Inhaled Air Trapping Effect of Japanese Bedding as a Risk of Sudden Unexpected Death in Infancy

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FUNAYAMA, M., MIMASAKA, S., IWASHIRO, K. and NOZAWA, R. *Inhaled Air Trapping Effect of Japanese Bedding as a Risk of Sudden Unexpected Death in Infancy*. Tohoku J. Exp. Med., 1998, **185** (1), 55-65 ——— We assessed some Japanese bedding on the assumption of the effects of air trapping using an infant mannequin. The change of CO₂ concentration in the airway of a mannequin head placed on bedding was continuously monitored using a CO₂ analyzer during simulated breathing. To compare the level of CO₂ dispersal among different items of bedding, CO₂ half time ($t_{1/2}$) values were used. The $t_{1/2}$ values were calculated by measuring the time required for the expired percent CO₂ to reach 1/2 the initial percent end-tidal P_{CO₂}. We also measured softness and resistance to airflow (R) of the same items. As for the bedding, 4 types of futon and several types of bottom sheets/towels were combined. The $t_{1/2}$ value in supine position was 9.8 seconds. When the model was placed prone on futon, the $t_{1/2}$ values increased to 14.1 seconds (hard mattress type) — 17.2 seconds (soft cotton-like futon). With respect to present Japanese baby futon (hard mattress type), there may be a relatively low potential for rebreathing to occur, compared with soft futon. In every case, the $t_{1/2}$ value was prolonged by the use of a towel spread on the futon. CO₂ dispersal may depend not only on the softness of the futon, but also on the combination of bottom sheet/towel and mattress. There was no relationship between R values and $t_{1/2}$ values. The potential of rebreathing increased in face down position among all bedding, and supine position was the best CO₂ dispersal position. ——— SIDS; sleeping position; bedding; rebreathing; mannequin model © 1998 Tohoku University Medical Press

The cause of sudden infant death syndrome (SIDS) is still unknown, but statistical analyses in many developed countries have indicated a close correlation between prone sleeping position and SIDS. Some investigators have pointed out that prone position, especially face down, may limit the exhaled carbon dioxide

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(CO₂) diffusion, and that some types of bedding can easily trap exhaled air (Kemp and Thach 1991, 1993, 1995; Kemp et al. 1993, 1994; Kemp 1996). To inhale one's own exhaled air, that is rebreathing, can induce hypercapnea. For infants who have a significantly higher arousal threshold for hypercapnea, the abnormal physiological response would be evoked, causing asphyxia, and it would result in death (Valdes-Dapena 1995). Kemp and his colleagues have reported the quantifying analyses on the potential for rebreathing using dolls or animals since 1991. Bedding they found to be dangerous were polystyrene bean pillow (Kemp and Thach 1991), sheepskin (Kemp and Thach 1993) and waterbed covered with comforter (Kemp and Thach 1995). Waterbeds presently made in the U.S. have warning labels stating never let infants sleep on it.

Until recently, however, many Japanese infants seem to have been bedded on thick futon filled with soft cotton or wool batting. At present, although most baby futon on sale in Japan are hard mattresses types, some families and day-cares use soft cotton or wool futon. In addition, various types of sheets or towels may be simultaneously used on the futon. In this report, we assessed some Japanese bedding on the assumption of the effects of rebreathing using an infant mannequin.

MATERIALS AND METHODS

The settings of infant mannequin and simulated breathing operations were performed according to Kemp and Thach's method (Kemp and Thach 1995). Briefly, the change of CO₂ concentration in the airway of a mannequin head placed with the face straight down on each item of bedding was continuously monitored using a CO₂ analyzer during simulated breathing. Using the same items, softness and resistance to airflow of bedding were also investigated.

Bedding. The measurement was performed on 20 items of bedding based on four types of futon and five kinds of bottom sheets or towels (Table 1). Some bedding had actually been used by infants diagnosed as having died of SIDS.

Setting of mannequin. An infant mannequin (Resusci Baby, Laerdal, Oslo, Norway), which was designed and used for resuscitation training, was used. The volume of the head and the trunk were 1260 ml and 2450 ml, respectively. As the specific gravity of human tissue seemed to be 1.071 kg per liter (Kemp and Thach 1991), the weight of the head and the trunk were set at 1350 g and 2620 g, respectively, by packing lead blocks in the head and body space. The mannequin's plastic face was covered by face-shaped rubber mask. A small hole at each naris position on the rubber mask was bored, and each cut end of a pair of tubes of Y-shaped oxygen-nasal canula was inserted into the hole. The other end of the canula was connected to a 100 ml glass syringe. Dead space volume of this tube system was 8 ml. To measure CO₂ concentration, a CO₂ analyzer (Oscar II, Datex-Ohmeda, Helsinki, Finland) was connected through a side port of the tube system. The CO₂ analyzer is normally used to monitor patients under general

TABLE 1. *Type of bedding studied*

Futon 1: Hard mattress type, sold in 1997. This futon was covered with 100% cotton and filled with 20% cotton and 80% polyester.
Futon 2: Hard mattress type, sold in 1990. This futon was covered with 100% cotton and composed of three layers. Both outer layers were filled with 70% cotton and 30% polyester, and the middle layer was filled with 50% cotton and 50% polyester.
Futon 3: Soft mattress type used in home. This futon was covered with 100% cotton and composed of three layers. Both outer layers were filled with 100% cotton, and the middle layer was filled with 100% wool. A four-month-old female was found dead in prone position on this futon covered with the cotton bath towel, towel 8 (SIDS case 1).
Futon 4: Soft mattress type used in a day care. We were not able to get information about the content. Probably, the cover and the batting were mainly made of cotton. It's surface was uneven with high and low sections as a result of the stitching. A two-month-old male was found dead in prone position on this futon covered with the cotton sheet, sheet 6 (SIDS case 2).
Sheet 5: A new thin cotton sheet.
Sheet 6: A thin cotton sheet; this sheet had covered futon 4 (SIDS case 2).
Towel 7: A new cotton hand towel.
Towel 8: A cotton bath towel used in home. A four-month-old female was found dead in prone position on futon 3 covered with this bath towel (SIDS case 1).
Sheepskin: A type of sheepskin from New Zealand sheep.

Fig. 1. Apparatus for measuring CO₂ dispersal of bedding. Before simulated breathing, the syringe was filled with 5%CO₂-95%N₂ gas mixture.

anesthetic and continuously measures %CO₂ at a rate of 200 ml/min. The change of %CO₂ through the CO₂ analyzer was recorded by a digital recorder (Omniace RT3300, NEC, Tokyo). Fig. 1 shows the setting of mannequin.

Gas production. Before simulated breathing operations, the glass syringe was filled with a 5% CO₂. The 5% CO₂ was produced using a gas mixture flow meter (RK1202M-B-1/8-N₂ 2000 ml, CO₂ 200 ml-1K-A, Kofloc, Tokyo). The gas flow

to each inlet was 1900 ml/min of N_2 and 100 ml/min of CO_2 , and the gas mixture from the outlet contained approximately 5% CO_2 (4.8%-5.2% CO_2).

Breathing operation. The syringe was filled to a volume of 80 ml with the 5% CO_2 gas, and was connected to the tube. Ten ml were flushed to fill the gas in the tube system for 2/3 of a second. Immediately after this 10 ml flushing, the syringe plunger was pulled back a volume of 30 ml for 2 seconds. The syringe plunger was then advanced a volume of 30 ml for 2 seconds. Pulling the plunger represented inspiration, and pushing it represented expiration; the simulated respiration was 15 breaths a minute. The plunger was repeatedly moved between the 70-ml mark and 100-ml mark on the syringe to the steady rhythm of an electrical metronome. Kemp and Thach (1995) explained that the 30 ml moving volume was the “tidal volume” and the remaining 70 ml volume was the “functional residual capacity” of an infant weighing 4-5 kg. The “breathing” was continued for 50-60 seconds. The simulation was repeated 5 times by each of the 5 examiners, thus, there was a total of 25 simulations on each item.

During the measurement, the mannequin was placed in a cubic plastic box (63 cm $\times$ 76 cm $\times$ 33 cm) to eliminate the effects of ambient environment, such as air draft. Before every new “respiration,” the air in the box was changed by a fan, and the model was repositioned on the bedding.

Quantifying of the “breathing” data. The % CO_2 tracing curve by simulated respirations was recorded on thermal paper. The curve was described as Fig. 2. Evaluation of the CO_2 dispersal was used the half time ($t_{1/2}$) values. The $t_{1/2}$ values were defined as the duration from the beginning of inspiration of the first breath to the time at which the percentage of CO_2 reached one-half the percent end-tidal P_{CO_2} (% P_{ETCO_2}) of the first breath. In most cases, the one-half % P_{ETCO_2} of the first breath fell between 2 breaths, therefore the $t_{1/2}$ was calculated by

Fig. 2. Continuous CO_2 tracing during simulated breathing. Baseline, that is the environmental CO_2 concentration, showed 0.025-0.15%. First wave indicated the flushing to the tube system by 10 ml advanced plunger and the peak CO_2 value showed nearly 5% CO_2 (4.8-5.2% CO_2). The following waves consisted of simulated breathing. Arrowhead *a*, the beginning of breath; arrow 1, percent end-tidal P_{CO_2} (% P_{ETCO_2}) of the first breath; arrow 2, % P_{ETCO_2} of the 10th breath. The half time ($t_{1/2}$) values were calculated by approximation (the method of least squares) using % P_{ETCO_2} of first 10 breaths.

Fig. 3. Records of CO₂ dispersal in case of supine (a) and face down on futon 4/sheepskin (b). In each case, two graphs showed a single exponential curve (top) and a linear equation (bottom), which were computed by the first 10 plots of %P_{ETCO₂} versus time, and ln %P_{ETCO₂} versus time, respectively. Closed circle in each graph showed the $t_{1/2}$ value.

approximation (the method of least squares). As mentioned in results, decrements in %P_{ETCO₂} were approximated by a single exponential curve, and the plots of ln %P_{ETCO₂} versus time were approximately expressed by a linear equation. In all cases, correlation coefficients and linear equations were computed using the first 10 plots (%P_{ETCO₂} of 10 breathing), and then the $t_{1/2}$ value of each case was calculated by substituting one-half concentration of first %P_{ETCO₂} to each linear equation (Fig. 3). When measuring the one-half concentrations of first %P_{ETCO₂}, the environmental CO₂ concentrations (0.025%-0.15%) were excluded.

Softness. The softness of bedding was defined by the area of the object in contact with bedding (Kemp et al. 1994). Technically, it was easier to use a glass ball instead of the mannequin head. The 1000 ml round-bottomed flask (outside diameter is 13.6 cm) was prepared and the weight was matched with that of the mannequin head, 1350 g. When the flask was placed on the bedding, the line of contact was circular in configuration. In our study, rectangle-shaped papers, one side of one end being adhesive, were used to measure the diameter of the "circle." The papers were inserted slowly between the bedding and the flask, and when resistance was felt, the sticky surface apex of the papers was regarded as the contact point between the bedding and the flask. With each bedding item, four papers were inserted in four directions at right angles to each other at 0°, 90°, 180°

Fig. 4. Formula calculating spherical surface area (S) in contact with bedding. S values (cm^2) were defined as bedding softness in our study. The diameters were measured in two perpendicular directions. The surface area (S) within the “circle” was calculated using the average diameter.

Fig. 5. Apparatus for measuring resistance to airflow (R) of bedding.

and 270° . The diameters were measured with a slide caliper in two perpendicular directions. The surface area (S) within the “circle” was calculated using the average diameter. Fig. 4 shows the formula used for calculating S values. The area of each item was measured 5 times.

Resistance to airflow. To measure the resistance to airflow (R) for bedding, a cylindrical pipe with a top, bottom and side opening was used in our study (Fig.

5). The inside diameter of the pipe was 6.0 cm, and the top opening and the side opening were clogged with rubber corks with pitot tube inserts. The pitot tube in the side opening was connected to a micro manometer (Manostargage, WO81F-81F5N, Okano), and the pitot tube in the top opening was connected to the gas flow meter (RK1202M-B-1/8-N₂ 2000 ml, CO₂ 200 ml-1K-A, Kofloc). The bottom opening was held firmly against the bedding with a load of 1350 g on the rubber inserted top opening; the pressure on the micro manometer was noted under a N₂ gas flow of 1000 ml/min. The pressure of each item was measured 5 times.

RESULTS

Fig. 3 shows the results of two typical items, i.e., tracings of simulated breathing, approximate single exponential curves computed from first 10 plots of %P_{ETCO₂} versus time, and approximate linear equations of 10 plots of ln %P_{ETCO₂}

TABLE 2. *Quantitative estimates of bedding*

Bedding	$t_{1/2}$ (seconds)	Softness (cm ²)	R (Pa)
Supine	9.8 ± 0.5	—	—
Futon 1	14.1 ± 0.9	14.8 ± 0.6	4.6 ± 0.2
/sheet 5	14.6 ± 0.8	16.7 ± 1.0	6.6 ± 0.1
/towel 7	16.6 ± 0.8	21.0 ± 1.5	4.5 ± 0.1
/towel 8	18.5 ± 0.7	28.4 ± 2.0	5.6 ± 0.1
/sheepskin	19.7 ± 0.4	56.6 ± 4.0	2.9 ± 0.1
Futon 2	15.6 ± 0.7	33.1 ± 3.5	11.8 ± 0.4
/sheet 5	14.6 ± 1.2	32.9 ± 2.6	14.2 ± 0.5
/towel 7	17.3 ± 0.6	41.2 ± 1.7	10.7 ± 0.8
/towel 8	18.7 ± 0.7	46.0 ± 2.7	10.1 ± 0.2
/sheepskin	19.7 ± 0.5	73.0 ± 4.8	4.0 ± 0.2
Futon 3	16.1 ± 0.9	45.7 ± 2.5	18.2 ± 0.6
/sheet 5	15.8 ± 1.0	43.9 ± 2.5	19.6 ± 0.4
/towel 7	16.7 ± 0.7	46.3 ± 3.3	13.7 ± 0.3
/towel 8	17.7 ± 0.6	51.8 ± 1.6	12.8 ± 0.9
/sheepskin	19.0 ± 0.5	78.8 ± 7.9	4.7 ± 0.2
Futon 4	17.2 ± 2.0	43.6 ± 4.7	10.3 ± 0.4
/sheet 6	15.0 ± 1.7	39.5 ± 3.6	13.7 ± 0.8
/towel 7	19.1 ± 0.9	43.6 ± 4.3	8.4 ± 0.5
/towel 8	19.3 ± 1.1	43.9 ± 1.6	9.2 ± 0.7
/sheepskin	20.2 ± 0.8	63.4 ± 1.0	3.7 ± 0.3

Data are expressed as the mean ± s.d.

R, resistance to airflow; Pa, Pascal (1Pa ≡ 1N/m²)

versus time. One is a low rebreathing potential situation; supine, and another is high potential; futon 4 covered with sheepskin. Correlation coefficients were 0.9999 and 0.9989, respectively. All other studies also showed linear correlation between $\ln \%P_{\text{ETCO}_2}$ and time, and correlation coefficients were all greater than 0.997.

The $t_{1/2}$ values, softness and R -values of the test items are shown in Table 2. When the doll was placed face down on the bedding, all of the $t_{1/2}$ values increased in comparison with those of supine position. The item that had most potential for rebreathing was the combination of futon 4 and sheepskin, 20.2 seconds, twice the $t_{1/2}$ value of supine position. The $t_{1/2}$ values and softness of futon 1, 2, 3 and 4 were 14.1 seconds and 14.8 cm²; 15.6 seconds and 33.1 cm²; 16.1 seconds and 45.7 cm²; and 17.2 seconds and 43.6 cm², respectively. Generally, there was a tendency for the softer bedding to decrease CO₂ dispersal, but the relationship between the two was not proportional. The combination of futon and towel increased $t_{1/2}$ values to a certain degree. For example, the time increase using all combinations of futon and towel 8 ranged from 1.6–4.4 seconds; futon 1 showed the maximum increase. The $t_{1/2}$ value of futon 1/towel 8 (18.5 seconds) was equal to that of futon 2/towel 8 (18.7 seconds), and greater than that of futon 3/towel 8 (17.7 seconds). However, futon 1/towel 8 (28.4 cm²) was harder than futon 2/towel 8 (46.0 cm²) or futon 3/towel 8 (51.8 cm²).

The $t_{1/2}$ values of the combinations of futon 4 and towels were 19.1–19.3 seconds, similar to the sheepskin combination (20.2 seconds). Covering futon 4 by sheet, however, shortened the $t_{1/2}$ values by 2.2 seconds. With the addition of sheet to other futon, $t_{1/2}$ values did not increase in all cases with the exception of those using futon 1.

It was assumed that R -values were more affected by the material of futon than by sheet or towel. In the case of sheepskin, R -values were very low. In our study, there was no relationship between R -values and $t_{1/2}$ values. The same is said with regard to between R -values and softness.

DISCUSSION

In many Western countries, a dramatic reduction in the number of SIDS cases has been reported since campaigns warning about the use of the prone sleeping position for infants (Hunt 1995; Wigfield and Fleming 1995). One hypothetical SIDS mechanism is airway obstruction, such as nasal obstruction due to occlusive materials. This mechanism was advanced for a long time, and in Japan, when dead infants have been found prone, some pathologists have diagnosed the death as asphyxia by smothering (Hata et al. 1997). However, in the early 1990s, another asphyxial mechanism was proposed to explain the relationship between infant death and prone sleeping position, that is rebreathing. Rebreathing is the inhalation of recently exhaled air, containing high level of CO₂. The accumulation of CO₂ in the blood may cause various ventilatory and/or circular distur-

bances to infants. Kemp and Thach's mechanical model system and $t_{1/2}$ values proved to be very useful for evaluating the limitation of CO₂ dispersal and the potential for rebreathing (Kemp and Thach 1995). In our experimental system, all CO₂ tracing curves were described as a single exponential curve, and the plots of $\ln P_{ETCO_2}$ versus times obtained from each case were linear similar to Kemp and Thach's result (Kemp and Thach 1995). It can be said that the $t_{1/2}$ values from our system also suggest the potential for rebreathing. Needless to say, the $t_{1/2}$ values of our study were not directly comparable with those of Kemp's studies (Kemp and Thach 1995). The $t_{1/2}$ value with respect to Kemp's sheepskin data was 43.6 seconds, and our values were 19.0-20.2 seconds. The difference may have been caused by the difference of bedding materials or experimental systems (such as the structure of the mannequin's face, the hood size or the sampling rate of the CO₂ analyzer)

With respect to present Japanese baby futon (futon 1), there is a relatively low potential for rebreathing to occur, compared with other futon. However, if futon 1 was used in combination with a towel, the potential of rebreathing approached that of other softer futon. The combination of futon and a bath towel (towel 8) increased the $t_{1/2}$ values by 1.6-4.4 seconds. The usage of a bath towel was connected to increased potential of rebreathing regardless of the type of futon. Compared with towel 7 and 8, a thin cotton sheet (sheet 5 and 6) did not increase the $t_{1/2}$ values, moreover this addition even decreased the potential for rebreathing on some types of futon (futon 4).

Forensic pathologists sometimes experience suffocation in infants due to the mechanical obstruction of the nose and mouth with occlusive materials such as filmy plastic bags. R values on plastic bags exceeded 200 Pascal (Pa) which is the maximum scale value of the micro manometer. R values of two SIDS cases (futon 3/towel 8 and futon 4/sheet 6) were 12-13 Pa, and the rise in the resistance to airflow was mild in comparison with vinyl. In addition, the sheepskin combination that seems to be very dangerous in prone sleeping position maximized the limitation of CO₂ dispersal in our study, although it had the lowest resistance to airflow. Even if the bedding has low resistance to airflow, it may cause considerable rebreathing.

CO₂ dispersal may be related to bedding softness to a certain degree, but not closely. Kemp and Thach (1995) pointed out that the CO₂ dispersal was reflected by the independent effects of softness and the porosity of the bedding. According to Kemp and Thach's conclusions, in the case of similar levels of softness, bedding composed of porous materials has more rebreathing potential than less porous bedding. In our items, the addition of a towel may result porous bedding characteristics. Most babies are not placed directly on futon but on futon covered with a sheet and/or a towel. Even if one uses a hard mattress-type futon, the potential for rebreathing may increase with the use of a cotton (bath) towel. However, it was difficult to determine whether these items were dangerous

to a baby or not. The most prolonged $t_{1/2}$ value recorded when using the combination of futon 4 and towel 8, which is only twice that in supine position, and 1.4 times that of a hard mattress (futon 1). We were inclined to think that the prolongation was not remarkable, at least compared with Kemp's results (Kemp and Thach 1995).

In addition, our approach was the analysis only of CO₂ dispersal simulation, and the results did not directly explain the cause of sudden unexpected infant death. Most infants have an arousal system, and when they fall into hypercapnea or hypoxia when in face down position, they will change breathing pattern and turn their face position, or will awake. In the 1991 report by Kemp's group (Kemp and Thach 1991), they emphasized that an infant who found dead face down on bedding which has high potential for rebreathing should be diagnosed as having died of asphyxia not SIDS, because such a death mechanism is closely related to suffocation. In their following papers (Kemp and Thach 1993; Kemp et al. 1993), however, although they stated that rebreathing might be a probable etiological mechanism of death, they mentioned relationships between rebreathing and other etiological hypotheses of the cause of SIDS, such as hyperthermia or defective arousal response. Bolton et al. (1993) also believed the combination of rebreathing and defective arousal response may cause sudden infant death. Bolton (1990) had previously observed that 2% of the infant population had abnormal responses to increased inspired CO₂ concentrations and paradoxical hypoventilatory response to hypoxia, and his group believed that those infants might be in a dangerous situation when placed in face down position (Bolton et al. 1993).

The rebreathing hypothesis has not been proved yet, and some researchers remain skeptical about this theory (Guntheroth and Spiers 1996). However, the potential for rebreathing increased, more or less, in face down on all bedding, and supine position was the best CO₂ dispersal position. Even if there may be a few "susceptible infants" (i.e., those who have higher threshold of arousal response to high CO₂ concentrations and those who easily develop SIDS), it is presently difficult to detect the abnormality and these infants may seem to be outwardly healthy. Therefore, supine position should be recommended to all "healthy" infants. The best way to prevent rebreathing is to place a baby on the back.

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