonate. The anatomic shapes are important because they modify the heat exchange coefficients and, thus, condition heat exchanges with the environment.

The body segments are articulated so that the posture to be modified. The mannequin is painted matte black, and its emissivity coefficient in the infrared (0.97) is close to that of human skin. During the experiments, local temperature data were recorded with 18 thermistor probes (10 kOhms at 25 °C): 5 on the trunk, 2 on each of the limbs, and 5 on the head. The mean surface temperature was calculated by weighting the local surface temperatures according to the corresponding segment's relative surface area (trunk: 28%; head: 23%; lower limbs: 30%; upper limbs: 19%).

Under thermal equilibrium conditions (reached within 45 min), the electrical power supplied separately to the mannequin's six body segments makes it possible to control the corresponding surface temperatures and to take account of the body's thermal heterogeneity. The electrical power was measured using command-and-control software (Control Pro, Labtech, Wilmington, MA, USA) and corresponds to the heat transferred to the environment. When thermal equilibrium was reached, the electrical power was recorded and averaged over 30 min.

2.2. Design of the Mathematical Model

The mathematical model was based on analytical calorimetry. The heat transfer equation can be written as a sum of heat flows (expressed in W per kg body mass):

$$S = M \pm R \pm C \pm K - E_{resp} - C_{resp} - E \tag{1}$$

where S is the body's heat storage (at equilibrium, heat gain is balanced by heat loss and so S = 0; for a neonate in this condition, homeothermy is reached, and the body's internal temperature stabilizes at between 36.5 and 37.5 °C), M is the metabolic heat produced by non-shivering thermogenesis in brown adipose tissue, R is radiative heat loss/gain (corresponding to the infrared radiation transferred between the skin surface and the various surfaces in the environment), C is convective heat exchanged by air moving over the skin surface and the upper airways (C_{resp}), K is the transfer of thermal energy from the mother's body to the neonate via skin–skin contact, and E is the evaporative heat loss through the skin and the upper airways (E_{resp}).

The electric heat power supplied to the mannequin balances the dry heat losses (R + C + K). In a clothed mannequin, R + C are reduced by a coefficient of heat exchange due to clothing (F_{cl}).

The degree of inter-infant variability in energy metabolism (M) was based on Bauer et al.'s measured range [15] from 1.11 to 2.70 W/kg. It should be noted that the mean value measured by these investigators (1.59 W/kg) was similar to that calculated by Chessex et al. on the first day of life for a neonate weighing 1500 g [26].

Evaporative losses through the respiratory tract (E_{resp} W/kg) [27] were modeled as:

$$E_{resp} = 0.0173\,M\,(P_e - P_i)\frac{A_D}{W_t} \tag{2}$$

where A_D is the total body surface area (m^2), W_t is the body mass (kg), and ($P_e - P_i$) is the difference in water vapor pressure between exhaled and inspired air (kPa).

The respiratory convective heat loss (C_{resp}, W/kg) was modeled as the heat exchanged by air moving out of the respiratory tract [27]:

$$C_{resp} = 0.0014\,M\,(T_e - T_i)\frac{A_D}{W_t} \tag{3}$$

where ($T_e - T_i$) is the difference between the expired air temperature (T_e) and the inspired air temperature ($T_i = T_a$) (°C) and M is the energy metabolism (W/m^2).

T_e was calculated according to Hanson's equation [28]:

$$T_e = 32.6 + 0.066\,T_a + 32\,M_{H_2O} \tag{4}$$

where T_a is the air temperature and M_{H_2O} is the mass of air vapor in the inspired air (g/L).

The water evaporation through the skin (E, W/kg) was modeled as:

$$E = he\,\omega\,Ae\,\left(P_{SH_2O} - P_{aH_2O}\right)F_{pcl}\frac{A_D}{W_t} \tag{5}$$

where he is the heat transfer coefficient by evaporation (W/mb/m^2) calculated from the Lewis relation (h_e = 1.67 h_c), ω is the fraction of body area that is wet (dimensionless; 0.06 when the skin is dry [29] and 1 when the skin is completely wet, as in an undried neonate), $Ps_{H_2O} - Pa_{H_2O}$ is the water vapor partial pressure difference between the skin (the saturation pressure for mean skin temperature) and air (mb), Ae is the skin surface area that exchanges by evaporation (0.805, calculated by subtracting the manikin–mattress contact area (0.195) from the total body surface area, and F_{pcl} is the reduction in the coefficient of latent heat exchange due to clothing (dimensionless).

2.3. Assessment of the Clothing-Associated Reduction in Thermal Insulation (F_{cl}, F_{pcl})

The reduction factor for dry heat exchange through the mannequin's covering (F_{cl}) was the ratio between the electrical power supplied to the covered mannequin ($(R + C)_{clo}$) and that supplied to the naked mannequin ($(R + C)_n$). To eliminate conductive heat loss (K), the mannequin was thermally insulated from the mattress (a fiberglass needle mat; thickness: 13 mm; thermal conductivity: 0.04 W/mK; Glass Fiber MG Model Needled Mat, Horst GmbH, Lorsch, Germany).

$$F_{cl} = \frac{(R + C)_{clo}}{(R + C)_n} \tag{6}$$

The covering's thermal insulation (I_{cl}, m^2 °C/W) can be determined by iterative calculation of the following equation [27]:

$$F_{cl} = [(h_r + h_c)\ I_{cl} + 1/f_{cl}]^{-1} \tag{7}$$

where h_r and h_c are, respectively, the coefficients of heat transfer by radiation and by convection (W/m^2/°C), and f_{cl} is the ratio between the surface areas of the clothed mannequin and the naked mannequin:

$$f_{cl} = 1 + 1.97\ I_{cl} \tag{8}$$

Given that the air velocity in the delivery room is assumed to be below 0.2 m/s, the convective heat transfer coefficient depends solely on the difference between the skin and air temperatures ($T_{sk} - T_a$). The value of h_c was calculated from the following equation [30]: $h_c = 1.87\ (T_{sk} - T_a)^{0.37}$

The radiation coefficient h_r (W/m^2/°C) can be computed as:

$$h_r = \sigma\ \varepsilon_{sk}\ A_r\ [(T_{sk} + 273)^4 - (T_r + 273)^4]\ (T_{sk} - T_r)]^{-1} \tag{9}$$

where σ is the Stephan–Boltzmann constant (5.67×10^{-8} W/m^2/°C), ε_{sk} is the emissivity of the skin 0.97; dimensionless), A_r is the body's effective radiating area (%), T_r is the mean radiation temperature (°C), and T_{sk} is the mean skin temperature (°C). The skin surface taking part in radiative heat exchanges (A_r) is equal to 0.575; this is the total body surface area less the surface area of the segments that radiate heat between them (0.77) and mattress–mannequin contact area when the mannequin is placed in the prone position (0.195). These values have been defined previously for a neonate [31] and for the mannequin used in the present study [32].

Again, given that the air velocity in the delivery room is assumed to be below 0.2 m/s, T_r was measured with a conventional black-globe thermometer (diameter: 15 cm; wall thickness: 0.6 mm) and calculated from the natural convection equation:

$$T_r = [(t_g + 273)^4 + 0.4 \times 10^8\ \mid t_g - T_a \mid^{0.25} (t_g - T_a)]^{0.25} - 273 \tag{10}$$

where t_g = is the black-globe temperature (°C).

In the case of porous, light fabrics, the latent heat loss reduction coefficient (F_{pcl}) was calculated from the thermal insulation (I_{cl}) and the coefficients for heat exchange by radiation (h_r) and convection (h_c) [27]:

$$F_{pcl} = [[1 + 2.22\ h_c\ [I_{cl} - (1 - 1/f_{cl})\ (h_r + h_c){-}1]]]^{-1} \tag{11}$$

The variations in mean body temperature ΔT_b (expressed in °C/h) were calculated from the body heat storage (S, in KJ/h), the body mass (kg), and the specific heat capacity of human tissues (C_p = 3.494 KJ/kg·°C):

$$\Delta_{Tb} = \frac{S}{m_b C_p} \tag{12}$$

2.4. The Experiments

A neonate at birth was simulated by considering the local skin temperatures, as measured using infrared thermography [9] (head: 34.4 °C; trunk: 34.6 °C; upper limbs: 34.4 °C; lower limbs: 34.1 °C), giving a weighted skin temperature (T_{sk}) of 34.36 °C. This is very close to the value measured by Karlsson with 10 skin thermistors (34.1 ± 0.4 °C) in newborns 10 min after delivery [14].

The mannequin was placed in an air-conditioned room with a T_a of 25.9 °C, i.e., close to the value of 25 °C recommended by the WHO. A second series of experiments was carried out at 20.9 °C, which corresponds to a comfortable T_a most often chosen by the mother in labor and the nursing staff. The relative air humidity was 45–50%. To simulate

SSC during the immediate postpartum period, the model was placed prone in direct contact with a heating mattress (CR1, Electro Concept, Saint Léonard de Noblat, France), the shape of which matched that of a mother's belly (Figure 2). We chose to set the mattress's surface temperature to 35.5 °C; we considered that the skin temperature of the trunk of a nude adult exposed for one hour to a temperature of 24 °C and a relative humidity of 45% in still air would be 32 °C [33] and that 3.5 °C should then be added to simulate the effects of labor (a thermal load raising the mother's internal body temperature by 1°C and the skin temperature by 3.5 °C). These conditions are defined as the alert threshold for hyperthermia in the ISO 7933 standard [27].

Figure 2. Photographs of the mannequin covered with a sheet (**left panel**) or a sheet + blanket set (**right panel**).

The mannequin was dressed in a cotton cap and a diaper and was covered with a cotton sheet (182 g/m^2) folded in half (i.e., a total of two fabric layers) or the same double sheet plus a polyester blanket (189 g/m^2) folded in half (i.e., a total of four fabric layers). The two clothing set conditions were tested in random order.

The ambient temperature and the mattress surface temperature were recorded using 12 thermistor probes (10 kOhms at 25 °C). One of the sensors was located in an open tube between the mannequin and the covering in order to measure the temperature of the air trapped there.

2.5. Statistical Analysis

The experimental conditions were studied in random order. Five measurements were made for each condition in order to assess the variability in the heat power supplied to the mannequin. In view of our comparisons of small samples, the effects of the thermal insulation of the coverings (a sheet alone vs. sheet + blanket at 20.9 °C and at 25.9 °C) were probed by applying nonparametric Mann–Whitney tests. The threshold for statistical significance was set to $p < 0.05$. Quantitative variables were expressed as the mean ± standard deviation (SD). Statistical analysis was performed using Statview software (version 5.0, Abacus Concepts Inc., Berkeley, CA, USA).

3. Results

The mean T_a was 20.9 ± 0.04 °C (mean ± SD radiant temperature (T_r): 21.2 ± 0.03 °C) or 25.9 ± 0.09 °C (T_r = 26.2° ± 0.05 °C). Depending on the experiment, the mean temperature of the mattress surface ranged from 35.35 ± 0.61 °C to 35.92 ± 0.57 °C. The mannequin's surface temperature was kept constant (between 34.34 °C and 34.39 °C) with an SD below 0.05 °C (i.e., lower than the measuring device's precision). T_a did not depend significantly on the covering condition (sheet vs. sheet + blanket) at 20.9 °C (p = 0.698;

z = 0.387) or 25 °C (p = 0.462; z = 0.735). The same was true for T_r when T_a was 20.9 °C (p = 0.439; z = 0.775) or 25.9 °C (p = 0.462, z = 0.735).

The fabric covering made it possible to establish a microclimate between the inner layer of fabric and the mattress surface (i.e., the simulated skin of the mother). With a T_a of 20.9 °C, the temperature under the covering was 22.75 ± 0.24 °C with the sheet and 23.72 ± 0.54 °C with the sheet + blanket. At 25.9 °C, the temperate was 27.25 ± 0.31 °C with the sheet and 28.09 ± 0.11 °C with the sheet + blanket.

The variables characterizing the total thermal insulation provided by the covering (sheet or sheet + blanket) and clothing (cap and diaper) are listed in Table 1.

Table 1. Variables characterizing the total thermal insulation provided by the covering (sheet or sheet + blanket) and clothing (cap and diaper) during simulated SSC. R and C are, respectively, the radiative and convective heat losses (in W/kg) for the clothed (clo) or nude (n) mannequin. F_{cl}, $I_{cl,}$ and F_{pcl} are, respectively, the reduction coefficients of dry and the insulation provided by the covering and clothing (m^2 °C/W). F_{pcl} is the reduction in latent heat exchange.

T_a	20.9 °C		25.9 °C	
Condition	**Sheet**	**Sheet + Blanket**	**Sheet**	**Sheet + Blanket**
$(R + C)_{clo}$	−4.31 ± 0.14	−3.76 ± 0.17	−2.76 ± 0.11	−2.30 ± 0.18
$(R + C)_n$	8.92 ± 0.10		5.34 ± 0.10	
F_{cl}	0.49	0.42	0.52	0.43
I_{cl}	0.15	0.2	0.15	0.21
F_{pcl}	0.42	0.36	0.48	0.39

The mannequin's measured dry heat losses (R + C + K) and the calculated respiratory and skin heat losses under the various experimental conditions and energy metabolism (M) values are summarized in Table 2.

At a T_a of 20.9 °C, increasing the thermal insulation reduced dry heat loss by 16.7% (p = 0.0019, z = 0.775). At 25.9 °C, this reduction was 17.8% (p = 0.0143, z = 2.449) (Table 2). The World Health Organization recommends maintaining SSC for at least one hour after delivery. Our simulations indicated that with an internal body temperature of 37 °C at birth, normothermia was estimated at a T_a of 25.9 °C with a sheet alone (36.52 ± 0.11 °C) and the sheet + blanket (37.09 ± 0.11 °C) but only when the neonate's energy metabolism was highly active (2.70 W/kg). Moderate hypothermia was never estimated for the other conditions. At a T_a of 20.9 °C, moderate hypothermia was estimated (i.e., body temperatures ranging from 32.79 to 34.40 °C), except for the condition with M = 2.70 W/kg and I_{cl} = 0.21 m^2 °C/°W.

Comparisons of the heat power values given in Table 1 (R + C) and Table 2 (R + C + K) showed that under our experimental conditions, the conductive heat gain was negligible and was not significant at a T_a of 20.9 °C regardless of the thermal insulation of the mannequin's covering (sheet: p = 0.1495, z = 1.441 and sheet + blanket: p = 0.6434, z = 0.463). At a Ta of 25.9 °C, the conductive heat gain was significant with the sheet (+0.24 W/kg; p = 0.0074, z = 2.68; 9.5% of the total dry heat exchange) but not with the sheet + blanket (p = 0.0881, z = 1.706).

The threshold for severe hypothermia (32 °C) was never reached—even for the lowest T_a and the lowest degree of thermal insulation (Figure 3).

Table 2. The mannequin's dry heat losses (R + C + K), evaporative heat losses from the respiratory tract (Eres) and the skin (E), and convective respiratory heat loss (Cres) at three different values of M. S is the body heat storage. Heat transfers and S are expressed in W/kg. dT_b/dt is the change in the mean body temperature (°C/h). T_b is the mean body temperature change calculated after an hour of SSC (°C) and an internal body temperature of 37 °C at birth. Only the values of C_{res} and E_{res} (which depend on energy metabolism; see Equations (2) and (3)) differed; the magnitudes of the other factors (R, C, K, and E) involved in the heat storage calculation remained the same.

Ta	20.9 °C		25.9 °C	
Conditions	**Sheet**	**Sheet + Blanket**	**Sheet**	**Sheet + Blanket**
		M = 1.11 W/Kg		
R + C + K	−4.48 ± 0.24	−3.73 ± 0.16	−2.52 ± 0.11	−2.07 ± 0.10
E	−0.69 ± 0.0009	−0.54 ± 0.0004	−0.59 ± 0.002	−0.48 ± 0.002
Eres	−0.0158 ± 0.0006	−0.0182 ± 0.0010	0.0196 ± 0.0009	−0.0222 ± 0.0003
Cres	−0.003 ± 0.000	−0.003 ± 0.000	−0.0029 ± 0.000	−0.0029 ± 0.000
S	−4.08 ± 0.23	−3.23 ± 0.16	−2.03 ± 0.11	−1.47 ± 0.10
dT_b/dt	−4.21 ± 0.24	−3.33 ± 0.16	−2.09 ± 0.11	−1.51 ± 0.11
Tb	32.79 ± 0.24	33.67 ± 0.16	34.91 ± 0.11	35.49 ± 0.11
		M = 1.59 W/Kg		
Eres	−0.0226 ± 0.0008	−0.026 ± 0.002	−0.028 ± 0.001	−0.0318 ± 0.000
Cres	−0.0045 ± 0.000	−0.0044 ± 0.000	−0.0042 ± 0.000	−0.0042 ± 0.000
S	−3.61 ± 0.23	−2.76 ± 0.16	−1.56 ± 0.11	−1.00 ± 0.11
dT_b/dt	−3.72 ± 0.24	−2.84 ± 0.16	−1.60 ± 0.11	−1.03 ± 0.11
Tb	33.28 ± 0.24	34.16 ± 0.16	35.40 ± 0.11	35.97 ± 0.11
		M = 2.70 W/Kg		
Eres	−0.0384 ± 0.001	0.0442 ± 0.0030	−0.0476 ± 0.0021	−0.0539 ± 0.0008
Cres	−0.0076 ± 0.000	−0.0076 ± 0.000	−0.0071 ± 0.000	−0.0071 ± 0.000
S	−2.52 ± 0.23	−1.67 ± 0.16	−0.47 ± 0.11	+0.09 ± 0.10
dT_b/dt	−2.60 ± 0.24	−1.72 ± 0.16	−0.48 ± 0.11	+0.09 ± 0.11
Tb	34.40 ± 0.24	35.28 ± 0.16	36.52 ± 0.11	37.09 ± 0.11

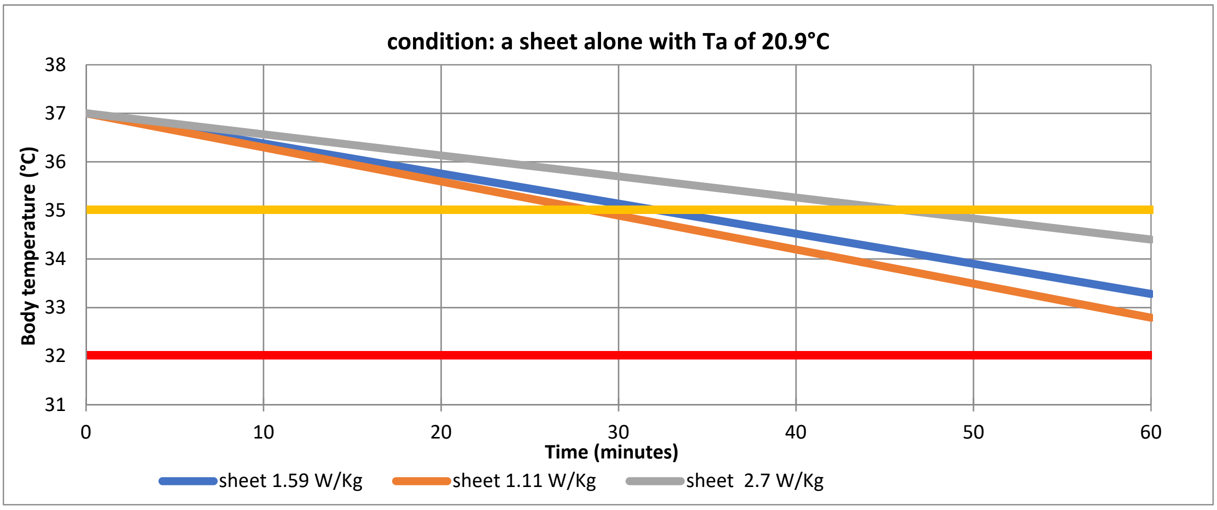

Figure 3. *Cont.*

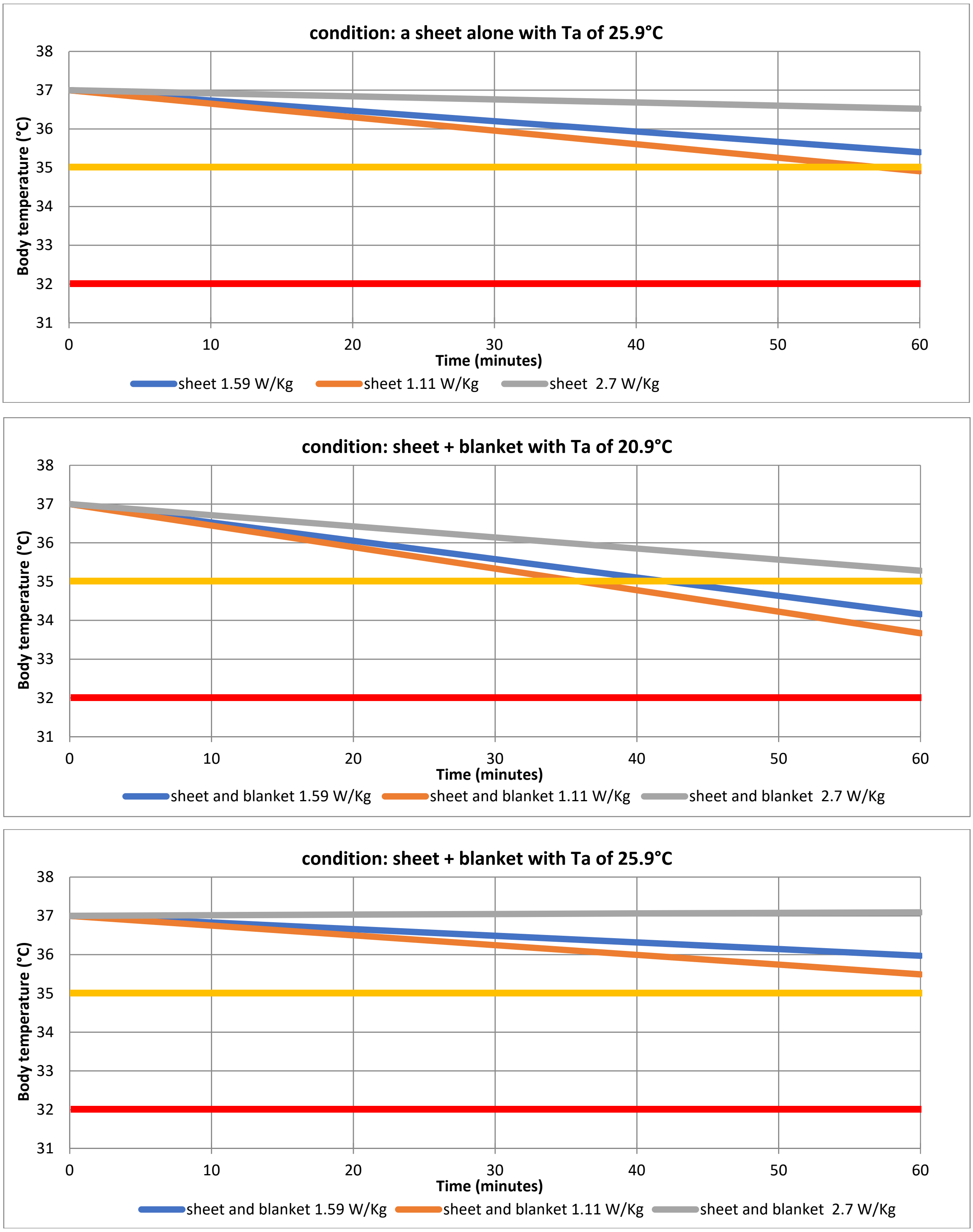

Figure 3. The change over time in the mean body temperature (°C) for three levels of metabolic heat generation (colored lines) at a T_a of 20.9 or 25.9 °C and for the two thermal insulation conditions of (a sheet alone or sheet + blanket). The horizontal yellow and red lines indicate the thresholds for moderate hypothermia (35 °C), and severe hypothermia (32 °C), respectively.

4. Discussion

The use of a thermal manikin and the calculation of a premature neonate's heat exchanges with the environment enables us to make several practical observations of value with regard to the modalities of early SSC (i.e., an hour of SSC immediately after delivery). It should be borne in mind that the present study's findings are limited to neonates dried at birth, wearing a cap and a diaper, and who are normothermic (i.e., a body temperature between 36.5 and 37.5 °C) at birth.

Our results suggest that with a T_a of 25.9 °C, SSC can warm up the neonate when the thermal insulation provided by the neonate's covering and clothing is moderate (a sheet alone; I_{cl} = 0.15 m^2 °C/W; T_b: 37.09 °C) or substantial (i.e., a sheet + blanket; I_{cl} = 0.21 m^2 °C/W; T_b: 36.52 °C) but only when the neonate's level of metabolic heat production is high. Maintaining the T_a recommended by the WHO would indeed reduce the incidence of neonatal hypothermia. Regardless of the level of metabolic heat production, a T_a of 20.9 °C cannot be recommended. However, this value is often selected by the nursing staff for their own thermal comfort. Our experiments showed that after one hour, a T_a of 20.9 °C induces a state of moderate hypothermia with T_b ranging from 32.79 °C to 34.40 °C. Under this condition, the threshold for moderate hypothermia (35 °C) is reached after 28 and 48 min of exposure, respectively.

However, a T_a of 25.9 °C alone is not sufficient. Our simulation showed that neonates whose metabolic heat generation cannot compensate for body heat losses (M < 2.7 W/kg) are likely to develop moderate hypothermia. Hence, SSC can only be recommended for thermally stable infants with a T_b of at least 37 °C at birth and a particularly active energy metabolism. This might explain the estimated inter-infant differences in the effectiveness of SSC and why some moderately hypothermic but well-covered premature infants require additional oxygen [13].

Many researchers have observed large interindividual differences in the cold resistance of preterm infants. Metabolic heat production depends on the nervous system's maturity and the mass of brown adipose tissue; hence, during cold exposure, metabolic activity sometimes fails to increase or can even decrease. Hey et al. [34], thus, reported that the absence of a metabolic response was due to a lack of brown adipose tissue. These considerations are especially relevant in premature neonates. A study in the rat [35] showed that in individuals with intrauterine growth retardation, high adenosine levels inhibited lipolysis during fetal growth [36]. This mechanism would explain the lack of brown adipose tissue in a premature neonate. In an infrared thermography study of cold exposure in newborns with a gestational age below 30 weeks, Oya et al. [37] claimed that brown adipose tissue could not produce enough heat to be effective against body cooling until the third trimester of pregnancy. Inter-infant differences in brown adipose tissue might, thus, be able to compensate (or not) for the infant's heat loss.

The effectiveness of vasomotor mechanisms should also be considered. In our present model, we considered that the neonate's vasomotor mechanisms were not efficient enough to influence the conservation of the heat produced by metabolic processes. Premature infants show vasoconstriction in certain regions of the body, such as the hands, feet, and calves [38,39]. Karlsson et al. [40] indicated that peripheral vasoconstriction (which normally reduces heat loss from the skin to the environment) was relatively ineffective. Vasoconstriction at the feet was effective but was accompanied by vasodilatation at the trunk (a large proportion of the body surface area), greater dry heat loss, and, thus, an increase in the risk of hypothermia.

Although our model does not take into account the physiological responses of a living organism, it has certain advantages. For example, one can accurately assess the impact of inter-infant variability in metabolic heat production and the thermal impact of the clothing used to protect the neonate in accordance with ISO standards [15,28]. To the best of our knowledge, this assessment has not previously been performed in premature neonates during SSC. Differences in body mass, gestational age, the thermal insulation of clothing, and care procedures can modify heat exchanges with the environment and, thus, mask small differences in body heat losses—especially in fairly small series with a greater probability of confounding factors.

In the present study, we chose to calculate the mean body temperature because it is reportedly a reliable index of body cool stress [23,24]. This choice was also based on older literature data [21,22], according to which body temperature stability depends on the regulation of heat flows between the skin surface and the environment (i.e., body heat storage) rather than the body's internal temperature alone. Using a model, thus, avoids the need to measure the infant's body temperature (e.g., rectal temperature) very frequently. Although the rectal temperature is still the gold standard body temperature, it is particularly invasive in premature newborns. There is a risk of anal perforation, and vagal stimulation can lead to arrhythmia, bradycardia, and apnea [41]. Tympanic and axillary measurements are less invasive but have to be corrected, and the magnitude of the correction is subject to debate in the literature.

Our study had a number of limitations. Firstly, the mannequin does not mimic convective and evaporative heat losses from the skin and the respiratory system, which have to be estimated mathematically (Equations (2), (3) and (5)). One of the determinants of skin evaporation is the fraction of body area that is wetted, which is based on a very old literature value from a study in adults [30]. This value is probably an underestimate in neonates, whose thin skin lacks keratin and is very permeable to water vapor [42]. Secondly, our model did not take into account changes over time in the thermal states of the mother and the neonate; we considered solely the variables known or assessed at birth. It would be interesting to measure changes over time in the skin temperature of the mother's trunk using infrared thermography. To the best of our knowledge, there are no literature data on these determinants of heat losses.

5. Conclusions

During early SSC with a T_a of 25.9 °C (as recommended by the WHO), homeothermy can be maintained but only when the premature neonate and the mother are well covered with porous fabrics ($I_{cl} \geq 0.15$ m^2 °C/W) and when the level of metabolic heat production is high (M: 2.70 W/kg). With a T_a of 20.9 °C, moderate hypothermia (requiring monitoring of the neonate's thermal status) was estimated—except for M = 2.70 W/kg and I_{cl} = 0.21 m^2 °C/W.

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References

1. Malaysian Very Low Birth Weight Study Group. A national study of risk factors associated with mortality in very low birthweight infants in the Malaysian neonatal intensive care units. *J. Paediatr. Child Health* **1997**, *33*, 18–25. [CrossRef]
2. Laptook, A.R.; Salhab, W.; Bhaskar, B.; Neonatal Research Network. Admission temperature of low birth weight infants: Predictors and associated morbidities. *Pediatrics* **2007**, *119*, e643–e649. [CrossRef] [PubMed]
3. Dahm, L.S.; James, L.S. Newborn temperature and calculated heat loss in the delivery room. *Pediatrics* **1972**, *49*, 504–513. [CrossRef] [PubMed]
4. Organisation Mondiale de la Santé. Bureau Régional du Pacifique Occidental. Premiers Soins Essentiels au Nouveau-né. Guide de Poche de Pratique Clinique. Bureau Régional de l'OMS pour le Pacifique Occidental. 2017. Available online: https://apps.who.int/iris/handle/10665/260404 (accessed on 28 February 2023).

5. Kattwinkel, J.; Niermeyer, S.; Nadkarni, V.; Tibballs, J.; Phillips, B.; Zideman, D.; Van Reempts, P.; Osmond, M. Resuscitation of the newly born infant: An advisory statement from the Pediatric Working Group of the International Liaison Committee on Resuscitation. *Circulation* **1999**, *40*, 71–88. [CrossRef]
6. World Health Organization. Maternal and Newborn Health/Safe Motherhood. Thermal Protection of the Newborn: A Practical Guide. World Health Organization. 1997. Report No.: WHO/RHT/MSM/97.2. Available online: https://apps.who.int/iris/handle/10665/6398 (accessed on 28 March 1997).
7. Färdig, J.A. A comparison of skin-to-skin contact and radiant heaters in promoting neonatal thermoregulation. *J. Nurse Midwifery* **1980**, *25*, 19–28. [CrossRef] [PubMed]
8. Christensson, K.; Siles, C.; Moreno, L.; Belaustequi, A.; De La Fuente, P.; Lagercrantz, H.; Puyol, P.; Winberg, J. Temperature, metabolic adaptation and crying in healthy full-term newborns cared for skin-to-skin or in a cot. *Acta Paediatr. Oslo Nor.* **1992**, *81*, 488–493. [CrossRef]
9. Christidis, I.; Zotter, H.; Rosegger, H.; Engele, H.; Kurz, R.; Kerbl, R. Infrared thermography in newborns: The first hour after birth. *Gynakol. Geburtshilfliche Rundsch.* **2003**, *43*, 31–35. [CrossRef]
10. Christensson, K.; Bhat, G.J.; Amadi, B.C.; Eriksson, B.; Höjer, B. Randomised study of skin-to-skin versus incubator care for rewarming low-risk hypothermic neonates. *Lancet Lond. Eng.* **1998**, *352*, 1115. [CrossRef]
11. Srivastava, S.; Gupta, A.; Bhatnagar, A.; Dutta, S. Effect of very early skin to skin contact on success at breastfeeding and preventing early hypothermia in neonates. *Indian J. Public Health* **2014**, *58*, 22–26. [CrossRef]
12. Jia, Y.S.; Lin, Z.l.; Lv, H.; Li, Y.M.; Green, R.; Lin, J. Effect of a delivery room temperature on the admission temperature of premature infants: A randomized controlled trial. *J. Perinatol.* **2013**, *3*, 264–267. [CrossRef]
13. Kardum, D.; Bell, E.F.; Grčić, B.F.; Müller, A. Duration of skin-to-skin care and rectal temperatures in late preterm and term infants. *BMC Pregnancy Childbirth* **2022**, *22*, 655. [CrossRef] [PubMed]
14. Karlsson, H. Skin-to-skin care: Heat balance. *Arch. Dis. Child.* **1966**, *75*, F130–F132. [CrossRef] [PubMed]
15. International Standards Organisation (ISO) 9920. *Ergonomics of the Thermal Environment-Estimation of the Thermal Insulation and Evaporative Resistance of a Clothing Ensemble*; 93571 Saint Denis La Plaine Cedex: Saint-Denis, France, 1995; pp. 313–372.
16. Bauer, J.; Werner, C.; Gerss, J. Metabolic rate analysis of healthy preterm and full-term infants during the first weeks of life. *Am. J. Clin. Nutr.* **2009**, *90*, 1517–1524. [CrossRef]
17. Silverman, W.; Agate, F.J. Variation in cold resistance among small newborn infants. *Biol. Neonat.* **1964**, *6*, 113–127. [CrossRef]
18. Adamson, S.K.; Towell, M.E. Thermal homeostasis in the fetus and newborn. *Anesthesiology* **1965**, *26*, 531–548. [CrossRef]
19. Pribylova, H.; Znamenacek, K. The effect of body temperature on the level of carbohydrate metabolites and oxygen consumption in the newborn. *Pediatrics* **1966**, *37*, 743–749. [CrossRef]
20. Gandy, G.M.; Adamson, K.; Cunningham, N.; Silverman, W.A.; James, L.S. Thermal environment and acid base homeostasis in human infants during the first few hours of life. *J. Clin. Investig.* **1964**, *43*, 751–758. [CrossRef] [PubMed]
21. Crosbie, R.J.; Hardy, J.D.; Fessenden, E. Electrical analog simulation of temperature regulation in man. In *Temperature: Its Measurement and Control in Science and Industry*; Hardy, J.D., Ed.; Part 3; Biology and Medicine: New York, NY, USA, 1963; pp. 627–635.
22. Houdas, Y.; Guieu, J.D. Le système thermorégulateur de l'Homme: Système régulé ou système asservi? *Arch. Sci. Physiol.* **1973**, *27*, 311–338.
23. Lenzi, P.; Libert, J.P.; Franzini, C.; Cianci, T.; Guidalotti, P.L. Short-term thermoregulatory adjustments involving opposite regional temperature changes. *J. Therm. Biol.* **1986**, *11*, 151–156. [CrossRef]
24. Libert, J.P.; Tourneux, P. The thermostatic control of body temperature. In *Vegetative Functions and Their Interactions in Neonates*; Chardon, K., Ed.; Research Sing Post Press: Ahmedabad, India, 2010.
25. Fenton, T.R.; Kim, J.H. A systematic review and metanalysis to revise the Fenton growth chart for preterm infants. *BMC Pediatr.* **2013**, *13*, 59. [CrossRef]
26. Chessex, P.; Reichman, B.L.; Verellen, G.J.; Putet, G.; Smith, J.M.; Heim, T.; Swyer, P.R. Influence of postnatal age, energy intake, and weight gain on energy metabolism in the very low-birth-weight infant. *J. Pediatr.* **1981**, *99*, 761–766. [CrossRef] [PubMed]
27. International Standards Organisation (ISO) 7933:1989 Modified. *Analytical Determination and Interpretation of Thermal Stress Using Calculation of Required Sweat Rate*; AFNOR, 93571 Saint Denis La Plaine Cedex: Saint-Denis, France, 1997; pp. 259–290.
28. Hanson, R.d.G. Respiratory heat loss at increased -core-temperature. *J. Applied Physiol.* **1974**, *37*, 103–107. [CrossRef] [PubMed]
29. Gagge, A.P. A new physiological variable associated with sensible and insensible perspiration. *Am. J. Physiol.* **1937**, *120*, 277–287. [CrossRef]
30. Hannouch, A. Analyses Numériques et Expérimentales du Transfert Thermique dans un Incubateur Néonatal avec un Mannequin Imprimé en 3D. Thèse de Doctorat, University of Angers, Angers, France, 2021. Available online: https://www.theses.fr/2021ANGE0051 (accessed on 23 November 2021).
31. Adams, A.K.; Nelson, R.A.; Bell, E.F.; Egoavil, C.A. Use of infrared thermographic calorimetry to determine energy expenditure in preterm infants. *Am. J. Clin. Nutr.* **2000**, *71*, 969–977. [CrossRef]
32. Museux, N.; Cardot, V.; Bach, V.; Delanaud, S.; Degrugilliers, L.; Agourram, B.; Elabbassi, E.B.; Libert, J.P. A reproducible means of assessing the metabolic heat status of preterm neonates. *Med. Phys.* **2008**, *35*, 89–100. [CrossRef]
33. Bazett, H.C. The regulation of body temperature. In *Physiology of Heat Regulation and the Science of Clothing*; Newburgh, L.H., Ed.; W.B. Saunders Company: Philadelphia, PA, USA; London, UK, 1949; Chapter 4, pp. 109–192.

34. Hey, E.N.; Katz, G. Temporary loss of a metabolic response to cold stress in infants of low birthweight. *Arch. Dis. Child.* **1969**, *44*, 323–330. [CrossRef]
35. Asakura, H.; Nakai, A.; Power, G.G.; Araki, T. Short term effects of different thermal conditions during uteroplacental ischaemia on fetal growth of Sprague-Dawley rats. *Reprod Fertile Dev.* **2002**, *14*, 355–361. [CrossRef]
36. Yoneyama, Y.; Wakatsuki, M.; Sawka, R.; Kamoi, S.; Takahashi, H.; Shin, S.; Power, G.G.; Araki, T. Plasma adenosine concentration in appropriate and small-for-gestational-age fetus. *Am. J. Obstet. Gynecol.* **1974**, *170*, 684–688. [CrossRef]
37. Oya, A.; Asakura, H.; Koshino, T.; Araki, T. Thermographic demonstration of non-shivering thermogenesis in human newborns after birth: Its relation to umbilical gases. *J. Perinat. Med.* **1977**, *25*, 447–454. [CrossRef]
38. Hey, E.N.; Katz, G. The range of thermal insulation in the tissues of the newborn baby. *J. Physiol. Lond.* **1970**, *207*, 667–681. [CrossRef]
39. Berg, K.; Celander, O. Circulatory adaptation in the thermoregulation of fullterm and premature newborn infants. *Acta Paediatr. Scand.* **1971**, *60*, 278–284. [CrossRef] [PubMed]
40. Karlsson, H.; Olegård, R.; Nilsson, K. Regional skin temperature, heat flow and conductance in preterm neonates nursed in low and in neutral environmental temperature. *Acta Paediatr.* **1996**, *85*, 81–87. [CrossRef] [PubMed]
41. Ellis, J. Neonatal hypothermia. *J. Neonat. Nurs.* **2005**, *11*, 76–82. [CrossRef]
42. Hammarlund, K.; Sedin, G. Water evaporation and heat exchange with the environment in newborn infants. *Acta Paediatr. Scand.* **1983**, *305*, 32–35. [CrossRef]