Influence of head position on thermal stress in newborns: simulation using a thermal mannequin

ELMOUNTACER BILLAH ELABBASSI, KAREN CHARDON, FRÉDÉRIC TELLIEZ, VÉRONIQUE BACH, AND JEAN-PIERRE LIBERT

Environnement Toxique Périmatinal et Adaptations Physiologiques et Comportementales, Faculté de Médecine, Université de Picardie Jules Verne, F-80036 Amiens Cédex, France

Received 15 April 2002; accepted in final form 6 June 2002

Influence of head position on thermal stress in newborns: simulation using a thermal mannequin. J Appl Physiol 93: 1275–1279, 2002; 10.1152/japplphysiol.00336.2002.—The influence of head position on thermal stress was assessed by using a heavily clothed thermal mannequin in three different body positions [supine, face straight up (FSU); supine, face to the side (FTS); prone, FTS] and with or without the head covered by a bonnet. The mannequin was exposed to air temperatures of 29, 32, 34, and 36°C. When the head is uncovered, body or head position has no impact on heat loss. When the head is covered, dry heat loss from the mannequin as a whole (and that from the head in particular) is lower when the head is covered, dry heat loss from the surface area of the face in contact with the mattress. In the FTS position and with the head covered, there was no difference in heat loss between the prone and supine positions. The results suggest that in heavily clothed newborns whose head is covered by a bonnet, thermal stress depends on the head position.

heat stress; clothing insulation; body position

THERMAL STRESS CAN TRIGGER various illnesses. As suggested by thermal modeling, the extent to which the skin of the head, and particularly the face, is exposed is an important determinant of body heat loss, notably when the newborn is heavily clothed or under thick bedding (7, 14). Thus excessive insulation can induce thermal stress, which may culminate in what appears to be a case of sudden infant death syndrome (14, 16, 24). The risk of thermal stress may be also enhanced by the prone position (7, 14, 16, 24), which could reduce heat losses from the body in general and the head in particular.

In newborns, the head is an important vector for heat exchange with the environment (2, 13, 20). This region accounts for a quarter of the total skin surface area, and the newborn brain is responsible for 44% of total metabolic heat production. Heat flux from the head is related to metabolic heat production and/or to cerebral blood flow. Hats decrease body heat loss in the naked newborn exposed to an air temperature of 30°C in an incubator (17). Covering the vault of the skull with a hat reduced oxygen consumption by 14.5% in prone, naked newborns exposed to an air temperature of 27°C, whereas body dry heat loss decreased by 23% (20). Similar findings have been reported by Marks et al. (13), who found that for clothed, healthy newborns wearing a head wrap and exposed at 25°C, dry heat losses from the head decreased by 12.1%.

Using a mathematical model of thermal balance, Nelson et al. (14) assumed that the face was the main route for heat loss when thick clothing and bedding were used. Their model suggested that hyperthermia may be related to sleeping position. In sleeping newborn piglets covered by bedclothes, Galland et al. (10) found that rectal temperature rose rapidly when thick bedding materials overlaid the head for 2 h. These authors hypothesized that body hyperthermia may be enhanced when the prone, human newborn sleeps under bedclothes.

In a previous study (6), we showed that there was no association between body position (supine vs. prone) and body overheating in a naked or heavily clothed mannequin with the head uncovered. However, in the prone position, a possible effect of body overheating due to impairment of heat loss from the covered head cannot be ruled out. This scenario has been suggested by Tuffnell et al. (24), who hypothesized that supine and lateral sleepers lose more heat from the head than prone-sleeping newborns.

In light of the head's large skin surface area, it is not surprising that covering the head hinders heat loss, although its importance as a heat exchanger with respect to the prone and the supine positions remains unclear.

The present study was designed to assess whether dry heat loss from the head differs between supine and prone positions and whether this difference could predispose infants to thermal stress when they are heavily clothed, with the head covered. To test this hypothesis, a mannequin corresponding to a small-for-gestational-
age newborn was used to simulate the dry heat exchanges between the body surface and the environment. Because many supine newborns usually sleep with their head to the side, the experiments were performed with the face directed either to the side or straight up. The thermal consequences of head turning were thus evaluated, because an increase in skin surface area contacting the mattress in the prone, “face to the side” position could decrease heat loss from the head.

METHODS

The anthropomorphic, thermal mannequin represents a small-for-gestational-age newborn (with a body surface area of 0.150 m² and a simulated birth weight of 1,400 g). This model was used because the large skin surface-to-volume ratio and the sharp curvatures of the body areas promote body heat loss to the environment. Small-for-gestational-age newborns are thus at greater risk of heat stress than term newborns. The mannequin was cast in copper and painted matte black, giving a surface emissivity of ~0.95. To take into account the thermal heterogeneity of the body, individual resistance wires heated each segment of the mannequin to a given set-point temperature, which was reached within 45 min (3, 6). The temperatures at various points on the mannequin’s outer surface were recorded by attached thermistors (Yellow Springs Instruments, series 409A, accuracy ±0.10°C). Each probe was protected from radiant energy by an aluminum foil patch. Eight thermistors were located on the head, six on the trunk, and two on each of the upper and lower limbs.

The closed-loop regulation was based on a simple model of a proportional integral and derivative (PID) regulator. Comparison of measured temperature with the set point of each body section generates an error signal, which fed to the PID controller for activation of a heating resistance.

To strictly control ambient conditions, the mannequin was placed in a single-walled, convectively heated incubator used for intensive care (BioMS C 2750, Toulouse, France). The mannequin lay on a hard mattress made of plastic foam; the mattress was covered with two cotton blankets (total thickness: 5 cm; thermal conductivity: 0.21 W/C°). The incubator air temperature was measured at a point located 10 cm above the center of the mattress, as recommended by relevant standards (American National Standards). The velocity of air circulating in the incubator compartment was recorded by use of a hot-globe anemometer (Testo 490) and set to 0.5 m/s. At thermal equilibrium, the electric power (P) supplied to the mannequin (expressed in W) balances the dry heat exchange by conduction (K), convection (C), and radiation (R) from the mannequin’s surface to the environment

\[ P = \pm K + C \pm R \]

The heat exchanges depend on the temperature of the mannequin’s surface (Tₐ) and that of the mattress (Tₐₐ), the radiant (Tᵣ), and the air (Tₐₐ) and can be formulated as follows

\[ K = hₐ(Tₐₐ - Tₐ) \quad C = hₐ(Tₐₐ - Tₐ) \quad R = hᵣ(Tᵣ - Tₐ) \]

where \( hₐ \), \( hₐₐ \), and \( hᵣ \) are the conductive, convective, and radiant heat transfer coefficients, respectively.

Experiments. Four experimental sessions were performed at incubator temperatures of 29, 32, 34, and 36°C. The mannequin was laid in one of three positions on the mattress: supine, face straight up (FSU); supine, face to the side (FTS); or prone, FTS. The surface area of the head in contact with the mattress was 9.2 \( \times 10^{-3} \) m² for supine FSU, 14.2 \( \times 10^{-3} \) m² for supine FTS, and 16.9 \( \times 10^{-3} \) m² for the prone position. In the supine FTS position, the nose and mouth could be seen and the head was turned 120° from the vertical (Fig. 1). 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). Experiments were performed on the clothed mannequin with or without its head covered with a bonnet (100% acrylic). The bonnet was chosen to cover a large portion of the head (85.5% of the surface area) without encroaching on the face, and so as to keep the bonnet firmly in place between the different experimental sessions. The bonnet was made of elastic material and hence molded itself to the shape of the head. Thus thermal insulation from clothing and bedding did not differ between the two body positions. With the bonnet, heat loss from the head was limited to the face. Regardless of the experimental conditions, the mean surface temperature (calculated from the set of local surface temperatures, weighted according to the relative surface area of each segment) was 36.97 ± 0.22°C (maximal value 36.40 ± 0.33°C; minimal value 35.83 ± 0.02°C), whereas the head surface temperature was 36.23 ± 0.04°C (maximal value 36.26 ± 0.02°C; minimal value 36.17 ± 0.01°C). For the rest of the body, the mean local surface temperatures were 36.47 ± 0.07°C for the trunk, 35.55 ± 0.45°C for the right arm, 35.62 ± 0.38°C for the left arm, 35.85 ± 0.42°C for the right leg, and 35.83 ± 0.43°C for the left leg. These values correspond to those currently recorded for clothed newborns nursed in the Pediatric Unit of the Amiens University Medical Center.

To ensure that a thermal steady state was reached, at least 60 min elapsed before recordings began. At least five measurements were made for each set of conditions.

Statistical analysis. The effect of air temperature, body position (supine FSU, supine FTS, and prone position) and head insulation (with or without a bonnet) on overall heat losses in general (and those from the head in particular) were tested by three-way ANOVA. When overall F-values were significant, the differences between the sets of experimental conditions were computed by using Student’s t-test. F- and t-values are given with their corresponding degrees of freedom (subscripts beneath F- and t-values). The level of significance was 0.05. Values are given as means ± 1 SD.

RESULTS

Statistical analyses showed that posture did not affect the overall surface temperature of the mannequin (supine FSU: 36.08 ± 0.25°C; supine FTS: 36.10 ± 0.23°C; prone position: 36.06 ± 0.19°C) or that of the head surface (supine FSU: 36.23 ± 0.03°C; supine FTS: 36.22 ± 0.05°C; prone position: 36.24 ± 0.04°C). For the temperature range experiments (29, 32, 34, and 36°C set points), the air temperatures actually measured were 29.25 ± 0.44, 31.80 ± 0.32, 33.59 ± 0.37, and 35.74 ± 0.54°C, respectively.

Figure 2 shows the total and local dry heat losses plotted against air temperature for the clothed mannequin, with or without its head covered with a bonnet. As expected under all experimental conditions, the total heat loss from the mannequin was reduced by increased air temperature (\( F_{3.96} = 900.51; P < 0.001 \)) and by the bonnet (\( F_{1.96} = 213.52; P < 0.001 \)). Under the bonneted experimental conditions, total heat loss was 0.40 W lower in the prone FTS position compared
with the supine FSU position ($t_{38} = 2.04; P = 0.043$). In the supine position, turning the head from the FSU to the FTS position reduced heat loss by a similar magnitude ($t_{38} = 2.05; P = 0.042$). Using the equation of body heat storage, $\Delta S = 0.835 \times \Delta T_b \times m_b$ ($\Delta S =$ change in body heat storage in W; $m_b =$ body mass, in kg; $0.835 =$ the specific thermal capacity of body tissues, in kcal·kg$^{-1}$·°C$^{-1}$; $\Delta T_b =$ mean body temperature change, in °C/h) for a newborn weighing 1,400 g, such a decrease in total dry heat loss (−0.40 W or −0.34 kcal/h) would induce an increase in mean body temperature ($\Delta T_b =$ of 0.29 ± 0.21°C/h) due to the change in body position and of 0.29 ± 0.35°C/h on turning the head to the side in the supine position. These effects were not found under bonnetless experimental conditions.

Local heat loss from the head was inversely related to air temperature ($F_{3,96} = 397.04; P < 0.001$) and was reduced by the bonnet (−15.3%; $F_{3,96} = 454.75; P < 0.001$). When the head was covered with the bonnet, local heat loss was lower in the prone position than in the supine FSU position (0.34 W, $t_{38} = 7.14; P < 0.001$; $\Delta T_b = 0.26 \pm 0.21^\circ$C/h). In the supine position, local heat loss was lower in FTS than in FSU trials (0.35 W, $t_{38} = 7.41; P = 0.001$; $\Delta T_b = 0.26 \pm 0.17^\circ$C/h). These decreases did not significantly differ ($P = 0.460$) from those found for total heat loss, i.e., measured from the mannequin as a whole (0.40 W). When the head was uncovered, there was no significant effect of body or head position on local dry heat loss.

The thermal effect of body or head position is particularly relevant at air temperatures of 29 and 32°C. At air temperature of 36°C, the heat supplied to the mannequin as a whole was entirely dissipated from the uncovered surface area of the face.

**DISCUSSION**

The present results, obtained from a nonliving model, cannot be compared directly to infant data, because the model cannot simulate adaptive thermoregulatory responses to a thermal challenge, i.e.,...
For the nude and clothed mannequin with the head uncovered, overall dry heat loss does not differ between the prone and the supine positions, thus confirming previous findings (6). Thermal effects of body or head position are only found in bonneted experiments. Covering the head with a bonnet reduces local dry heat loss by 15.3\%, a value which is comparable to that recorded by Marks et al. (13), who found that, in healthy newborns exposed at 25°C, dry heat loss from the head is decreased by 12.1\% with the head wrap in place. The total dry heat loss decreases significantly by 0.40 W as a function of head or body position and is mainly explained by changes in local heat loss from the head (0.35 W). For a newborn weighing 1,400 g, such a heat loss reduction could induce an increase of mean body temperature of 0.29°C/h. Thus small changes in the head surface area (from FSU to FTS) exposed to the air may decrease body dry heat loss, thus leading to a rise in body temperature.

The present results show that under nonextreme thermal loads, thermal stress related to the prone position can be avoided if the entire head and neck remain exposed to the environment. Jardine and Haschke (12) also found (using piglet experiments) that if the head was uncovered, the animal was able to lose enough heat to avoid hyperthermia compared with experimental conditions under which the body and head were completely covered with blankets. Similarly, Anderson et al. (2) reported that heavily clothed, sleeping newborns lost sufficient heat through the head (and occasionally the hands) to maintain normal patterns of abdominal skin and rectal temperatures. As reported by several authors (2, 13, 14, 20), the head is an important route for heat dissipation in newborns. It is obvious that the mattress is a factor that contributes to head heating, partly by insulating the exposed surface available for heat loss (by contact between the face and the mattress), and partly by reducing air exchange around the face.

In heavily clothed newborns with a large portion of the head covered, the contribution of local head dissipation increases with rising air temperature. At an air temperature of 36°C, almost 100\% of the heating power supplied to the mannequin as a whole is dissipated via the face; the heat losses to the environment are strongly impaired over the rest of the mannequin, both by clothing insulation and by a decreased difference between the air temperatures and that of mannequin’s surface, which reduces the convective and radiative heat losses.

The present data emphasize that more attention should be paid to the role of the head in heat dissipation mechanisms, especially in heavily dressed newborns, because when heat cannot be easily eliminated from the body, brain overheating can occur. Under bonneted conditions, our results show that local and overall heat losses depend on head position, which could be a thermoregulatory behavioral component occurring in newborns sleeping supine. Turning the head from the FTS to the FSU position increases the head skin surface area available for heat exchange with the

changes in metabolic heat production, vasomotor tone, and evaporative water losses via the skin and respiration, and changes in behavior. Consequently, the present data only deal with the newborn’s ability to lose heat by conduction, convection, and radiation in thermal steady states. Moreover, our model cannot take into account changes in the newborn’s capability to regulate its body temperature (and heat dissipation) during the different sleep stages (5). However, it should be noted that, in clothed newborns, humidity increases over time in the microclimate formed underneath bedclothes, thus decreasing evaporative water loss and creating an environment that is an ineffective means of body cooling. Using a mannequin also avoids the high interinfant variability in terms of thermal response, which can mask minor differences in exchanges of body heat with the environment. Moreover, the model allows one to assess the effect of body position, which is difficult with human subjects: for obvious ethical reasons, placing infants in the prone position is currently discouraged (1), as is exposing them to thermal environments that are outside the thermoneutral range.
environment but would only be efficient in older newborns, able to increase their muscular activity so as to spontaneously turn their head into the FSU position. This thermoregulatory behavioral component could also explain the observation that the risk of thermal stress increases in prone sleepers, because in this position it is difficult to turn the head: the face surface area in contact with the insulating mattress is higher, reducing body heat loss. In heavily clothed newborns, i.e., when insulating material limits heat loss to the face, increased body heat storage associated with the reduction of heat loss from the head could overheat the body. Such a process could be exacerbated by various illnesses that by various routes also lead to elevated body temperature and thus shorten the time to attain lethal hyperthermia. Additional factors such as infection, dehydration (21), or malformations of the central nervous system (8) can induce an upward resetting of the hypothalamic threshold temperature for sweating, which thus impairs evaporative skin cooling and/or restriction of dry heat loss through vasoconstriction. A rapid increase in brain temperature might trigger vasally mediated cerebral ischemia as suggested by Sunderland and Emery (22) and could be at the origin of febrile convulsions (19). Hemorrhage shock andencephalopathy could also be associated with brain hyperthermia (18, 23). Other possibilities are related to depressed levels of consciousness (9) and localized damage to the respiratory center (11), which could trigger transient chemoreception dysfunction, respiratory instability, or an increase in the incidence and duration of apnea. It is difficult to draw firm conclusions concerning these events, because the degree and duration of thermal stress required to produce brain overheating have not been assessed.

In conclusion, the present data emphasize that dry heat loss from the mannequin as a whole and from the face in particular is reduced when the clothed thermal mannequin is placed in the prone position with the head covered. In the supine position, thermal consequences mainly depend on the head position (FSU or FTS). Turning the head could be an adaptive thermal response of the newborn confronted with a thermal challenge. The data underline the importance of the face in dry heat loss regulation and show that body position can influence thermal stress but only when the head is covered.

We are greatly indebted to the Regional Council of Picardy and the French Ministry of Research and Technology for financial support of this work.

REFERENCES