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Determining temperature ratings for children's sleeping bags

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A B S T R A C T

Manufacturers label their sleeping bags with a temperature rating to assist consumers in selecting a bag that will provide them with an acceptable level of thermal protection under the expected conditions of use. These temperature ratings are typically based on thermal manikin testing and whole-body heat loss models. Due to physical and physiological differences between children and adults, existing adult sleeping bag temperature rating models cannot be applied to children's bags. Therefore, a model for determining the temperature ratings of children's sleeping bags is proposed. Issues related to measuring the thermal insulation of children's sleeping bags are also discussed. The results of the model indicate that an older child has a higher temperature rating than a younger child for the same level of insulation. This is due to the higher sleeping metabolic rate of younger children.

1. Introduction

Manufacturers label their adult sleeping bags with a temperature rating to help consumers select a bag that will provide them with an acceptable level of thermal protection under the expected conditions of use. These temperature ratings are normally determined by first using a thermal manikin to measure the insulation provided by the sleeping bag when used with auxiliary products (e.g., pad, clothing). The measured insulation value is then used in a whole-body heat loss model to predict the environmental temperature for comfort. Several adult temperature rating models for sleeping bags have been developed and validated (Huang, 2008; McCullough et al., 2005) including the models used in EN 13537, Requirements for Sleeping Bags (2012). However, due to physical and physiological differences between children and adults the existing adult temperature rating models cannot be applied to children's bags.

1.1. Purpose

A body heat loss model based on the physiology of children has already been developed for clothing (McCullough et al., 2009). The purpose of this paper is to modify this model for children's sleeping bags. This is a difficult task because children grow rapidly – changing in physical size and physiology until they reach adulthood. The size of the child's sleeping bag stays the same, so the fit of the child in the bag will vary over time as well. This paper attempts to address some of these issues.

2. Sleeping bag overview

Sleeping bags are used to provide thermal protection for people sleeping outdoors or in a cabin or tent. In addition, children's sleeping bags are used for indoor “slumber parties” and for backyard camping in mild weather. Styles of sleeping bags include mummy, barrel, semi-rectangular, and rectangular. Mummy styles have a hood, but the other styles often do not. The children's market is dominated by lightly insulated rectangular sleeping bags which are often decorated (e.g., with licensed characters, bright colors, etc.) to make them attractive to children. Bags are produced for the adult market in sizes for both men and women. Children's bags are designed to fit the smaller stature of children, and are commonly designated with terms such as “kid”, “youth”, “junior”, “girls”, or “boys”. The product description usually includes an appropriate age range or a maximum height of the child that will fit the bag. The maximum height for a child-size sleeping bag is typically between 54 inches (1.4 m) and 66 inches (1.7 m). Children's bags are also available in other sizes to target specific markets (e.g., preschool age), although these are less common.

3. Methodology for determining insulation

To determine a temperature rating, the insulation provided by

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the sleeping bag system is first measured using a thermal manikin. For adult sleeping bags, the thermal insulation is measured by testing the bag on an adult-size manikin according to ASTM F 1720 (2016) or EN 13537 (2012). EN 13537 (2012) includes temperature predictions based on adult physiology and explicitly states that it is not applicable to children. Thus, ASTM F 1720 (2016) is the only applicable standard. It specifies the use of a thermal manikin formed in the shape and size of an adult male or female, so modifications to the test method need to be made to test the smaller children's bags. These modifications and associated issues are discussed in section 3.1. Because the insulation value will be used to predict a temperature rating, the sleeping bag should also be tested with appropriate auxiliary products (see section 3.2).

3.1. Manikin size issues

There are two possible approaches to modify the ASTM F 1720 (2016) test method: 1) test the bag on a child-size manikin, or 2) scale the bag to fit an adult-size manikin. Although the thermal manikin testing of clothing and sleeping bags has become widespread over the past several decades, child-size manikins are extremely rare. Thermetrics, a major manufacturer of manikins in the United States, has produced a "size 10" child manikin for AITEX in Spain. They have also produced a smaller "size 8" child manikin for the Institute for Environmental Research at Kansas State University.

Under static manikin testing conditions where there is no body movement, loose garments generally provide more insulation than tight garments due to gaps of still air between the body and garment layers (Chen et al., 2004; Li et al., 2013; McCullough, 1993). Thus, if a bag is too loose or tight fitting on a thermal manikin (i.e., the "wrong size" on the manikin), the results may over- or underestimate the thermal insulation as compared to a bag that fits properly. To avoid these fit issues, if a child-size manikin was not available then a bag style would have to be scaled up to fit an adult-size manikin. Likewise, if a small child bag was to be tested on a large child manikin (or vice versa), the bag would have to be scaled to fit the manikin. This would not be an easy task. The design, materials, and proportions of the bag would have to stay the same as the actual product for sale. The thermal resistance of the external air layer may also be affected by changes in the outer surface area-to-volume ratio of the scaled up sleeping bag and changes to the length of the bag. In addition, the insulation of the sleeping bag itself may be affected by changes in the bag construction when scaling it to fit an adult-size manikin. Even if children's bags are tested on a child-size manikin the fit is going to vary across styles of bags. This is because the sizes are not consistent from manufacturer to manufacturer. This is not a problem with clothing which is produced in numerous sizes (i.e., the proper fit can be achieved).

There are no published studies on the heat transfer implications of scaling children's sleeping bags to fit adult-size manikins. Kuklane et al. (2004) examined the effect of manikin body size by comparing two baby manikins to an adult manikin. For undressed conditions, external air layer insulation measurements were similar for all manikins when contact with surrounding surfaces was minimized. They also placed the nude manikins on an insulating surface, but these results were affected by the fact that the baby manikins had rigid body parts that prevented the arms and legs from touching the surface, whereas the adult manikin had arms and legs in contact with the surface. Kuklane et al. (2004) concluded that there were no significant differences between manikins of different sizes for undressed conditions. A comparison of clothed manikins of different sizes was not included in the study. Fukazawa et al. (2009) compared the convective heat transfer coefficients for an adult female shaped thermal manikin and a 6 month-old size baby shaped thermal manikin that were in a standing posture and facing the air stream. Both manikins were unclothed, but the adult female manikin wore a wig whereas the baby was bald. The convective heat transfer coefficient of the whole body was found to be about 1.6 times greater for the baby as compared to the adult.

Measuring insulation of sleeping bag systems on a thermal manikin should yield accurate and repeatable results. Further research is needed to determine the effects of testing one size of bag on assorted sizes of manikins, as well as scaling bags to fit different sizes of manikins. Due to these sizing issues, children's bags should be tested on a child-size manikin, and the height of the manikin should be within the height range given by the manufacturer in the product literature.

3.2. Auxiliary products

According to ASTM F1720 (2016), thermal manikin tests may be conducted on a sleeping bag by itself (option #1) or in combination with auxiliary products (option #2). Because the insulation value is being used to determine a temperature rating, it is recommended that the sleeping bag be tested with auxiliary products such as clothing and a ground pad. This is more representative of actual use conditions. For example, EN 13537 (2012) specifies that thermal underwear, socks, and a ground pad are used with the sleeping bag during the manikin test. Environmental conditions vary widely from winter to summer and from outdoor to indoor use, and one set of garments may not be a logical solution for all conditions. For instance, if a children's bag is designed for "slumber party" use, lightweight sleepwear may be more appropriate than thermal underwear. The intended end use of the sleeping bag should be taken into consideration when selecting auxiliary products.

4. Heat transfer model for determining the temperature rating

After the thermal insulation of a sleeping bag system has been measured using a thermal manikin, the result can be used to calculate the temperature rating. The temperature rating is an estimate of the environmental temperature at which a person can remain thermally neutral in a sleeping bag or sleeping bag system. Thermal neutrality occurs when the total body heat loss is equivalent to the heat generated by the body (i.e., no heat debt). This can be expressed by a simple heat balance equation (ASHRAE, 2013):

$$Q_{met} = Q_{sk,d} + Q_{sk,e} + Q_{res,d} + Q_{res,e} \tag{1}$$

where

Q_{met} = the body metabolic energy generation per unit surface area (W/m^2)
$Q_{sk,d}$ = dry heat transfer from the body (W/m^2)
$Q_{sk,e}$ = evaporative heat transfer from the body (W/m^2)
$Q_{res,d}$ = the dry energy loss due to breathing (W/m^2)
$Q_{res,e}$ = the evaporative loss due to breathing (W/m^2)

Due to their physical and physiological nature, children differ from adults in their response to thermal stress. These responses include changes in body temperature, metabolic rate, circulation, hormones, sweat rate, sweat composition, and fluid regulation. These differences have already been examined and summarized in a chart by McCullough et al. (2009). Additionally, Falk (1998) has published a review of the effects of thermal stress in the pediatric population. The physical and physiological differences between children and adults that should be accounted for in heat loss models include a higher surface area to mass ratio, a lower skin temperature in the cold, and a higher level of metabolic heat production. To further complicate matters, these variables change with age until the child becomes an adult.

McCullough et al. (2009) developed a predictive model for children's cold weather clothing based on a whole body heat loss approach and taking into account the physiology of children. This model has been modified here to apply to children's sleeping bags. The key model inputs are highlighted below, followed by the assumptions and limitations of the temperature rating model. The equations used for the development of the KSU child sleeping bag model are given in the Appendix.

4.1. Metabolic energy generation

Metabolic rate during sleep may be affected by many factors, including sleep stage, menstrual and seasonal cycles, temperature, diet, day-time physical activity, and movement during sleep (Schoffelen and Westerterp, 2008). Schoffelen and Westerterp (2008) found a rapid decline in metabolic energy generation for the first two to three hours following the onset of sleep, but also reported that other studies found metabolic rate to be either relatively constant during the night, or steadily declining during the night.

In the children's sleeping bag model, the metabolic energy generation per unit surface area (Q_{met}) was assumed to be a constant for sleep (dependent on age). Childs (1993) found that the predicted value for basal metabolic rate (BMR) – based on the equations of Schofield (1985) – was a good approximation of metabolic rate in sleeping children. The study included children with ages ranging from 4.5 months to 14 years, and the metabolic rate was measured at least two hours after the child fell asleep, making it a suitable approximation for use in the model. The Schofield (1985) equations estimate BMR based on age, weight, and sex. Growth charts from the National Center for Health and Statistics (2000) were used with these equations to estimate metabolic energy generation for the 50th percentile boy in each age group (see Fig. 1). The temperature rating model was developed for children up to 14 years old, because the study by Childs (1993) that was used to estimate the sleeping metabolic rate only included children up to 14 years of age. Older children are also likely to buy an adult size sleeping bag rather than a child size bag, and will rely on the adult temperature ratings provided by the manufacturer.

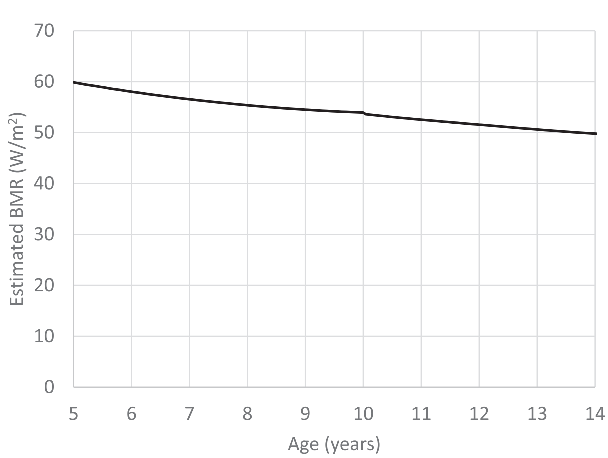

Fig. 1. Estimated sleeping metabolic energy generation per unit surface area (Q_{met}) by age for the 50th percentile male child.

4.2. Permeability index of sleeping bag systems

In order to determine evaporative heat transfer from the body ($Q_{sk,e}$), the total evaporative resistance of the sleeping bag system was estimated from the total thermal resistance value, using the permeability index (i_m). The permeability index is an indicator of evaporative performance of textile systems (McCullough, 1993). Values range from 0 to 1, where 0 indicates that the system is completely impermeable to water vapor and 1 is the ideal case for air (Parsons, 2014). For sleeping bag systems measured on a manikin, the permeability index has been found to be in the range of 0.1–0.4 (Kuklane, 2012; Wu and Jintu, 2009). A value of 0.4 seems high for sleeping bags, since this was the same value identified for typical clothing ensembles worn in a standing posture (Parsons, 2014). Sleeping bags are used in the supine position, so a significant percentage of body surface area is in contact with a more impermeable surface, which should result in a lower permeability index. A value of 0.3 was selected as a reasonable estimate for use in the model. Note that the larger the value of the permeability index, the warmer the temperature rating due to an increase of evaporative heat loss in the model. The evaporative heat loss accounts for approximately 15–20% of the total heat loss in the model.

4.3. Pulmonary ventilation rate

The pulmonary ventilation rate was used in the calculations for dry and evaporative heat loss from respiration ($Q_{res,d}$ and $Q_{res,e}$, respectively). The pulmonary ventilation rate (kg/s) for adults can be estimated as a function of metabolic rate (Fanger, 1970). However, this relationship may not be valid for children, especially under special circumstances such as sleeping. For this model, the pulmonary ventilation rate was estimated based on the respiratory frequency and tidal volume. The respiratory frequency for different ages of children was obtained from Fleming et al. (2011). The tidal volume was approximated as 8 mL/kg body mass, which is an interspecies constant in newborns and adults (Mortola and Noworaj, 1985).

4.4. Skin temperature

In order to use the model to predict a temperature rating, an average skin temperature must be identified. The literature indicates that children have a lower skin temperature than adults in the cold (see Section 4). However, the main purpose of a sleeping bag is to insulate the user from the environment. Therefore, skin temperatures that correspond to conditions of thermal neutrality and thermal comfort were considered.

There is evidence that under thermo-neutral conditions the skin temperatures between children and adults are not significantly different (Inoue et al., 2006, 2009; Tsuzuki et al., 2008). Less information is available regarding skin temperatures in sleeping grade school age children. Recently, Okamoto-Mizuno et al. (2016) compared skin temperatures of sleeping preschool age children and their mothers, and found significantly lower distal and proximal skin temperatures in the children. However, compared to the mothers most of the children in the study were more active during the night and slept uncovered, which probably contributed to the lower bed climate temperature. Regardless, a higher skin temperature results in a warmer temperature rating and it was therefore decided to use an adult skin temperature estimate in the model.

For adults, most estimates of skin temperature for thermal comfort have been developed with awake subjects. For example, for sedentary activities in the absence of sweating, skin temperatures associated with comfort are 33–34 °C (ASHRAE, 2013). It is more difficult to establish a relationship between thermal comfort and skin temperature during sleep, because thermal comfort is subjective and cannot be directly assessed during sleep. However, subjects may attempt to recall their sleeping thermal comfort upon waking and sleep quality may be used as an additional indicator. Lan et al. (2014) found that the thermoneutral temperature required by sleeping people was greater than that for the waking state. A sleeping "neutral" thermal sensation vote corresponded to a skin temperature slightly greater than 34.5 °C and a "slightly cool" vote corresponded to approximately 34 °C (Lan et al., 2014). Other studies also indicated a skin temperature greater than 34 °C while sleeping (Kräuchi, 2002; Kubo et al., 1999; Lee and Park, 2006; Pan et al., 2012; Van Someren, 2006; Yetish et al., 2015). Therefore, a skin temperature of 34.5 °C was selected for use in the model.

4.5. Assumptions and limitations

This predictive model can be used to determine the temperature rating of a sleeping bag or sleeping bag system for a child of a given age if the insulation value is known. However, it is important to keep in mind the assumptions that were used in the development of the model and its limitations. Many of these were carried over from the predictive model for children's cold weather clothing (McCullough et al., 2009), but there were some essential changes and additions. The key assumptions and limitations are listed below:

- The radiant temperature was assumed to be the same as the air temperature. In outdoor environments, radiant heat gain/loss may affect thermal comfort.
- Lavie and Berris (1998) reported that physiological responses to room air temperature changes were similar for a sleeping person (excluding the rapid eye movement stage) and a person who was awake. Therefore, in this model it was assumed that thermoregulation during the sleeping state is similar to the wakeful state.
- Steady-state conditions were assumed, but conditions during actual sleeping bag use may be changing. For example, people may adjust their clothing, the bag closure, or their body position. The environmental conditions may change during the night. Metabolic rate and body temperature may fluctuate during sleep as well.
- The effect of wind was not used in the model.
- Relative humidity was assumed to be 50% for the model, since this is a parameter that may vary widely from day to day. However, in cold environments, where the ability to evaporate sweat is not as important for maintaining thermal comfort, humidity does not play an important role.
- It was assumed that there is no "pumping effect". If the individual is a restless sleeper and moves around a lot in the bag, there may be an increase in convective and evaporative heat loss to the environment (McCullough, 1993).
- Human variability was not considered in the model. A standard 50th percentile male child was used for modeling. Some physical and physiological variables may affect thermal comfort and thermoregulatory responses that were not included in the model. The issue is further complicated by the fact that children are growing and maturing, and thus the physical and physiological differences are changing as they age. Additionally, children grow and mature at their own rate, resulting in wide interpersonal variation.
- A whole body heat loss model was used to determine the temperature rating for comfort. The insulation of the sleeping bag or sleeping bag system was assumed to be uniformly distributed over the entire surface of the body. In reality, some parts of the body may be exposed to the environment (e.g., the face) or have less insulation than others (depending upon the auxiliary products used and the construction of the bag). Additionally, localized cooling and discomfort can still occur, particularly in the feet.
- It was assumed that the person is not shivering in the model, since the temperature rating is for conditions of thermal neutrality and thermal comfort.
- The youngest age child included in the model was 5 years old.

4.6. Bag sizing issues

Although children are growing and changing as they age, clothing for children can be supplied in different sizes to fit them (i.e., 8, 10, 12; Small, Medium, Large). However, sleeping bag manufacturers tend to take more of a "one-size-fits-all" approach. For example, a given sleeping bag will not fit all 8-year old children the same, due to interpersonal variation in the population. The size of the child relative to the size of the bag will also change over time as the child grows. This same issue is seen to a lesser degree with adult sleeping bags, due to interpersonal variation in the adult population. As with adult bags, the sleeping bag temperature rating for children is only intended to serve as a guideline for consumers to assist them in making informed decisions. The actual environmental temperature for thermal neutrality will vary depending on changing environmental factors, clothing worn, and the physiological characteristics of the user. For the sake of repeatability, variables in the test procedure and temperature rating model must be controlled.

5. Results and discussion

If the total thermal insulation of a sleeping bag system is known, then a temperature rating can be determined using the KSU child sleeping bag model. Total insulation values ranging from 1.5 to 9 clo were used to predict the corresponding temperature rating in degrees Celsius for ages 5 through 14 years old. These results were used to develop the regression equations in Table 1. The results may be converted from degrees Celsius to Fahrenheit. To avoid introducing errors due to rounding it is recommended that the result in degrees Celsius be carried out to three decimal places before converting to degrees Fahrenheit.

The relationship between the insulation value and temperature rating for select ages is shown in Fig. 2. The KSU adult sleeping bag model was added for reference. It uses a permeability index of 0.4 and has been validated with human subject testing (McCullough et al., 2005).

The KSU child sleeping bag model results indicate lower temperature ratings for younger children. At first glance, this seems to

Table 1
Regression equations to determine the temperature ratings for sleeping bags for different age children, where TR = temperature rating (°C) and I_t = total thermal insulation of the sleeping bag system and surface air layer (clo). All curves fit with $R^2 > 0.99$.

Age (yrs)	Temperature Rating (°C)
5	$TR = -0.0562 \cdot I_t^2 - 5.9900 \cdot I_t + 33.460$
6	$TR = -0.0543 \cdot I_t^2 - 5.7488 \cdot I_t + 33.467$
7	$TR = -0.0527 \cdot I_t^2 - 5.5628 \cdot I_t + 33.479$
8	$TR = -0.0516 \cdot I_t^2 - 5.4241 \cdot I_t + 33.493$
9	$TR = -0.0491 \cdot I_t^2 - 5.2771 \cdot I_t + 33.491$
10	$TR = -0.0487 \cdot I_t^2 - 5.2148 \cdot I_t + 33.501$
11	$TR = -0.0451 \cdot I_t^2 - 4.9943 \cdot I_t + 33.507$
12	$TR = -0.0420 \cdot I_t^2 - 4.8275 \cdot I_t + 33.511$
13	$TR = -0.0409 \cdot I_t^2 - 4.7222 \cdot I_t + 33.528$
14	$TR = -0.0384 \cdot I_t^2 - 4.5876 \cdot I_t + 33.534$

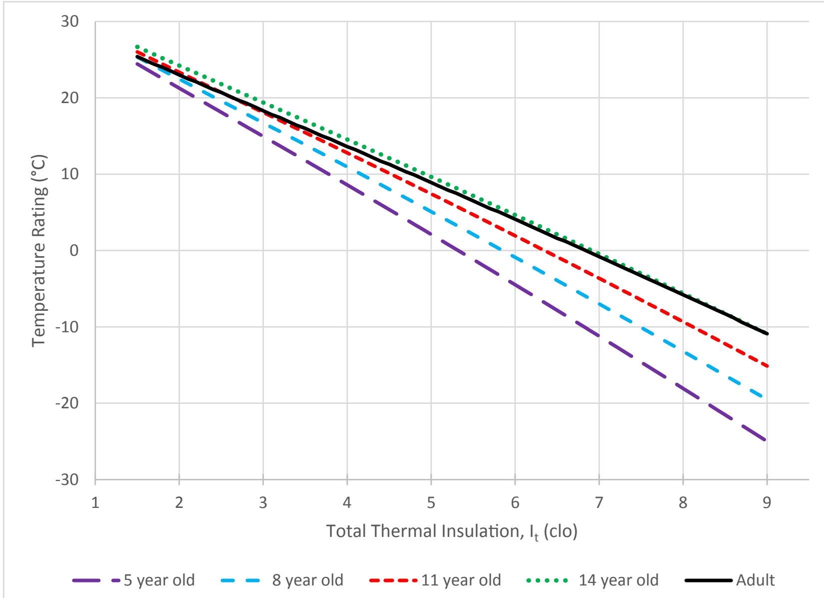

Fig. 2. Results of the KSU whole body heat loss model for select ages (years).

be in conflict with the child clothing temperature rating model (McCullough et al., 2009), which produces a temperature rating that is higher for a 4 year old than a 10 year old. This is because the child sleeping bag model uses the BMR as an estimate for sleeping metabolic rate. As a result, the sleeping metabolic rate is higher for younger children than it is for older children (see Fig. 1). The child clothing model takes activity into consideration, and estimates metabolic rate by adjusting the BMR with a Physical Activity Level (PAL) multiplier (McCullough et al., 2009). The PAL multiplier for different ages and activity rates was estimated from the International Dietary Energy Consultancy Group report (1989) and the WHO report (2004). For example, the PAL multiplier for a 4 year old walking slow and walking fast was estimated to be 2.1 and 2.6, respectively (McCullough et al., 2009). The PAL value increases with age, and as a result a 10 year old has a higher metabolic rate than a 4 year old for the same activity rate.

For the sake of validation, the model was extended to children up to 18 years old and compared to the adult validation data with human subjects (McCullough et al., 2005). The results were found to be within (or slightly warmer than) the 95% prediction limits for neutral thermal sensation (see Fig. 3). Because for older children the model converges to the adult validation data, it gives confidence in the results. It is also important to keep in mind that the temperature rating is intended to serve as a guideline, rather than a guarantee of performance. During actual use, other factors such as personal characteristics, changing weather conditions, and auxiliary products may significantly affect the thermal performance of the sleeping bag system.

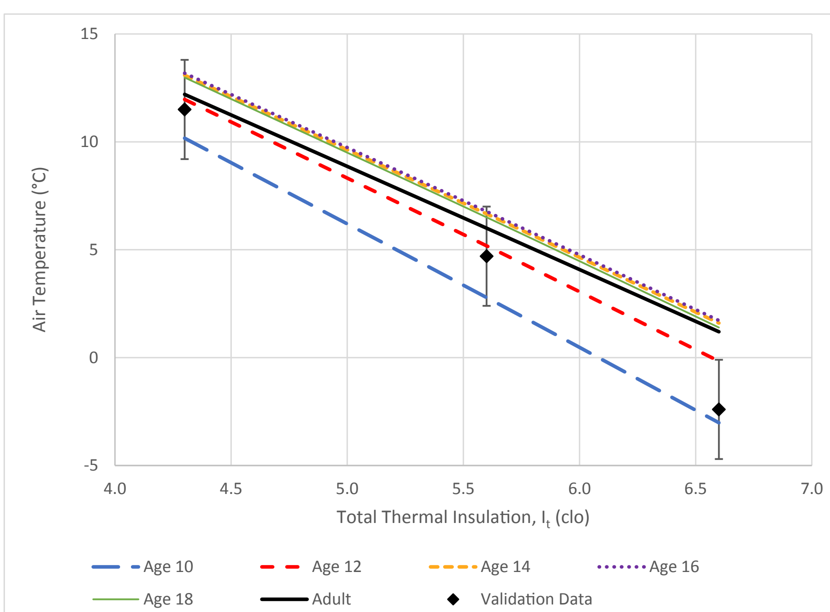

Fig. 3. Comparison of model results to validation data. The validation data were obtained from McCullough et al., (2005), and correspond to a neutral thermal sensation vote during human subject testing of select sleeping bags.

6. Conclusions

A whole-body heat loss model that takes into consideration the unique physiology of children was used to determine a temperature rating based on the total thermal resistance of a sleeping bag system and a child's age. For the model results to be meaningful to consumers, the measurement of the thermal insulation needs to be accurate and repeatable for input into the model. Determining the insulation of a bag for a given age of child still presents some challenges.

The model predicted lower temperature ratings for younger children (under 12 years old) than adults. Younger children were found to have a lower temperature rating due to a higher metabolic rate. Even though the children's model predicted temperatures that were colder than the adult model, they were developed with a more conservative approach. This includes the selection of a higher value for the mean skin temperature. Since the KSU adult model yielded a warmer temperature rating, it could safely be used to calculate temperature ratings for children's bags. However, the children's model can be tailored for different ages.

Appendix

This model provides an estimate of the environmental temperature that results in thermal neutrality for a person using a sleeping bag or sleeping bag system. In this model there is no net heat gain or loss. This can be expressed by the heat balance equation (ASHRAE, 2013):

$$Q_{met} = Q_{sk,d} + Q_{sk,e} + Q_{res,d} + Q_{res,e} \tag{A.1}$$

where

Q_{met} = the body metabolic energy generation per unit surface area (W/m^2)
$Q_{sk,d}$ = dry heat transfer from the body (W/m^2)
$Q_{sk,e}$ = evaporative heat transfer from the body (W/m^2)
$Q_{res,d}$ = the dry energy loss due to breathing (W/m^2)
$Q_{res,e}$ = the evaporative loss due to breathing (W/m^2)

The environmental temperature is composed of the air temperature, the ground temperature, and the radiant temperature. For the purposes of the model, these temperatures were assumed equal and uniform. The temperature rating is the environmental temperature which satisfies equation (A.1). The components of the energy balance are determined using the following equations.

Dry heat loss from the skin

$$Q_{sk,d} = \frac{(T_{sk} - T_e)}{R_{t,d}} \tag{A.2}$$

where

T_{sk} = the average skin temperature (°C)
T_e = the environmental temperature (°C)
$R_{t,d}$ = the total thermal resistance provided by the sleeping bag system (m^2·°C/W)

Evaporative heat loss from the skin

It was assumed that the person using the bag will not be actively sweating. This is a valid assumption, since sleeping bags are intended to insulate the user against cold environmental conditions. Additionally, the model assumed that the user is in a condition of thermal neutrality. However, there will still be evaporative losses due to passive diffusion through the skin. This was calculated as:

$$Q_{sk,e} = \frac{(P_{sk} - P_e)}{R_{t,e} + R_{sk,e}} \tag{A.3}$$

where

P_{sk} = the average vapor pressure for the skin (kPa)
P_e = the vapor pressure of the environment (kPa)
$R_{t,e}$ = the total evaporative resistance of the bag (m^2·kPa/W)
$R_{sk,e}$ = the evaporative resistance of the skin, 0.33 m^2 kPa/W for typical conditions (Fanger, 1970)
P_{sk} is equal to the saturation pressure at the skin temperature

$$P_{sk} = P_{sat}(T_{sk}) \tag{A.4}$$

The relative humidity of the environment was assumed to be 50%. Thus, the vapor pressure of the environment is

$$P_e = P_{sat}(T_e)/2 \tag{A.5}$$

where P_{sat} is the saturation pressure for water vapor (kPa)

The total evaporative resistance was not determined experimentally, but estimated from the total thermal resistance using the Lewis relation and permeability index:

$$R_{t,e} = R_{t,d}/(Lr \cdot i_m) \tag{A.6}$$

where

Lr = Lewis ratio, approximately equal to 16.5 °C/kPa (ASHRAE, 2013).
i_m = permeability index for the bag system, assumed value of 0.3.

Dry heat loss from respiration

$$Q_{res,d} = m_{res} \cdot c_{p,a} \cdot (T_{ex} - T_e) \tag{A.7}$$

where

m_{res} = the "respiration rate" per unit body surface area (kg/m^2·s)
$c_{p,a}$ = the specific heat of air, approximately 1006 J/kg·K at typical conditions
T_{ex} = the temperature of the exhaled air (°C)
T_e = the environmental temperature (°C)

The respiration rate, m_{res}, was estimated from the respiratory frequency and tidal volume.

$$m_{res} = 6 \cdot 10^{-7} \cdot Vt \cdot Rf \cdot \rho / A \tag{A.8}$$

where

Vt = tidal volume (mL/breath)
Rf = respiratory frequency (breaths/minute)
ρ = density of air, 1.1614 kg/m^3 at 300 K

A = body surface area (m^2)

The exhaled air temperature was estimated according to Holmér (1984).

$$T_{ex} = 29 + 0.2 \cdot T_e \tag{A.9}$$

Evaporative heat loss from respiration

$$Q_{res,e} = m_{res} h_{fg}(W_{ex} - W_e) \tag{A.10}$$

where

H_{fg} = the heat of vaporization of water, approximately 2,430,000 J/kg
W_{ex} = the humidity ratio of the exhaled air (n.d.)
W_{ex} = the humidity ratio of the environment (n.d.)

The humidity ratios were calculated from the vapor pressures.

$$W_{ex} = 0.622\ P_{ex}/(P_t - P_{ex}) \tag{A.11}$$

$$W_e = 0.622\ P_e/(P_t - P_e) \tag{A.12}$$

where

P_t = the total atmospheric pressure, 101.325 kPa

Metabolic energy generation

The metabolic energy generation per unit surface area was approximated using basal metabolic rate.

$$Q_{met} = BMR/A \tag{A.13}$$

where

A = body surface area (m^2)
BMR = basal metabolic rate (W)

The BMR was estimated using the equations of Schofield (1985).

$$BMR = 0.249 \cdot weight - 0.127 \text{ (Male under 3 years old)} \tag{A.14}$$

$$BMR = 0.095 \cdot weight + 2.110 \text{ (Male 3–10 years old)} \tag{A.15}$$

$$BMR = 0.074 \cdot weight + 2.754 \text{ (Male 10–18 years old)} \tag{A.16}$$

There is a small disparity at the junction of the different regression equations, and equation (A.15) was used in the model for 10 year olds. The body surface area was approximated using the Haycock et al. (1978) height-weight formulas.

$$A = W^{0.5378} \cdot H^{0.3964} \cdot 0.024265 \tag{A.17}$$

where

H = height (cm)
W = weight (kg)

Adult temperature ratings are generally based on the “standard” adult male. The same convention was used here, and growth charts from the National Center for Health and Statistics (2000) were used to estimate the 50% percentile boy in each age group.

Skin temperature

The skin temperature for thermal comfort during sleep was estimated to be 34.5 °C.

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