Rebreathing expired gases from bedding: a cause of cot death?

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Abstract

The reported association of cot death and sleeping prone could be due to rebreathing of expired gases. A mechanical model simulating the respiratory system of an infant, exhaling warm humidified air with an end tidal carbon dioxide of 5%, has been used to investigate this. Some commonly used bedding materials caused an accumulation of carbon dioxide of 7% to over 10% with the model lying face down. This phenomenon persisted even with the head inclined at 45°, but only on very soft materials, and could be a cause of cot death in a baby unresponsive to asphyxial blood gas changes. A coir fibre mattress allowed complete dispersal of exhalate as did a rubber sheet between any mattress and the covering sheet.

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Studies in New Zealand,¹ Australia,^{2,3} England,⁴ France,⁵ and the Netherlands⁶ have identified the prone sleep position as a major risk factor for sudden infant death syndrome (SIDS). Where community intervention to change babies sleep position away from prone has occurred, there has been marked declines in SIDS and total postneonatal mortality.^{7,8}

The mechanism by which lying prone might increase the risk of SIDS in infants is subject to debate.^{9,10} A recent investigation of 25 deaths of infants found prone and face down with nose and mouth buried in a cushion filled with expanded polystyrene beads (of whom 19 were diagnosed as having died of SIDS), concluded

that accidental suffocation by rebreathing was the likely cause of 22 (88%) of the deaths.¹¹

In this study we have used a mechanical model to assess the degree of rebreathing likely to occur in an infant placed to sleep prone with head face down, at 45° or at 90° to a variety of sleeping surfaces.

Methods

THE MODEL

A model of a 3 month old infant's head and respiratory system was constructed similar to that described by Bolton *et al* (fig 1).¹² The head was anatomically moulded using silicon plastic and of an appropriate weight for a 3 month infant (1.3 kg). A motor driven syringe pump (Harvard rodent respirator model 681), was used to ventilate the 'nostrils' at a rate of 40 'breaths' per minute with a 'tidal volume' of 27 ml. A glass mixing chamber (volume=200 ml), together with the pump, formed the equivalent volume of the lungs of a 6 kg baby. A 10 ml silicone tube connected the 'lungs' to the nostrils to constitute the dead space of the model's respiratory system. The tubing divided distally to allow air flow through the two nostrils.

The mixing chamber was warmed by continuously circulating heated water through a surrounding water jacket. The temperature of the water was adjusted so that the temperature of the air reaching the nostrils was always $37.0 \pm 0.5^\circ\text{C}$ at the conclusion of each run. Humidity within the system was provided by placing water soaked gauze within the mixing chamber.

DATA COLLECTION

Thermistor probes were used to measure temperatures of the air reaching the nostrils (positioned at the end of the dead space tubing) and ambient air (positioned 5 cm in front of the head). A capacitive humidity probe was used to measure relative humidity at the same ambient site. All data for temperature and humidity were recorded by a multichannel data logger system (Squirrel; Grant Series 1200).

For each experiment, carbon dioxide was continuously trickled into the mixing chamber at a rate of 35 ml per minute which produced an 'alveolar plateau' of about 5% carbon dioxide (equivalent to an arterial oxygen pressure of 36 mm Hg (4.80 kPa)) when the face was unobstructed. Air was sampled from a catheter situated just inside the nostril and the profile of carbon dioxide for each breath was measured by a Normocap carbon dioxide monitor (Datex Instrumentarium Corporation)

Figure 1 Apparatus for determining rebreathing of carbon dioxide when lying prone. Carbon dioxide was fed into the lungs at a fixed rate comparable with the carbon dioxide production of a 3 month infant. Resulting end tidal carbon dioxide was sampled just inside the nostril. Each breath was warmed and humidified.

sampling at a rate of 50 ml per minute. This sampling rate was considered to be low enough not to interfere with the build up of gases as it was less than 5% of the total ventilation. The carbon dioxide monitor was calibrated against standard gases. Pressure within the nostril was recorded using a Grass volumetric pressure transducer (PT5A). The pressure recordings and the tidal volume allowed the resistance to gas flow to be calculated for each bedding material. Outputs from the carbon dioxide monitor and pressure transducer were relayed through the integrated hardware/software system of the MacLab (Analog Digital Instruments Pty Ltd) to an Apple Macintosh Computer (Apple Computer Inc).

HEAD POSITIONING

The angle between the head's sagittal plane and the horizontal was measured using a brass rod fixed to the back of the head. The rod had a freely rotating, weighted protractor on it, which maintained a vertical position while the head, the brass rod, and a pointer rotated indicating the angle of the head. The weight of the brass rod, pointer, and protractor were included in the 1.3 kg weight of the head. The head was allowed to rest with its full weight onto the bedding at the specified rotation. Experiments were conducted with the head placed in each of three positions: (i) at 90° to the bedding, (ii) at 45° to the bedding, and (iii) face down to the bedding.

BEDDING MATERIALS

Twenty combinations of under bedding materials commonly used in New Zealand were tested.* These comprised 12 using either a soft (foam chip or woollen) or hard (coir fibre or foam slab) mattress covered with a cotton sheet with or without a waterproof layer under the sheet. When a waterproof layer was used it was either a 'Protect-a-cot' woollen blanket or a rubber sheet. The remaining combinations tested were sheepskins of four different fibre

Figure 2 Carbon dioxide profile when face down into soft bedding. This trace shows the quick rise of inspired carbon dioxide when face down on soft bedding. The arrow indicates when the head is in the appropriate position. *1 mm Hg=0.133 kPa.

lengths (15, 30, 40, and 60 mm) either uncovered or covered with a cotton sheet. A hard covered book was used as a control.

EXPERIMENTAL PROTOCOL

For each run the model was first placed face to the side with the head suspended well above the bedding and table and ventilated as described above until the percentage of inspired carbon dioxide reached equilibrium. Equilibrium was defined as less than 0.2% change in the inspired carbon dioxide concentrations over 20 seconds. The model was then placed in the test condition and run to equilibrium again. Each experiment was repeated six times in each of the three head positions. Room and head temperature and room humidity were monitored continuously. Humidity and room temperature varied between 30 and 50% and 20 to 24°C respectively and did not correlate with changes in carbon dioxide rebreathing concentrations. Draughts did affect carbon dioxide rebreathing and experiments were therefore carried out in a partitioned off, draught-free area of the laboratory.

A typical time course of an experiment showing carbon dioxide accumulation is shown in fig 2.

Results

The table shows the mean (SEM) inspired carbon dioxide concentrations at equilibrium from all surfaces tested.

FACE DOWN TO BEDDING

The table shows that negligible rebreathing (less than 2% of carbon dioxide accumulation) occurred with the model placed face down onto the two firm mattresses. The hard covered book also resulted in minimal rebreathing (0.62 (0.04)%). Softer mattresses and all four sheepskins (with or without the cotton sheet covering) showed much greater carbon dioxide accumulation (6.95 to greater than 10%).

The average time to reach 10% inspired carbon dioxide was less than 90 seconds.

Mean (SEM) inspired carbon dioxide (%) with the face at different angles to common infant under bedding materials

Sleeping surface	Face to side	Face at 45°	Face down
Hard covered book	0.18 (0)	0.22 (0.01)	0.62 (0.04)
Bedding uncovered			
Sheepskin 15 mm	0.23 (0)	0.55 (0.02)	>10
Sheepskin 30 mm	0.15 (0)	0.57 (0.04)	9.95 (0.02)
Sheepskin 40 mm	0.35 (0.02)	8.47 (0.29)	>10
Sheepskin 60 mm	0.79 (0.06)	>10	>10
Bedding and cotton sheet			
Coir fibre mattress	0.18 (0)	0.31 (0.01)	0.96 (0.02)
Foam slab mattress	0.17 (0)	0.29 (0.01)	1.88 (0.09)
Woollen mattress	0.18 (0.01)	0.35 (0.01)	6.95 (0.45)
Foam chip mattress	0.14 (0.01)	0.84 (0.03)	>10
Sheepskin 15 mm	0.24 (0.01)	0.53 (0.02)	9.53 (0.19)
Sheepskin 30 mm	0.27 (0.01)	0.68 (0.04)	9.14 (0.25)
Sheepskin 40 mm	0.26 (0.01)	1.06 (0.02)	9.64 (0.15)
Sheepskin 60 mm	0.33 (0.01)	0.89 (0.03)	9.43 (0.24)
Woollen waterproof layer between mattress and sheet			
Coir fibre mattress	0.18 (0)	0.30 (0.01)	0.93 (0.02)
Foam slab mattress	0.17 (0)	0.31 (0.01)	4.32 (0.27)
Woollen mattress	0.17 (0)	0.30 (0.01)	2.36 (0.14)
Foam chip mattress	0.20 (0.01)	0.81 (0.02)	7.05 (0.33)
Rubber sheet between mattress and sheet			
Coir fibre mattress			0.78 (0.03)
Foam slab mattress			0.96 (0.04)
Woollen mattress			1.1 (0.03)
Foam chip mattress			0.88 (0.05)

45° TO BEDDING

All mattresses tested showed less carbon dioxide accumulation when the head was at 45° than when placed face down. These concentrations were all negligible (less than 1%).

Mean inspired carbon dioxide concentrations at equilibrium for the short wool fibre sheepskins (15 and 30 mm) without a cotton sheet were small (less than 1%), but reached greater concentrations with the longer fibre lengths (8.47 (0.29) and greater than 10% with 40 and 60 mm fibre lengths respectively). With a longer fibre length sheepskin the nose, even with the head at 45°, was surrounded by wool. Covering the sheepskins with a cotton sheet produced only small changes on the short wool fibre skins, however, large differences were observed for the longer fibre sheepskins. For 40 mm fibre lengths without a cotton sheet cover, 8.47% carbon dioxide accumulation was reduced to 1.06 (0.02)% with covering and for 60 mm fibre lengths, 10% carbon dioxide accumulation was reduced to 0.89 (0.03)% with covering.

90° TO BEDDING

All surfaces produced negligible carbon dioxide accumulation (less than 0.8%) when the model was placed at 90° to the bedding.

WATERPROOF LAYER

The addition of a rubber sheet between any mattress and the sheet reduced carbon dioxide build up (0.78–1.15% carbon dioxide). A woollen waterproof layer below the sheet however did allow accumulation on the foam chip mattress (7.05 (0.33)%) and on the foam slab mattress (4.32 (0.27)%).

AIRWAY RESISTANCE

Airway resistance was found to be similar to the reported values for normal infants.^{13 14} The mean resistance when the face was unobstructed was 0.6 (0.04) kPa/l/sec. The greatest resistance was found when the model was face down into the long haired sheepskin (60 mm fibres). This resistance was 20 kPa/l/sec. This represents a pressure swing of about 0.35 kPa, which would not be considered enough to disturb or endanger a sleeping infant.

Discussion

Using a mechanical model of the infant head, we have found that considerable rebreathing occurred when the head was face down into soft under bedding. An infant placed to sleep in the prone position would normally have its head to the side, but this is the only position (unlike supine or lateral) that would allow the face to turn partially or directly into the bedding. Although in our mechanical model, direct face down contact with the surface caused the greatest amount of rebreathing in any of the materials studied, with the head at 45° to the uncovered long fibre sheepskin, the

equilibrium concentration of inspired carbon dioxide (greater than 10%) is of concern if it mimics the real life situation. With the head face down the two firmest mattresses (coir fibre and foam slab) gave the best gas dispersal.

Our experiments would indicate that the lethal potential of polystyrene bead filled cushions, reported by Kemp and Thach,¹¹ applies to all soft bedding materials. In that study three of the deaths occurred on the first night the baby had slept on the cushion and another 11 of the 19 deaths occurred on the only occasion on which they had been sleeping face down. These events presumably occurred among a considerable population of babies who suffered no ill effects from sleeping on the cushions.

Our results suggest that these deaths may have occurred from a failure of the babies concerned to respond to a high inspired carbon dioxide. Bolton *et al* have shown that 2% of an infant population may have inadequate responses to increased inspired carbon dioxide concentrations and paradoxical hypoventilatory response to hypoxia.¹⁵ If one of these unresponsive babies found itself face down on bedding that did not allow adequate dispersion of expired gases it would not respond and thus it is likely that the first exposure would result in death.

The normal physiological response to rebreathing would be that the hypercapnia and hypoxia would stimulate an increase in ventilation, positional movement, and arousal. McCulloch *et al* have reported that a near-miss SIDS infant had a significantly higher arousal threshold to alveolar carbon dioxide pressure, 54.9 mm Hg (7.32 kPa) compared with 48.4 (6.46) for normal infants,¹⁶ and other authors have identified deficiencies in ventilation and arousal responses in siblings of SIDS victims, infants with a history of apnoea, and others.^{17–19} Neuropathological studies have shown that decreased myelination in motor and arousal areas of the brainstem of SIDS victims suggest that inappropriate arousal responses could have been a factor in the death of these infants.²⁰

If the infant arouses, then the next consideration is whether or not the infant could move away from this potentially lethal environment. A conclusion of Kemp and Thach's study of 25 SIDS victims sleeping prone on polystyrene cushions was that movement of the head from side to side to escape the stimuli could exacerbate the situation by causing a deeper pocket to be formed in the cushion for more expired gas trapping.¹¹

Controlled lifting of the head in the prone position is not usually accomplished until 3 months of age.²¹ At 3 months of age the infant can maintain the lift with the face at an angle of 45–90° to the bed.^{22–24} The ability of infants to turn from the prone to the supine position is usually accomplished by 24 weeks.^{22 23 25 26} This positional change could occur only if the infant is not tightly swaddled. Thus it is possible that a premature or slowly developing infant may not be able to clear its face from the bedding, especially if a depression is formed in the

Figure 3 Inspired oxygen and carbon dioxide pressures. The carbon dioxide values are from an actual experimental trace. The oxygen values are computed assuming there is no ventilatory response to the stimulus and that the respiratory quotient stays constant. *1 mm Hg = 0.133 kPa.

bedding. It also suggests a good reason why there are not so many deaths from SIDS in the first six weeks of life as during this time prone sleeping infants are unlikely to raise their head and place it face down.

If the infant was unable to escape a severely hypercapnic environment, the hypercapnia itself could kill. If inspired air contains 10% carbon dioxide, this gives an inspired carbon dioxide pressure of 71 mm Hg (9.46 kPa) with an arterial carbon dioxide pressure being even greater. Carbon dioxide narcosis is associated with arterial carbon dioxide pressure of over 80 mm Hg (10.70 kPa).²⁷ Figure 3 shows the actual inspired carbon dioxide pressure of the model when face down on soft bedding. Assuming that the carbon dioxide accumulation is the result of re-inspiration of all the expired gases, we have calculated the corresponding inspired carbon dioxide pressure assuming a normal respiratory quotient and breathing air. Figure 3 shows that after 30 seconds the inspired carbon dioxide pressure is greater than 50 mm Hg (6.67 kPa) and inspired oxygen pressure would be around 65 mm Hg (8.66 kPa).

In conclusion, our data imply a dangerous situation for the infant who is put to sleep prone, whose head turns directly into or at 45° to certain soft bedding materials, and who may be or become unresponsive to the lethal challenge of rebreathing. We believe that all infants should be placed to sleep in the supine position or side with lower shoulder forward unless there is a clear medical reason for sleeping prone (abnormalities of the upper airway or severe gastro-oesophageal reflux). In the recommended sleep positions (back or side) the use of soft bedding would be acceptable, in fact there is evidence to support the use of sheepskins for low birthweight infants,²⁸ but if the infant must be placed prone or may possibly

turn so that its face is into the soft bedding then a rubber sheet should be placed between mattress and sheet or a firm bedding surface used.

*Since submitting this paper we have tested a mattress featuring holes in the head area and in the carry cot below, which is commonly supplied to British consumers. The mattress behaved exactly like others made from soft materials.

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