Thermoregulation and Environmental Influences on Energy Expenditure of the Low Birthweight Infant

Eric Jéquier

Facility of Medicine, Institute of Physiology, University of Lausanne, 1005 Lausanne, Switzerland

At the moment of birth, the newborn infant is abruptly exposed to the thermal environment of the delivery room and the body temperature immediately begins to fall. There is a rapid cooling of the skin, and with the first deep breaths, the internal temperature of the infant decreases. The fast cooling after birth is due to a sudden increase in heat losses with a lack of sufficient thermogenic response, the heat production being lower than the total heat losses. The cooling of the newborn is particularly efficient because of the high surface area/body mass ratio, 50% to 80% of the body surface being exposed to the environment, depending on the baby's posture (1). There are two additional reasons for the rapid fall of the body temperature at birth: first, the wet skin enhances heat losses by evaporation, an extremely efficient process to remove heat from the body; and second, the thermal insulation due to the skin and underlying tissues is very small, due to the minimal amount of subcutaneous adipose tissue.

The low birthweight infant is more prone to thermal instability and hypothermia than the full-term infant because of a higher surface area/body mass ratio, a thinner layer of subcutaneous adipose tissue, and an increased risk of developing birth asphyxia. It is well known that preterm infants who are exposed to a cool environment and suffer from excessive cooling have higher mortality than infants of similar birthweight and gestation whose internal temperature is maintained in a more physiological range (2). Thus the prevention of hypothermia is a major concern in the nursing of low birthweight infants.

Recent advances in neonatology have permitted the long-term survival of infants weighing 700 to 800 g, which corresponds to a gestational age of about 24 weeks. It is particularly important to understand the four physical avenues of heat transfer affecting the thermal equilibrium of these tiny infants, since hypothermia represents a life-threatening risk.
THE FOUR AVENUES OF HEAT LOSS

There are four modes of heat loss to the environment: conduction, radiation, convection, and evaporation.

Conduction of heat occurs between the infant's skin and the mattress on which the infant rests. Conductive heat losses are usually very small because the mattress is a good insulator and therefore the temperature gradient between the skin and the mattress is negligible. Since conductive heat losses are proportional to this temperature gradient, this quantity of heat loss may be usually neglected.

Heat losses by radiation \((R)\) are due to the emission of infrared radiation. A simplified equation to compute \(R\) is the following one:

\[
R = h_r(T_{sk} - T_{ob})A_r
\]  

where \(h_r\) is the heat transfer coefficient by radiation, with a value of about 5 W·m\(^{-2}\)·°C\(^{-1}\); \(T_{sk}\) is the mean skin temperature; \(T_{ob}\) is the temperature of the surrounding objects, or of the walls of the incubator; and \(A_r\) is the body surface that exchanges radiant energy with the environment; it is dependent of the posture of the infant.

In practical terms, \(R\) mainly depends on the temperature of the walls on the inside of the incubator. This temperature has an intermediate value between the air temperature inside the incubator and the cooler external temperature of the room. It is important to understand that the incubator air temperature, which is usually measured and monitored, does not represent the temperature of the inner wall of the incubator, the latter being the main determinant of the radiant heat losses. In single-walled incubators, wall temperature is typically 2° to 4°C lower than air temperature.

Heat losses by convection \((C)\) can be estimated from a simplified formula:

\[
C = h_c(T_{sk} - T_a)A_c
\]  

where \(h_c\) is the heat transfer coefficient by convection, \(T_a\) is the air temperature inside the incubator, and \(A_c\) is the body surface that exchanges convective energy with the environment. The value of \(h_c\) depends on air velocity and is about 4 to 6 W·m\(^{-2}\)·°C\(^{-1}\) under the usual nursing conditions of a preterm newborn in an incubator.

Heat losses by evaporation \((E)\) include insensible evaporation of water from the skin surface and evaporation of water through respiration.

The driving force for heat exchange by evaporation is the water vapor pressure gradient from the surface (skin, or alveoli in the lungs) to the ambient air. The equation for computing \(E\) is as follows:

\[
E = h_e(P_{ws} - P_{wa}) \times A_w
\]  

where \(h_e\) is the evaporative heat transfer coefficient (W·m\(^{-2}\)·mmHg\(^{-1}\)), \(P_{ws}\) is the water vapor pressure of the surface (skin or alveoli), \(P_{wa}\) is the water vapor pressure of the ambient air, and \(A_w\) is the area of skin (or of alveoli) covered with water (wetted area).

The above equation shows that the cutaneous heat loss by evaporation is proportional to the water vapor pressure gradient between the skin and the ambient air.
Therefore, the choice of an adequate water vapor pressure in the air inside the incubator is important to limit evaporative heat loss in low birthweight infants. Most incubators have the facility to raise the relative air humidity to as high as 95%. It is, however, the absolute value of the water vapor pressure of the ambient air that determines the rate of evaporative heat loss, and not the relative humidity per se.

The relative contribution of the four modes of heat loss depends upon the difference in temperature between the infant's mean skin temperature and the environment, the velocity of airflow, the water vapor pressure of the ambient air, and the exposed surface area for heat exchange. Under thermoneutral conditions, heat losses occur mainly by radiation and convection in infants weighing more than 1000 g, but evaporative heat loss can exceed all other modes of heat loss in infants weighing 700 to 800 g (3).

**OPTIMAL THERMAL ENVIRONMENT**

The optimal thermal environment for low birthweight infants is usually considered to be the "thermoneutral zone," which is defined as "the range of ambient temperature within which metabolic rate is at a minimum and within which temperature regulation is achieved by non-evaporative physical processes alone" (4). The non-evaporative physical processes are those autonomic and behavioral responses (such as peripheral vasoconstriction and changing posture) that modify the thermal conductance between the organism and the environment.

An important practical question is the fact that the neutral thermal environment cannot be defined in terms of ambient temperature alone, since air velocity, the temperature of the inner walls of the incubator, and the air humidity are factors that affect the infant's heat losses. Ideally, it would be of interest to measure the temperature gradients between the infant's skin and the incubator environment (both ambient air temperature and the inner wall temperature of the incubator should be considered, since this would allow control of heat losses by convection and radiation, the two main modes of heat loss in most infants). In the clinical setting, however, it is impractical to measure these three temperatures and to calculate heat losses. In practice, this approach can be simplified by measuring the infant's skin temperature and the air temperature inside the incubator. The thermoneutral zone has been determined experimentally mainly by taking into account the air temperature of the incubator; the latter varies with the conditions of air humidity and the infant's body weight and postnatal age (5–8).

**THE LIMITATION OF HEAT LOSSES BY RADIATION AND CONVECTION**

The external temperature gradient ($ETG$) is defined as the gradient of temperature between skin temperature ($T_s$) and ambient temperature ($T_a$):

$$ETG = T_s - T_a$$  \[4\]

In healthy term newborns, there is a linear relationship between heat losses by
radiation and convection and external temperature gradient (Fig. 1), whereas evaporative heat loss is much less affected between values of 1° and 5°C (9). The figure clearly shows the quantitative importance of the external temperature gradient on heat losses in newborns at term. In preterm newborns of less than 1500 g, the gradient is kept near to 1°C to minimize heat losses by radiation and convection, since evaporative heat losses are important in these tiny infants.

The clinical interest in measuring skin temperature in low birthweight infants stems from the fact that the skin temperature is correlated with metabolic rate in the infants nursed in incubators (10,11). The skin temperature that corresponds to the thermoneutral zone has been shown to range between 36° and 36.5°C for very low birthweight infants, but it decreases with age and is dependent upon body weight and skin insulation.

Incubators for low birthweight infants are used with either manual control of air temperature, or with servo-control of air temperature or skin temperature. All three procedures are capable of providing an adequate thermoneutral environment (12) with similar skin temperatures, rectal temperatures, and metabolic rate. Although the skin temperature servo-control system appears to be optimal, careful monitoring of the infant is still very important because the infant can be overheated if the skin probe becomes detached.

THE LIMITATION OF HEAT LOSSES BY EVAPORATION

Equation 3 shows that heat loss by evaporation depends on the gradient of water vapor pressures between the skin (or the alveoli in the lungs) and that of ambient
air. It is therefore of interest to know whether the metabolic rate of infants can be influenced by increasing the humidity of the air inside the incubator. Our study (13) showed that in full-term healthy infants nursed at a thermoneutral air temperature, increasing the relative humidity from 20% to 50% resulted in a decrease in total heat loss and metabolic rate, whereas a further rise in relative humidity to 80% had no influence on heat loss but caused an increase in metabolic rate. These results and those of Miller et al. (14) show that a relative humidity around 50% can be considered as neutral for full-term newborn infants on the first day of life. A relative humidity lower than 50% results in increased evaporative and total heat losses that cause a rise in metabolic rate. At 80% relative humidity and above, a rise in internal temperature and increased respiratory work due to a higher respiratory rate may account for the slight stimulation of metabolic rate.

In very low birthweight infants, with their high evaporative losses, the relative humidity in the incubator should in theory be kept high to limit total heat loss, but there is no clear evidence that increasing the humidity within an incubator reduces the infant’s metabolic rate. Sauer et al. (15) reported that in low birthweight infants a rise of relative humidity from 38% to 59% at an ambient temperature of 35°C resulted in a decrease of evaporative heat loss by 40%, but, neither metabolic rate nor body temperature showed a significant difference between the two levels of humidity. Most studies (13,15,16) support the concept that increasing the humidity within an incubator reduces insensible water loss at any environmental temperature, but it reduces metabolic rate only if infants are nursed at an ambient temperature slightly lower than that of the thermoneutral zone.

The use of high humidity to reduce the metabolic rate of infants may not be an appropriate procedure when using a skin temperature servo-control incubator since a decrease in evaporative heat loss due to higher humidity might be accompanied by a regulated decrease in the air temperature of the incubator; as a consequence, the non-evaporative heat loss increases to maintain a constant skin temperature, with no reduction in the infant’s metabolic rate. In addition, high humidity may also lead to overheating of the infant if the environmental temperature is not adequately adjusted (17).

**DEVICES USED TO REDUCE HEAT LOSS FROM THE INFANT**

Different devices are used to limit heat losses of very low birthweight infants nursed in incubators. A thermoplastic polymer heat shield placed over the infant reduces insensible water loss and radiant plus convective heat losses of low birthweight infants. Infants nursed in a subthermoneutral environment showed a decrease in metabolic rate when heat shields were used (18), but the efficacy of heat shields has not been proven when the infant’s skin temperature is maintained by servo-control (19).

The development of double-walled incubators is an interesting approach: the inner wall temperature of the incubator is maintained at a set level by warm air on both sides of the wall. Thus the heat loss from the infant by radiation is reduced and can be precisely controlled. The advantage of the double-walled incubator compared to
the single-walled incubator is, however, not obvious when the latter procedure is used with a servo-control mechanism to monitor skin temperature (20).

Radiant warmers are devices such as a plastic hemicylindrical canopy containing a radiant heat source that facilitates obtaining a positive heat gain by radiation of the infant (21). However, these devices increase convective and evaporative heat losses; they may be used with caution to warm infants during resuscitation in the delivery room, but their usefulness appears to be limited. Another device is a thin polyethylene blanket covering the infant, which results in a decrease in evaporative heat loss from the skin and may contribute to a decrease in the infant’s oxygen consumption (22).

In practice, it is important to monitor skin temperature carefully in low birthweight infants and to adjust the environmental temperature and humidity inside the incubator to maintain a stable and physiological skin temperature. This goal can be achieved by using various types of equipment, and the experience of the pediatricians and the nurses in charge of the infants is more important than the type of equipment used.

CONCLUSION

Low birthweight infants have a limited capacity to maintain their body temperature when nursed in a subthermoneutral environment. However, they display an attempt at homeothermy by increasing their metabolic rate under these conditions, probably through activation of brown adipose tissue (23,24), though the lipid supply and the recruitment of brown adipose tissue is not sufficiently developed in low birthweight infants to allow more than a limited thermogenic response. Therefore both the larger body surface/body mass ratio of low birthweight infants, which favors heat loss, and the limited capacity of non-shivering thermogenesis place them at increased risk of hypothermia. It is not well understood why low body temperature increases mortality in low birthweight infants; depletion of body energy stores due to a prolonged elevation of metabolic rate, even if the latter is modest, may be an explanation. It is therefore important that the clinician understands the processes whereby low birthweight infants attempt to regulate their body temperature in order to provide them with the most suitable thermal environment.

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DISCUSSION

Dr. Vonderweid: Your presentation was very interesting but I feel that it may not apply
to the majority of low birthweight babies in the world. We need to realize that the majority
of such babies worldwide are not nursed in incubators or under radiant warmers, because
they are born in countries where such equipment is unaffordable. It would be helpful to
discuss alternative methods of warming and nursing low birthweight infants such as, for
example, the "kangaroo" method of simply wrapping the baby at the mother's breast, or
the use of heated mattresses, or other methods that may be applicable to managing such
infants in developing countries.

Dr. Jéquier: Obviously I could not deal with everything in 20 minutes. It is true that
the so-called kangaroo method, where the mother has her child at the breast wrapped in
a microenvironment, is claimed to be an efficient way of maintaining body temperature in
the infant, though I don't think it has been properly studied. You mentioned heated mattresses.
This could be a cheap alternative for caring for low birthweight infants, but great care must
be taken not to overheat the mattress and thereby have a net gain in heat by conduction.
About 38°C should be sufficient.
Dr. Verellen: You showed us that in an incubator radiation is the major route of heat loss. We also saw that under the radiant heater, convection and evaporation are the major routes. If you consider the skin-to-skin "kangaroo" method, you might perhaps imagine that conduction would be the major route of heat transfer and, as the mother's skin is likely to be cooler than the infant's, that there would be a net transfer from the infant to the mother.

Dr. Jéquier: When a mother has her baby next to her in skin-to-skin contact don't forget that both are producing heat and that, depending on the area of contact, evaporational and radiant losses from the baby will be reduced. It is unlikely that the baby's skin temperature will be significantly above the mother's to allow conduction to be a major source of heat loss from the baby.

Dr. Verellen: But do you think conduction plays an important role in this situation?

Dr. Jéquier: Conduction may play a role in this situation, but even if there is some degree of heat transfer from baby to mother by this route, the heat loss will still be much less than would occur by other routes, if the baby was lying free.

Dr. Sedaghatian: You showed how as the age of a preterm infant increases the neutral temperature falls. If the infant is nursed in an incubator, does the difference between skin temperature and core temperature become wider with age? In other words should the skin temperature be set at a lower value?

Dr. Jéquier: The so-called set point of 36.5°C is the recommended skin temperature for tiny babies in incubators. It is an interesting point as to whether this temperature should be set somewhat lower after a few days. It could be that a slight stimulation of metabolic rate due to the ambient temperature being slightly below neutral might be a desirable stimulus for heat production. I personally feel that it is wise to decrease the so-called set point temperature after 1 or 2 weeks.

Dr. Evrard: We are convinced that the use of blankets is important. Have you any advice as to when they can be discontinued? Is this a question of postnatal age or of postconceptional age?

Dr. Jéquier: I think it has been shown that the use of thermal blankets decreases heat loss by evaporation. If evaporative heat loss cannot be maintained in any other way, for example by adjusting the humidity inside an incubator, then it is wise to continue to use the blanket. However, I am against giving too much definite advice. I don't think we have any idea about how long we should continue to use them. A pediatrician could answer this better than I can.

Dr. Orzalesi: It will depend to a certain extent on the gestational age and weight of the baby, but the characteristics of the skin change very rapidly and I think the period during which the use of blankets is really important is the first 4 or 5 days after birth. However, it seems to me that it might be best to put the baby in a plastic bag rather than under a blanket. It is worth remembering also that the head forms a very substantial portion of the surface area, so maybe more attention should be paid to reducing heat loss from the head. A final point is in relation to the environment. Radiant losses are proportional to the temperature of the environment so it is very important to maintain adequate temperatures in resuscitation areas, transport ambulances, and so on.

Dr. Singh: When babies are cold there is an increased energy demand. Can you tell us how great the increase is likely to be? How much extra nutrition should we allow for a baby nursed in a cool environment?

Dr. Jéquier: There are no recent studies on the effects of cold in tiny infants and it is now ethically not possible to do such studies. We do know, however, that very preterm infants, especially those below 1000 g, have a limited capacity to increase their oxygen consumption
in response to cold. Such babies should as far as possible be kept in a thermoneutral environment.

Dr. Singh: Should premature babies be clothed when nursed under the open-field system or must they be naked under the radiant heater?

Dr. Jequier: Clothes are of course not normally used because they impede observation of the baby. However, they are an efficient form of thermal insulation and I sometimes wonder why they are not used more.

Dr. Putet: I should like to underline the unphysiological nature of radiant heated open-field nursing. There is a large positive gain in heat by radiation through the skin facing the warmer, and considerable losses of heat by radiation from the sides of the body. Hence the skin facing the warmer is usually hotter than recommended and the skin on the baby’s sides is usually colder than recommended.