Effects of body posture on air gap and heat transfer of clothed infant using a baby manikin

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Abstract. Body posture affects the heat transfer between infants and surroundings. The purpose of this study was to investigate the air gap thickness as well as the heat transfer at the infant’s body surface when the infant posture changed from standing to lying down (supine). Visual and quantitative air gap distributions were achieved using 3D body scanning technology and reverse engineering software. Global and local heat transfer coefficients were also obtained by baby manikin test. The results showed that the local air gap thickness significantly decreased in supine posture compared to standing, especially at the diaper zone. Moreover, the supine posture reduced the local heat exchange although the corresponding air gap thickness decreased. The different linear regression models between air gap thickness and heat transfer coefficient were therefore built in both standing and supine postures. For the air gap thickness with the range of 4.00-9.05 mm, the coefficient was always lower when lying down than standing. The findings provided useful information for the improvement of infant clothing design and the modelling of heat and mass transfer in infant clothing for different body postures.

1. Introduction

Sudden infant death syndrome (SIDS) has become a major public health problem in both developed and developing countries[1,2]. It was postulated that thermal stress related to excessive clothing insulation was a risk factor of SIDS[3]. Selection of appropriate clothing is therefore critical in maintaining the thermal-physiological comfort and reduce the thermal stress of infants.

Currently, a number of variables which may affect the heat transfer of clothing have been explored (e.g. fabric characteristics, garment fit and style, air speed, and body posture and movement)[4–7]. However, previous researches almost focused on adults, and thus such findings may not apply in infants. Due to the extremely large body surface area to weight ratio, heat exchange in infants is generally larger than in adults, and accordingly, infants are more thermally vulnerable[8]. More importantly, infants are always in supine posture, which is inconsistent with the standing and sitting that commonly performed by adults. Previous studies have been proved that body postures obviously affect the distribution and size of the enclosed air gap (air gap between skin and clothing) and then affect heat transfer coefficients[9,10]. In this regard, it is necessary to investigate the air gap distribution and the heat transfer for a clothed infant in different postures, especially the supine posture.

The size and distribution of the air gap have been commonly studied. It is known that the air gap is not evenly distributed and depends on body postures and body regions[11,12]. Theoretically, when a baby is lying down, the enclosed air gap at each body region varies significantly due to the...
gravitational force and the pressure from the mattress compared with the standing posture. For example, the body region to support clothing is changed from the shoulder to the front of the torso, which makes the air layer thickness at the shoulder become larger and that for the front of torso is smaller. The importance of air layer thickness for the heat transfer through clothing have also been well recognized and some universal laws have been obtained[13]. In generally, thermal insulation of air gap is non-linearly related to air layer thickness due to the complex natural convection. Zhang et al. [14] found the total heat flux decreased with the increase of air gap thickness, whereas the decreasing rate gradually slowed down when the air gap thickness was greater than 10-13 mm. Mert et al. [15] investigated the effect of a heterogeneous vertical air gap on dry heat loss and showed the heat fluxes for different shapes of air layers changed diversely with the air layer thickness. The orientation of air gap also plays an important role in the heat loss[16]. Most air gaps are vertical when a human body is in standing posture but horizontal when the body is lying down. Udayraj et al. [17] found thermal protection with the vertical air gap was significantly better than that for the horizontal air gap and the difference increased as the air gap thickness increased. Although above studies have explored the effect of thickness and orientation, no quantitative results reported about the distribution of air gap and heat transfer mechanism in lying postures, especially for an infant.

Focusing on the measurement of air gap and heat transfer, previous studies generally used adult thermal manikin combined with three-dimensional (3D) body scanning technology[10,18]. In contrast, few study obtained geometric data of the outer surface morphology of real babies[19,20]. Recently, Thermetrics (a manufacturer of testing and measurement instrumentation systems) has produced a new baby thermal manikin, which provides an effective method to study the heat transfer of infant surface under different postures. Additionally, it offers a method to obtain geometric data of the realistic infant. Combined with the reverse engineering software, the size and distribution of air gap under infant clothing could be obtained.

Therefore, the purpose of this study was to quantify the effects of infant posture on the air gap and the heat exchange between infants and environments. The global and local mean air gap thickness and the sensible heat transfer coefficients in both standing and supine postures were respectively achieved and compared. The outcomes of this study were expected to offer valuable information for infant clothing design and be helpful for developing realistic infant clothing models to simulate the heat and mass transfer.

2. Methods

2.1. Test garments and body postures
Two typical summer infant garments (73/48) were selected in this study, as shown in Figure 1. All samples were made of single jersey knitted fabrics which contained 100% cotton. Sample G1 was a coverall while G2 was separated with top and bottom. The setting of infant clothing samples took the influence of styles into consideration.

Supine and standing postures were selected for 3D scanning and manikin test. For a baby, the supine posture is the most commonly used. Although babies rarely stand, upright posture may occur when being picked up by a caregiver. The standing posture as an idealized state is used as a reference to the supine posture.

2.2. 3D scanning and post-processing
Handyscan 3D (Creaform, Lévis, QC, CAN), a hand-held 3D laser scanner, was used to capture 3D data of the surface of the nude and clothed baby manikin. The acquisition accuracy of this apparatus is 0.03 mm. The 3D scanning was conducted in the experimental chamber with the temperature of 22 ± 0.5 °C and the humidity of 50 ± 10%. To minimize misalignment, some markers were set to locate parts of the manikin. The infant manikin was scanned in dress firstly and then naked in order to reduce error caused by operation. This operating procedure applies to each test samples and it need to be totally repeated four times (2 test samples × 2 body postures).
The manikin was suspended by the head when the standing posture was scanned. No other part of the body was in contact with other objects. When it turned into the supine posture, the manikin was put on a mattress made of EPE (Expand able poly ethylene). Due to the restriction from the mattress, it was difficult to obtain the scan of the back side of head, limbs and torso where the manikin closely next to mattress. As a result, a significant portion of data was lost in the final models. Therefore, these missing body parts were excluded in the analyses and discussion.

All grid data obtained from the scans were imported into Geomag ic Qualify software to be post-processed. Through polygonal data optimization operations such as filling holes, reducing noise, and removing features, relatively smooth and complete geometric models of baby manikin were achieved. The clothed models were aligned with the corresponding nude models set as references and the distance between the two model surfaces was recognized as the thickness of enclosed air gaps.

2.3. Manikin tests
A baby manikin (Thermetrics, Seattle, WA, USA) for scanning and heat flux measurements was used to simulate a 9-month old male baby with the height of 73.0 cm, 51.8 cm for abdomen and 52.1 cm for hip (Figure 2). The manikin consisted of a carbon fiber-epoxy body form with distributed heating wires and wire sensors for accurate control and measurement of skin temperature. It contained 19 independently heated thermal zones and the zone divisions are depicted below in Figure 3. The manikin's joints were flexible so that it could strike different body postures.

![Figure 1. Test samples](image1)

![Figure 2. The baby manikin](image2)

![Figure 3. The manikin zone divisions](image3)

The manikin tests were conducted under constant temperature (CT) mode and the manikin’s surface temperature of each zone maintained at 35 ± 0.5 °C. The air temperature (T_a), relative humidity (RH) and air velocity (V_a) were set as 22± 0.5 °C, 50 ± 5 % and 0.4 ± 0.1 m/s, respectively. The tests were in accordance with ISO 15831. The heat flux generated at each zone representing the local heat loss on real baby surface was recorded in real time by ThermDAC8® Control Software. The local heat transfer coefficients of infant when wearing three infant garments under two body postures were determined. Each scenario shall be repeated three times and the averages were figured out.

2.4. Statistical analysis
Paired samples t-test was used to investigate whether there were differences in the air gap thickness and heat transfer coefficient in standing and supine postures. The significant level was set at p<0.05. Linear Regression Analysis was applied to build the relationship between air gap thickness and heat transfer coefficient. All statistical analysis was conducted using the spss v22.0 software (IBM Corp., Armonk, NY, USA).

3. Results
3.1. Air gap thickness

Figure 4 shows the colour maps of air gap thickness for two infant garments in two body postures after post-processing. The gap thickness distribution can be distinguished obviously by the colours. Dark blue represented the clothing at these regions were in contact with the body surfaces of the baby or the body passed through the clothing due to the systematic errors caused by scanning and alignment. These regions were excluded in the analyses. By contrast, red and yellow represented more air was gathered at these regions. Compared to the other regions, the diaper zone gathered most air in standing posture, however, the air lessened evidently in supine posture.

Figure 5 presents the mean air gap thickness and their standard deviations (SD) for the global and four local body regions in standing and supine postures. According to the SDs, the air gaps at the diaper zone, front thigh and upper arm were more heterogeneous while that for the chest was more even. The global air gap thickness had no differences ($p=0.476$) between two body postures. The local air gap thickness significantly decreased as the posture changed from standing to lying down ($p=0.032$). The largest change rates of air gap thickness for G1 and G2 were 52.5% and 52.1%, respectively, at the diaper zone. However, the variations of air gap thickness at the chest for two garments were minor, and even a slightly increasing trend was found for G2.

![Figure 4. The colour maps of enclosed air gap thickness](image)

![Figure 5. Mean air gap thickness](image)

3.2. Heat transfer coefficient

The global and local heat transfer coefficients at manikin body surface when wearing G1 and G2 are shown in Figure 6. The global heat transfer coefficients in two body postures varied significantly ($p=0.020$). The local heat transfer coefficients ranged from 4.44 to 7.43 W/°C·m² and a significant difference was found between two body postures ($p=0.044$). The local heat transfer coefficients in supine posture were lower than that for standing.
Figure 6. The heat transfer coefficients

4. Discussion

The supine posture, which is often performed by infants as well as the standing posture set as a reference were compared to investigate the air gap distribution and the heat transfer.

4.1. Effects of postures on air gap thickness

The present study found that the body posture had an evident effect on local air gap thickness. Compared with the standing posture, the air gap formed at the front body was significantly smaller in supine posture owing to the change in the direction of gravitational force. Nevertheless, the effects of body posture on air gap distribution were dependent on the body regions, being strongest at the diaper zone while weakest at the chest. In standing posture, the garment hanged downwards with a certain distance from the infant body surface below the protruding abdomen due to the gravitational force, contributing to the largest air gap at the diaper zone, as shown in Figure 7(a). By contrast, the garment fell over the front of the body and conformed to its shape in supine posture, and accordingly the relatively small air gap formed at the diaper zone, with approximately 50% reduction of air gap thickness compared with the standing posture. However, the chest was flat and lower than the abdomen, making the garment follow the shape of chest. As a result, the air gap at the chest was small and the absolute value of the change of air gap thickness due to the posture change was not significant.

Furthermore, the design feature also affected the contribution of body posture on the air gap, especially at the regions which were close to the openings. For example, the different configuration of ease allowance at the front and back of the thigh resulted in the different effect of posture change on air gap thickness.

4.2. Effects of body postures on heat transfer coefficients

As expected, the change of the thickness and orientation of air gap due to the body posture led to the change of the heat transfer coefficients at the infant’s body surface. In the previous study, Mert et al [15] evaluated the effects of homogenous and heterogeneous vertical air gaps with different fold sizes on heat transfer using a heated cylinder. The heat transfer coefficient decreased with the increase of mean air gap thickness without the occurrence of natural convection (the air gap thickness is less than 30 mm) [13]. In the present study, air gap was unevenly distributed. The greatest air gap thickness was 15.44 mm, which is far below 30 mm. Figure 8 displays the air layer thickness and the corresponding heat transfer coefficients in standing and supine postures. Except for two points where air gap...
thickness was greater than 14mm (natural convection occurred), two groups of points showed obvious linear distribution in the coordinate system, respectively. Generally, greater air gap contributed to the small heat transfer coefficient, which was consistent with the widely accepted rules.

The two fitting lines for the scatter in standing and supine postures and their linear regression models are also shown in Figure 8. The two points mentioned above were excluded. It can be seen that the dotted line was always lower than the solid line, which illustrated that the supine posture had smaller heat transfer coefficients than the standing posture when the air gap thickness was same (the range is 4.00-9.05 mm). Moreover, the discrepancy of the coefficients between two body postures enlarged with the increase of air gap thickness. This phenomenon may be explained by the change of thermal plume development around the infant manikin due to the change of the body orientation. The reduction of heat transfer coefficients for supine posture compared to the standing posture was also found in the previous numerical simulation for an naked adult manikin[10]. At present, this study confirmed that the same was true for the clothed infant manikin. In addition, although the air layer thickness decreased, the supine posture reduced the heat transfer coefficients at the diaper zone, front thigh and upper arm. Therefore, it seemed that the orientation of the air gap had a more significant influence on heat transfer than the thickness.

![Figure 8. The relationship between mean air gap thickness and heat transfer coefficient](image)

5. Conclusion
The air gap distribution in infant clothing and heat transfer at the body surface under two different body postures were investigated in the present study. Two linear regression models were also proposed to predict the heat transfer for two body postures. The result indicated that the selected body postures had an evident effect on the air gap thickness and heat transfer coefficients. The supine posture reduced the local air gap thickness significantly compared to the standing posture, especially at the diaper zone. Moreover, the supine posture had a smaller heat transfer coefficient than the standing posture when the air layer thickness was same due to the change of thermal plume around the body. These conclusions will be beneficial to the evaluation for the heat transfer at the body surface for clothed infant in different postures and the improvement of infant clothing design.

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