Assessment of dry heat exchanges in newborns: influence of body position and clothing in SIDS

ELMOUNTACER BILLAH ELABBASSI, VÉRONIQUE BACH, MALEK MAKKI, STEPHANE DELANAUD, FRÉDÉRIC TELLIEZ, ANDRÉ LEKE, AND JEAN-PIERRE LIBERT
Unité de Recherches sur les Adaptations Physiologiques et Comportementales, Faculté de Médecine, 80036 Amiens Cédex, France

Received 28 September 2000; accepted in final form 5 February 2001

Elmountacer Billah Elbassi, Véronique Bach, Malek Maki, Stephane Delanaud, Frederic Telliez, Andre Leke, and Jean-Pierre Libert. Assessment of dry heat exchanges in newborns: influence of body position and clothing in SIDS. J Appl Physiol 91: 51–56, 2001.—A dramatic decrease of sudden infant death syndrome (SIDS) has been noted following the issuance of recommendations to adopt the supine sleeping position for infants. It has been suggested that the increased risk could be related to heat stress associated with body position. In the present study, the dry heat losses of small-for-gestational-age newborns nude or clothed were assessed and compared to see whether there is a difference in the ability to lose heat between the prone and supine positions. An anthropomorphic thermal mannequin was exposed to six environmental temperatures, ranging between 25 and 37°C, in a single-walled, air-heated incubator. The magnitudes of heat losses did not significantly differ between the two body positions for the nude (supine 103.46 ± 29.67 W/m² vs. prone 85.78 ± 34.91 W/m²) and clothed mannequin (supine 59.35 ± 21.51 W/m² vs. prone 63.17 ± 23.06 W/m²). With regard to dry heat exchanges recorded under steady-state conditions, the results show that there is no association between body position and body overheating.

EPIDEMIOLOGICAL STUDIES SHOWED that the risk of sudden infant death syndrome (SIDS) is associated with clothing insulation and room heating (6, 29). Signs of profuse sweating are also present at the scene of SIDS in 35.7% of cases (14). Thus the evidence, although inconclusive, strongly suggests that heat stress may be a primary or contributory factor in SIDS; infants are not able to dissipate excess body heat. Thermal stress can be particularly important in premature and small-for-gestational-age infants characterized by high values of the ratio between skin surface area and body mass; the greater this ratio, the greater the body heat exchanges.

Prone sleeping has also been recognized as a major risk factor for SIDS in various epidemiological studies (4, 5, 7, 13, 20, 24). In 1992, the American Academy of Pediatrics recommended that infants be placed in the supine sleeping position, and, since that time, the rate of SIDS has decreased by >40% (1).

The increased risk for the prone position can arise through various mechanisms involving rebreathing of expired gases (19), altered vestibular influences on cardiovascular and respiratory control mechanisms (10, 21), increased arousal threshold (8), and heat stress (11, 16, 18, 20, 25). As reported by Ponsonby et al. (20), there is evidence that swaddling increases the risk of SIDS in prone-sleeping newborns. Clothing precludes air circulation over the skin surface and acts as a barrier that blocks body heat losses to the environment (16). As reported by Fleming et al. (6), in the supine position, the adverse effects of heavy dressing are less important than in the prone position unless the head is completely covered. Using a theoretical model to estimate the thermal balance of newborns, Nelson et al. (16) assumed that, in the heavily dressed infant, heat loss was impaired by placing the head face down or by covering the head with bedding. North et al. (18) and Tuffnell et al. (25) showed that supine-sleeping infants displayed lower rectal temperatures than those sleeping prone. Supine sleepers lose body heat more rapidly in the first 2 hr after bedtime. Thus it appears that thermoregulation is compromised by the prone position, but this never has been proven. There is no published information on the changes in the modes of heat exchange when comparing the supine with the prone position. Most studies (15, 26, 28) deal with the supine, lateral, fetal, and spread-eagle postures, which modify dry heat exchanges through convective and radiative heat-transfer coefficients (h_c and h_r, respectively).

From these various reports, it may be assumed that the prone position can reduce the exposed body surface area and contribute to a decrease in body cooling, hence increasing the risk of SIDS. To test the relationship between body posture, clothing, and heat transfers from the body to the environment, a multisegment mannequin corresponding to a small-for-gestational-age newborn was used to model the changes in heat transfers and compare the prone and supine positions.

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

http://www.jap.org
8750-7587/01 $5.00 Copyright © 2001 the American Physiological Society
METHODS

The multisegment, anthropomorphic, thermal mannequin represents a small-for-gestational-age newborn with a body surface area of 0.150 m² and a weight (i.e., simulating a birth weight) of 1,400 g (Fig. 1). It was cast in copper and painted matt black (surface emissivity = 0.95). Each segment of the mannequin was heated by separate resistance wires, and the temperatures at various points of the outer surface were measured by attached thermistors (Yellow Springs Instruments, series 409A; accuracy of ±0.10°C). Each probe was protected from radiant energy by an aluminium foil patch.

Eight thermistors were located on the head, six on the trunk, and two on each of the upper and lower limbs. The mean surface temperature \( T_s \) of the mannequin was calculated from the set of local surface temperatures weighted according to the relative surface area of each segment

\[
T_s = 0.17 T_{\text{head}} + 0.34 T_{\text{trunk}} + 0.34 T_{\text{lower limbs}} + 0.15 T_{\text{upper limbs}}
\]

To take into account the regional thermal heterogeneity of the body, each segment was separately heated to reach a set-point temperature. The temperature of the head was set to 36.40°C, the trunk to 36.60°C, and the upper and lower limbs to 35.54°C, respectively \( (T_s = 35.74°C) \). These values corresponded to those currently recorded in incubators of newborns nursed in the Pediatric Unit of Amiens Medical Center at their thermoneutral air temperature as defined by Hey (12). The response patterns of temperature regulation of the different body sections are shown in Fig. 2. After an initial overshoot, thermal equilibrium was reached within 45 min, and the error signals (differences between the set-point temperatures and the surface temperatures measured on the different segments) never exceeded 0.30°C.

The mannequin was laid on a mattress in a single-walled, convectively heated incubator used for intensive care (BioMS C 2750; BioMS, Toulouse, France) to strictly control the ambient conditions. The plastic foam mattress was hard and was covered by two cotton blankets (total thickness of 5 cm).

Air temperature \( (T_a) \) was measured at a point situated 10 cm above the center of the mattress, as recommended by relevant standards (American National Standard). The incubator wall temperatures were also recorded by thermistors covered by a reflective radiation shield and located at the center-point of each wall.

The temperature distribution over each inner incubator wall was measured with an infrared camera (Thermovision 550, AGEMA, Danderyd, Sweden; accuracy of ±2°C between −20 and 250°C). The difference between the coldest and warmest regions of the wall never exceeded 0.45°C in the range of wall temperatures of 20–38°C.

The temperature distribution over each inner incubator wall was measured with an infrared camera (Thermovision 550, AGEMA, Danderyd, Sweden; accuracy of ±2°C between −20 and 250°C). The difference between the coldest and warmest regions of the wall never exceeded 0.45°C in the range of wall temperatures of 20–38°C. The air velocity circulating in the incubator compartment was measured with a hot-globe anemometer (Testo 490) and set at 0.5 m/s. The mattress surface temperature was recorded under the trunk of the mannequin.

**Experiment.** There were six experimental conditions at \( T_a \) of 25, 30, 32, 34, 35, and 37°C. The nude or clothed mannequin was placed in a relaxed prone (face to the side) or supine position (face straight up; Fig. 1) on the mattress. The head surface area contacting the mattress did not greatly differ between the two positions (supine, 9.2 \( \times \) 10⁻² m²; prone, 16.9 \( \times \) 10⁻² m²) accounting for 0.61 and 1.13% of the total surface area of the mannequin. Clothing consisted of a diaper, cotton swaddling, a pajama (80% cotton, 20% polyester), and a lightly padded sleeping bag with sleeves (40% cotton, 60% polyester). In the two positions, the head was always uncovered. Under these experimental conditions, it can be assumed that the heat losses from the head did not strongly differ between the supine and prone conditions. For each trial, at least 10 measurements were made to assess the repeatability of the measures. To ensure that a thermal steady state was reached, at least 60 min elapsed before recordings began.

**Calculations.** At thermal equilibrium between the mannequin and the environment, the heating power \( (P) \) supplied to the mannequin balances the dry heat losses by conduction \( (K) \), radiation \( (R) \), and convection \( (C) \) (all expressed in W/m²)

\[
P = \pm C \pm R \pm K
\]
Depending on the heat flow direction, the quantities are considered to be positive when the heat is transferred from the environment to the surface of the mannequin.

The convective heat exchange (C) is proportional to the temperature difference between Ta and Tm, and to h, (W/m²·°C). For the clothed mannequin, a reduction factor due to clothing thermal insulation (Fcl, dimensionless) must be taken into account

\[ C = h_c(T_a - T_m)F_{cl} \]  

Similarly, the radiative heat exchange (R) can be formulated as follows

\[ R = h_r(T_r - T_m)F_{cl} \]  

where \( h_c \) and \( h_r \) is measured in watts per meter squared per degree Celsius and \( T_r \) is the mean radiant temperature (°C) calculated from the incubator wall temperatures according to the method of LeBlanc (15).

The ratio between the heating powers transmitted to the clothed and nude mannequin determines \( F_{cl} \) because, for a nude mannequin, \( F_{cl} = 1 \).

The calculations of \( h_c \) and \( h_r \) can be made for the nude mannequin by solving the following equation

\[ P \pm K = h_c(T_a - T_m) \pm h_r(T_r - T_m) \]  

Conductive heat (K) is transferred from warmer surfaces to contacted cooler surfaces and depends on the temperature difference between the surface of the mattress and the mannequin (Tm), and on the mattress's thermal conductivity.

During thermal steady state, the temperature difference between two surfaces in contact tends to be zero. As previously demonstrated by Apedoh et al. (3), the thermal conductivity of the plastic mattress covered by two cotton blankets is very low (0.21 W/m°C). As a result, we can assume that the conductive heat flow is negligible. This agrees with other studies (22, 23) that demonstrated that conduction is small enough to be neglected in body heat storage; for a naked newborn weighing 1,500 g, conductive heat loss amounts to 1–3% of the total dry heat loss. Covering the mannequin reduces the conduction compared with the nude model because clothes decrease the thermal conductivity.

Equation 5 can be rewritten as follows

\[ \frac{P}{T_r - T_m} = h_r(T_a - T_m) \pm h_r(T_r - T_m) \]  

where \( h_c \) and \( h_r \) are the slope and y-intercept values, respectively, of the least square linear regression.

Statistical analysis. The effects of Ta, body position (prone vs. supine), and clothing (with or without clothes) were tested by three-way ANOVA. When overall F values were significant, the differences between experimental conditions were computed by Student’s t-tests. F and t-values are given with their corresponding degrees of freedom (subscripts beneath F and t-values). Because multiple comparisons can lead to problems of intercorrelation between tests and inflate the probability of type 1 errors, the accepted level of significance was reduced to 0.01. Linear regression analyses were used to determine \( h_c \) and \( h_r \).

Mean values are given with one standard deviation (SD). The coefficient of variation calculated from the ratio between the standard deviation and mean are also indicated when relevant.

RESULTS

The experiments were performed at six levels of environmental temperature (mean values of 25.5, 30.0, 32.0, 33.9, 35.4, and 36.7°C). Standard deviations of the means and errors in the control of Ta calculated from the coefficient of variation ranged from 0.3 to 0.5°C and from 0.3 to 2.0%, respectively. Statistical analysis showed that posture \( (F_{1,198} = 1.378; P = 0.242) \) and clothing \( (F_{1,198} = 1.704; P = 0.193) \) had no effect on Ta, assuming that the experimental conditions were strictly controlled. Table 1 shows the mannequin Ta for the six different air temperatures and four mannequin conditions (prone and supine positions, each with and without clothes). The error in the control of the mannequin Tm ranged from 0.03 to 0.14%.

The surface temperature was not modified by the posture (supine 35.77 ± 0.20°C vs. prone 35.87 ± 0.19°C; \( F_{1,198} = 0.929; P = 0.336) \).

There was a slight (0.43°C) but significant increase \( (F_{5,198} = 302.801; P < 0.001) \) in Tm with Ta. This increase did not differ between the prone and supine positions \( (F_{5,198} = 0.499; P = 0.777) \). Statistical analysis also revealed that there was a clothing effect on Tm \( (F_{1,198} = 938.510; P < 0.001) \), which is larger for the clothed (35.97 ± 0.16°C) than nude (35.70 ± 0.15°C) mannequin.

For the nude mannequin placed in the supine position, the temperature of the surface of the mattress (36.86 ± 0.42°C) did not differ \( (t_{78} = 1.163; P > 0.05) \) from that of the body segments in contact with the mattress (36.37 ± 0.33°C). In the prone position, a similar statement can be drawn (35.89 ± 0.63°C vs. 36.41 ± 0.03°C; \( t_{78} = 0.812; P > 0.05) \). The conductive heat loss, being proportional to the difference between the temperature of the surface of the mattress and the mannequin surface and to the low thermal conduc-

<table>
<thead>
<tr>
<th>Ta (°C)</th>
<th>Prone</th>
<th>Supine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nude</td>
<td>Clothed</td>
</tr>
<tr>
<td>25.5 ± 0.5</td>
<td>35.60 ± 0.01</td>
<td>35.73 ± 0.01</td>
</tr>
<tr>
<td>30.0 ± 0.5</td>
<td>35.57 ± 0.01</td>
<td>35.79 ± 0.02</td>
</tr>
<tr>
<td>32.0 ± 0.5</td>
<td>35.68 ± 0.03</td>
<td>35.80 ± 0.05</td>
</tr>
<tr>
<td>33.9 ± 0.4</td>
<td>35.70 ± 0.03</td>
<td>35.98 ± 0.08</td>
</tr>
<tr>
<td>35.4 ± 0.3</td>
<td>35.91 ± 0.05</td>
<td>36.14 ± 0.10</td>
</tr>
<tr>
<td>36.7 ± 0.3</td>
<td>35.99 ± 0.06</td>
<td>36.20 ± 0.05</td>
</tr>
</tbody>
</table>

Values are means ± SD in °C. Ta, air temperature; X, mean value for pooled data.
ity of the mattress (0.21 W/°C), is negligible, as previously assumed (0.10 W in the 2 body positions).

Figure 3 shows that the heating power transmitted to the nude or clothed mannequin decreases linearly with increasing $T_a$ ($F_{5,198} = 168.329; P < 0.001$). As expected, the clothing reduced the dry heat loss from the mannequin surface to its environment ($F_{1,198} = 292.839; P < 0.001$). There was no significant difference in the magnitudes of dry heat losses between the prone and supine positions ($P_{1,98} = 0.238; P = 0.626$) for the nude (supine = 103.46 ± 29.67 vs. prone = 85.78 ± 34.91 W/m²; $t_{144} = 1.030; P = 0.304$) and clothed mannequin (supine = 59.35 ± 21.51 vs. prone = 63.17 ± 23.06 W/m²; $t_{74} = 1.543; P = 0.124$) whatever the thermal condition.

To assess the modalities of heat exchanges between the supine and prone positions, $h_r$ and $h_c$ were obtained by linear regression from Eq. 6: in the supine position, $h_r = 5.22 ± 0.23$ W/m².°C ($t_{136} = 22.681; P < 0.001$) and $h_c = 9.71 ± 0.87$ W/m².°C ($t_{136} = 11.219; P < 0.001$; $r^2 = 0.57$); in the prone position, $h_r = 4.53 ± 0.17$ W/m².°C ($t_{42} = 27.545; P < 0.001$) and $h_c = 9.89 ± 0.70$ W/m².°C ($t_{42} = 14.234; P < 0.001$; $r^2 = 0.84$).

Statistical analysis showed that $h_r$ was not modified by the posture ($t_{136} = 0.143; P > 0.05$), whereas $h_c$ was lower ($t_{136} = 2.412; P < 0.001$) in the prone position.

Taking into account the temperature distribution over the inner incubator walls leads to an error of 0.45°C in $T_h$. As a result, the maximum and minimum values of the heat transfer coefficients were 5.02–5.44 W/m².°C for $h_r$ and 9.59–9.82 W/m².°C for $h_c$ in the supine position. In the prone position, $h_r$ ranged from 4.36 to 4.72 W/m².°C and $h_c$ from 9.78 to 9.99 W/m².°C.

The mean values of $F_{cl}$ for sensible heat exchange were $0.62 ± 0.13$ and $0.71 ± 0.17$ in the supine and the prone positions, respectively. The factor is modified neither by the body position ($F_{1,61} = 1.707; P = 0.196$) nor by the changes in $T_a$ ($F_{5,61} = 1.999; P = 0.098$). For pooled data, $F_{cl} = 0.66 ± 0.15$. The intrinsic insulation ($I_{cl}$) can be determined by solving the equation of Nishi and Gagge (17)

$$I_{cl} = (1 - F_{cl})/F_{cl}(h_c + h_r)$$

In the supine and prone position, $I_{cl} = 0.041$ m².°C.W⁻¹ (0.26 clo) and 0.028 m².°C.W⁻¹ (0.18 clo), respectively, since 1 clo = 0.155 m².°C.W⁻¹.

DISCUSSION

The present results strongly suggest that body position and risk of thermal stress induced by increased body heat storage are two independent factors in SIDS, since posture does not impair the ability to exchange dry heat. In the literature, this relation has not been thoroughly investigated because it is difficult to obtain homogeneous databases that take into account the gender difference, body mass, age, thermal environment, clothing insulation, and nursing care of newborns, all of which are specific factors affecting the ability of the newborn to exchange heat with the surroundings. Interinfant variability can mask minor differences, especially in fairly small series, and the problem of confounding factors is thus highlighted. As shown by the standard deviations of the $T_h$s, the mannequin surface temperatures, and heating power supply, the errors in the repeatability of thermal experimental conditions are small; therefore, the contributions of the thermal environment on body heat balance can be assessed with the thermal mannequin. When the differences in the surface temperature of the nude and clothed mannequin (0.24 ± 0.01°C) on one hand and $h_r$ and $h_c$ on the other are taken into account, the differences in dry heat exchanges in the supine and prone positions are 3.58 and 3.46 W/m². Compared with the mean value of the heating power transmitted to the mannequin, this cumulative difference corresponds to a maximal error of ~3.5% for the nude mannequin and ~5.5% for the clothed model. This difference is insignificant and does not bias the present data.

As previously reported (2), the thermal mannequin is the most successful device yet for testing the effect of clothing and body position (prone vs. supine) on body heat transfers. This question is difficult to investigate with human subjects because parents are now discouraged from placing infants in the prone position. Moreover, the model solves the problem of the safety of measurements near the heat tolerance limits of the newborns. However, the model does not take into account the adaptive thermoregulatory processes involving changes in metabolic heat production, behavioral and vasomotor responses, and evaporative cooling through the skin or respiratory system, all of which can act to keep the body temperature constant. To simulate water heat loss and the effects of wetted clothing, future improvements should include a sweating capacity in the model. Thus the present data only refer to the capabilities of newborns to lose dry heat to the environment, which is particularly important after 2 wk of

Fig. 3. Mean heat power (±SD) transmitted to the nude mannequin (left) or clothed mannequin (right) lying in the supine (○) or prone (■) position as a function of air temperatures ($T_a$).
life. The measurement of dry heat exchanges with a small-for-gestational-age newborn is thus a relevant method for analysis of the contribution of thermal condition and clothing in body overheating, but only when a thermal equilibrium between the body and environment is reached.

As expected, in all experimental conditions, the mannequin heat losses are inversely related to $T_a$ and are reduced by clothing. For the nude mannequin, the heat losses do not depend on body posture. This contradicts the assumption that newborns sleeping prone are more vulnerable to hyperthermia than those sleeping supine. With regard to the heat transfer coefficients, the posture only modifies $h_r$.

In the literature, the relationship between various postures and the heat transfer coefficients has been extensively studied using physical or physiological measurements, but little attention has been paid to the comparison between the prone and supine positions. For newborns lying supine and exposed to free convection, Leblanc (15) found 4.80 and 6.40 W/m$^2$·°C for $h_c$ and $h_r$, respectively. Using an electrically heated simulator, Ulmann et al. (26) reported $h_c$ values ranging from 4.52 to 5.55 W/m$^2$·°C for newborns lying in convectively heated incubators of different forms. Using a heated mannequin corresponding to a full-term-sized newborn, Wheldon (28) found $h_c$ values of 4.00 in the fetal position and 3.90 and 4.91 W/m$^2$·°C in relaxed and spread-eagle positions, respectively, whereas $h_r$ varied from 3.10, 3.70, and 4.90 W/m$^2$·°C, respectively. It is difficult to compare these various values with those of the present study because Wheldon’s mannequin had a relatively simple shape without feet, hands, toes, fingers, eyes, mouth, ears, and nose, all of which would increase the heat transfer coefficients. Moreover, in the present study, each segment was electrically heated to simulate regional skin temperature heterogeneity, which can modify heat exchange. Air velocities, which vary greatly from one experiment to another, can also be at the origin of the discrepancy between $h_c$ values.

When the mannequin is clothed, the heat loss does not differ between the prone and supine positions, indicating that there is no increased risk of overheating associated with thermal insulation when sleeping prone. The mean values of the reduction factors with clothing are 0.62 and 0.71 in the supine and prone positions, respectively. Although the clothing is held constant, the present data strongly suggest that the increased risk from the prone position may arise through factors other than those involved in physical dry heat exchanges. This partly agrees with the results of North et al. (18), who found that, in the period before an adult-like night-time body temperature appeared, the sleeping position did not modify the nocturnal rectal temperature. Once this body temperature pattern appeared, North et al. found that rectal temperature is lower in supine-sleeping infants compared with those sleeping prone or lateral. During this period, the newborns sleeping nonprone moved more than those sleeping prone and uncovered their upper limbs while the face was fully exposed. This behavioral response, which cannot be taken into account in our model, enhances body cooling.

The present results agree with those of Tuffnell et al. (25) who found (using a mathematical model of body cooling fitted to the decrease in rectal temperature of newborns) that the rectal temperature recorded during the sleep period was not changed by body position and reached the same value for prone, supine, and lateral sleepers. The rate of body heat loss was only significantly reduced in the prone subjects at bedtime, but it is difficult to claim that this difference is sufficient to produce heatstroke (27). Tuffnell et al. assumed that the falling rectal temperature could result from a lowering of the metabolic rate occurring at sleep onset and from a change in the body thermal insulation. Supine sleepers can also lose more heat from the head and are able to expose limbs to increase body heat loss compared with infants sleeping prone. As reported for newborn piglets, head covering can induce lethal rises in brain temperature (9). These differences between data from nonliving models and infants can be explained by the fact that the mannequin does not take into account the dynamic autonomic or behavioral thermal responses that occur at the beginning of the sleep period. It thus should be stressed that the results reported in the present study are restricted to steady-state situations. Moreover, a possible effect of elevated brain temperature due to impairment of heat dissipation when the face is completely covered by bedding cannot be ruled out.

In conclusion, the present results suggest that when autonomic and behavioral thermoregulatory responses remain constant, the increased mortality by SIDS observed epidemiologically in the prone position is not related to an increased risk of overheating induced by an increase of body heat storage due to increased $T_a$, associated or not with insulation by clothing.

We are greatly indebted to the Regional Council of Picardy and the French Minister of National Education, Research and Technology for their financial support of the expenses incurred.

REFERENCES


