Arch Dis Child 1998;**78**:323–328

Mechanical model testing of rebreathing potential in infant bedding materials

James N Carleton, Ann M Donoghue, Warren K Porter

Abstract

Rebreathing of expired air may be a lethal hazard for prone sleeping infants. This paper describes a mechanical model to simulate infant breathing, and examines the effects of bedding on exhaled air retention. Under simulated rebreathing conditions, the model allows the monitoring of raised carbon dioxide (CO_2) inside an artificial lung–trachea system. Resulting levels of CO_2 (although probably exaggerated in the mechanical model compared with an infant, due to the model's fixed breathing rate and volume) suggest that common bedding materials vary widely in inherent rebreathing potential. In face down tests, maximum airway CO_2 ranged from less than 5% on sheets and waterproof mattresses to over 25% on sheepskins, bean bag cushions, and some pillows and comforters. Concentrations of CO_2 decreased with increasing head angle of the doll, away from the face down position. Recreations of 29 infant death scenes also showed large CO_2 increases on some bedding materials, suggesting these infants could have died while rebreathing.

(*Arch Dis Child* 1998;**78**:323–328)

Keywords: sudden infant death syndrome; rebreathing; carbon dioxide; infant breathing model

Recent studies have implicated the prone sleeping position as a risk factor for sudden infant death syndrome (SIDS).[1–5] In an effort to explain this association, one current hypothesis holds that rebreathing of expired air may cause lethal asphyxia in susceptible face down infants.[6–9] Several pieces of evidence lend support to this hypothesis. For instance, face down exposure to some bedding materials has resulted in documented rebreathing in rabbit models, leading to lethal hypoxia and hypercarbia.[6–8 10] Also, in a recent study on prone sleeping infants,[11] all of 11 subjects tested spent some time sleeping face down. End tidal carbon dioxide (CO_2) measurements showed that all experienced some rebreathing when face down on soft bedding. One infant showed "moderate to marked asphyxia while positioned face down without any evidence of arousal from sleep". Recently identified brain deficiencies in SIDS infants[12] suggest they may lack the protective reflex responses of normal infants to hypercarbia and asphyxia experienced during sleep. Furthermore, there is evidence that some SIDS events may be preceded by a period of hypoxia.[13 14]

Directorate for Laboratory Sciences, US Consumer Product Safety Commission, Washington DC, USA
J N Carleton
A M Donoghue
W K Porter

Correspondence to: Warren K Porter, US Consumer Product Safety Commission, Chemistry Division, 10901 Darnestown Road, Gaithersburg, MD 20878-2611, USA.

Accepted 31 October 1997

According to the rebreathing hypothesis, some bedding materials may act to retard the dispersal of exhaled gases, retaining the gases near a face down infant's mouth. With each subsequent breath the infant takes in an air mixture which is progressively less adequate to sustain life. An infant who remains face down on certain types of bedding for more than a short period of time might therefore be susceptible to rebreathing induced asphyxiation. The more conducive an item is to rebreathing, the more hazardous the item would be. Kemp and Thach[6] used the term "rebreathing potential" when referring to this property, and suggested that measurements of physical variables such as porosity could help identify bedding materials in which rebreathing potential is likely to be high.

If rebreathing is a contributing factor in some SIDS deaths, then given that different bedding materials presumably differ in rebreathing potential, the risk of SIDS for prone sleeping infants should be unevenly distributed across bedding types, after adjustment for known risk factors. Evidence of such an association was reported, showing that the risk of SIDS was six times greater among Australian infants who slept prone on natural fibre mattresses (filled with ti-tree bark or kapok fibres) than among those who slept prone on other types of mattresses, including foam mattresses.[1] These natural fibre mattresses are described in the report as being soft, fluffy, and generally enclosed in a permeable cotton cover which allows the free passage of air.

Another study used a mechanical model to investigate simulated rebreathing on sheepskins and four kinds of mattresses commonly used in New Zealand.[15] In that study, sheepskins of various lengths and softer mattresses resulted in rapid build up of end tidal CO_2 to relatively high levels (more than 10%), when the model was placed face down on them. In the case of the mattresses, a waterproof (impermeable) layer between the mattress and sheet was found to substantially reduce the carbon dioxide build up. A limitation of this model was the inability to measure CO_2 concentrations of more than 10%.

The data summarised in this report were collected as part of the infant suffocation project of the Consumer Product Saftey Commission (CPSC), an ongoing investigation into the potential rebreathing hazards associated with infant bedding products. This investigation encompasses a wider range of products than previous rebreathing studies, and focuses on materials associated with infant deaths, many of which have been diagnosed as cases of

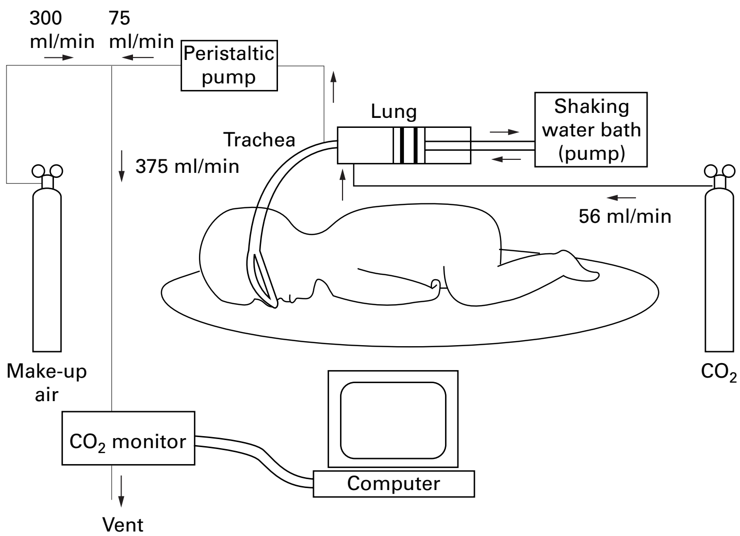

Figure 1 Schematic representation of the mechanical model.

SIDS. As part of the investigations, bedding from infant death scenes was gathered, and in depth interviews with the parents or guardians conducted. In each case the person who discovered the dead infant was asked to place a doll in a position similar to that in which the infant was found.[16] Photographs were then taken of these dolls and sent to the laboratory to allow approximate recreations of the death scenes to be conducted.

A mechanical model similar to the one used by Bolton *et al*[15] was used to examine these death scene bedding items and other bedding not directly associated with infant deaths. Unlike the Bolton model, which sampled end tidal air, our model samples CO_2 from inside the trachea where it joins the lung. Also unlike the Bolton model, our system is capable of measuring CO_2 concentrations as high as 50%. The primary purpose of this work was to identify bedding materials which may be capable of causing hazardous levels of rebreathing in infants. The maximum (that is, equilibrium) CO_2 concentration achieved during a 15 minute face down run on any given bedding provides a relative indication of the bedding's inherent rebreathing potential. This establishes a method for examining and comparing rebreathing potential between bedding types, or as a function of other variables such as construction details or environmental conditions.

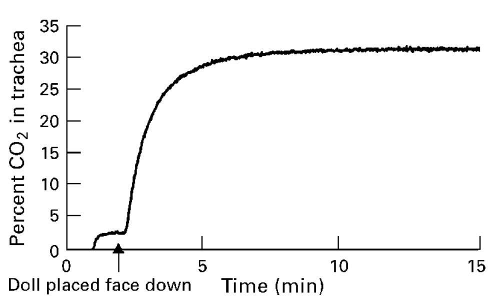

Figure 2 Example mechanical model run, face down on a sheepskin.

Methods

MODEL

The model employed a brass syringe mounted on a laboratory shaking water bath as a mechanical "lung", with the bath functioning as a pumping mechanism. Figure 1 provides a schematic representation of the model.

The syringe barrel, of 4.5 cm (1.75 inch) internal diameter, was locked in place against the chassis of the bath, while the rocker arm pushed the plunger back and forth inside the barrel. Two rubber O rings formed an airtight seal between the plunger and the inside of the barrel, so that the internal volume of the lung could be varied in a sinusoidal fashion between 65 and 100 ml when the bath motor was turned on. The bath motion was set such that 35 ml "breaths" were delivered at a constant rate of 45/min. This rate was verified with a stopwatch before the beginning of each experiment. The model's lung volume, breathing rate, and breath volume were selected to simulate the alveolar air volume, tidal volume, and respiratory frequency, respectively, of an infant.[17,18] CO_2 was fed from a tank into the lung at 56 ml/min to simulate a mean lung concentration of 5%, a normal alveolar value.[19] Constancy of the gas flow was assured with an in line flowmeter. A length of PVC tubing (4 mm internal diameter) serving as a "trachea" led from an opening in the lung to a Y connector, which was attached to two tubes connected to the nares of an infant sized doll. Thus the lung caused simulated breathing to take place at a constant rate and tidal volume through the nares of the doll. The total dead volume inside the trachea, Y connector, and nare tubes was 10 ml. The resistance to air flow through this apparatus was 39 cm H_2O/l/s, which is within the normal range for the respiratory system of a nose breathing newborn infant.[18] The doll's head contained 980 g of lead pellets in an internal volume of 915 ml, to approximate the 1.071 kg/l density of human tissues.[19] The head, which was capable of rotating sideways relative to the body, was marked off in 15° increments so that the head angle could be precisely set.

CARBON DIOXIDE MEASUREMENTS

A gas sampling port was located near the end of the trachea immediately adjacent to the lung. This led to a peristaltic pump which was set to withdraw 75 ml/min of tracheal air for analysis. The air passed through a calibrated rotameter, allowing visual verification of flow rate constancy. The gas was then routed through an infrared monitor (Vacumed Co 17600, Ventura, California, USA) which measured the CO_2 content of the sampled gas. However, in order to accommodate the high flow requirements of the monitor, the gas was first combined with 300 ml/min of air from a cylinder (for a 5:1 air to tracheal gas ratio). This dilution of tracheal gas in air had the added benefit of extending to 50% the maximum CO_2 that could theoretically be measured, and minimised the perturbing effect that a 375 ml/min withdrawal rate would have had on tracheal gas equilibrium. The monitor was

Table 1 Number of items with mean airway maximum %CO_2 falling into each of three concentration ranges, in face down tests using a mechanical model

Item class (n)	*Max % CO_2 ranges* 3.4–10.0	10.1–20.0	20.1–32.2
Sheepskins			
Natural fibre, 2.0 to 3.8 cm nap (5)			5
Natural fibre, 5.1 to 6.4 cm nap (3)			3
Synthetic fibre, 2.0 cm nap (1)			1
Pillows and cushions			
Bean bag cushions (3)			3
Pillows, infant size, polyester filling (6)	1	1	4
Pillows, adult size, polyester filling (5)	1	2	2
Pillows, adult size, foam filling (2)		2	
Pillow, adult size, down filling (1)	1		
Pillows, decorative (2)	2		
Couch cushions (2)	2		
Foam rubber, bare, flat surface, 6.4 cm thick (1)			1
Foam rubber, bare, "egg crate" surface, 4.8 cm thick max (1)		1	
Comforters			
Comforters, infant size, polyester filling (26)	8	17	1
Comforter, adult size, down filling (1)		1	
Comforter, adult size, polyester filling (1)	1		
Blankets, quilts, sheets			
Blankets/quilts (5)	5		
Sheets, plain (2)	2		
Sheets, quilted (1)		1	
Miscellaneous items			
Infant sleeping bags, polyester filling (2)		2	
Carry cots, 2.3 to 3.3 cm foam pad in bottom (2)		1	1
Mattress and bassinet pads, plastic encased (12)	12		

interfaced through an analogue to digital conversion board (Cyberesearch Inc, CYDAS-16, Brantford, Connecticut, USA) to a personal computer, allowing CO_2 concentrations inside the trachea to be recorded as a function of time. The software used for data collection automatically multiplied CO_2 concentrations by a factor of five, to account for the dilution of the sampled gas.

The CO_2 monitor was calibrated at the beginning of each day on which testing took place, using bottled air for the zero, and 4.95% CO_2 in nitrogen for the span. The span gas was certified as being traceable to National Institute of Standards and Technology (NIST) standards. While in use, all gases (CO_2, air, calibration gases, and sampled tracheal gas) passed through rotameters mounted on a control panel. The rotameters allowed ongoing visual confirmation of proper flow rates, and periodic readjustment as needed.

REBREATHING TESTS

Three types of tests were performed: face down tests on individual bedding items, tests at various head angles for selected items, and death scene recreations. The latter involved bedding samples (frequently consisting of multiple items) retrieved from the scenes of unexpected infant deaths, with the doll positioned as closely as possible to the positions in which the infants were reportedly found. In most of these cases the infants had been found face down, with nose and mouth against the bedding.

Table 2 Airway maximum per cent carbon dioxide at various head angles on five bedding items

Model head angle (degrees)	*Bedding item* *Bean bag cushion*	*Sheepskin**	*Carry cot*	*Comforter†*	*Pillow†*
0	34.1 (0.6)	31.1 (1.5)	19.4 (0.6)	30.0 (2.2)	28.1 (1.2)
15	25.4 (3.4)	31.1 (1.2)	14.3 (0.9)	21.5 (2.5)	20.7 (2.9)
30	13.5 (3.2)	28.6 (1.0)	11.2 (1.4)	10.9 (1.1)	16.8 (0.6)
45	7.8 (0.9)	21.3 (1.2)	5.3 (1.1)	5.8 (1.0)	10.3 (1.5)
60	7.9 (1.5)	14.2 (0.8)	4.1 (0.1)	4.8 (0.9)	7.1 (0.2)
75	4.5 (0.8)	9.7 (1.9)	3.7 (0.1)	3.2 (0.1)	4.5 (0.1)
90	2.7 (0.2)	6.8 (1.1)	3.5 (0.2)	2.9 (0.3)	3.3 (0.1)

Values are mean (SEM) for three replicates of each test. *6.4 cm nap. †Items are infant sized and filled with polyester batting.

Except for the death scene recreations, tests began with the doll placed on the bedding, with the head turned 90° to one side, and the pumping motor running. After establishing a baseline tracheal air reading at 0%, the CO_2 flow into the lung was turned on. Within about 90 seconds the measured CO_2 typically reached equilibrium at about 2.5%, with the doll's breathing unimpeded. Next the head was turned face down into the bedding (fig 1), or to the specific head angle being tested. In all cases, a new CO_2 equilibrium was achieved within 15 minutes. Maximum concentrations for each run were recorded to the nearest 0.1%. The death scene recreations were done in the same way, except that they began with the doll already in the death scene pose. A minimum of three repetitions for each test were performed, and the mean and standard errors for maximum % CO_2 were calculated. In the results from the tests at different head angles, the coefficient of variation (CV) for replicates within each treatment was calculated, and the mean (SD) % CV among treatments was 5.4 (1.1), range 3.0 to 40.5.

Results

Figure 2 shows the results from a typical run, in this case a face down test on a sheepskin. Because the response time of the monitor in our system (~8 seconds to reach 90% instrument saturation) was slow compared with the model's breathing rate, the instantaneous concentration changes associated with individual breaths are not visible in the trace. Instead the measured CO_2 represents a running, time weighted average of air concentrations at the sampling point inside the model trachea. After the doll was placed face down, the CO_2 rose dramatically, in this case eventually reaching equilibrium at about 30%. The magnitude of this CO_2 increase was found to vary as a function of bedding type, and to a lesser extent between different items of the same general type.

Table 1 summarises the maximum CO_2 values from the tests performed on individual items, according to general bedding type. The results are divided into three concentration intervals over the range from 3.4% to 32.2% (the highest and lowest values measured, respectively). The tabulated values reflect the mean results measured over all repeat tests on a given item.

Sheepskins of all nap lengths, and bean bag cushions, consistently showed the highest CO_2 concentrations (over 20.0%). Results for pillows and comforters (defined for our purposes as quilts composed of a layer of fibrous batting, enclosed in a woven fabric cover) were more varied. Some polyester fibre filled pillows, both adult and infant sizes, fell in the highest range,

Table 3 Recreations of infant death scenes (facedown position except where otherwise indicated) with the mechanical model

*Items under doll during test**	*Max % CO_2*
Comforter/blanket/quilted sheet	28.7 (1.2)
Pillow/comforter/sheet	26.6 (0.2)
Sleeping bag/comforter/bassinet pad	26.4 (2.8)
Pillow/comforter	25.7 (3.2)
Comforter	22.9 (4.2)
Comforter/sheet/mattress/bassinet pad	20.1 (6.7)
Comforter/comforter/couch cushion	17.3 (3.7)
Pillow, adult size	16.7 (5.2)
Sheepskin, natural fibre, 3.8 cm nap†	16.6 (5.1)
Comforter/sheepskin, natural fibre, 5 cm nap	15.4 (3.5)
Blanket/comforter/mattress	14.9 (0.8)
Pillow, adult size	14.7 (1.8)
Sheet/quilted sheet	14.3 (1.7)
Comforter	13.8 (2.8)
Blanket/comforter/sheet	13.7 (3.1)
Blanket/bassinet pad/bassinet	12.8 (3.0)
Quilt	12.6 (1.7)
Comforter	12.2 (4.8)
Comforter (adult, down filled)	11.6 (1.2)
Comforter	11.1 (4.0)
Sheet/mattress	10.8 (1.6)
Comforter	10.5 (0.5)
Comforter/pillow	10.5 (2.0)
Comforter/mattress	10.3 (4.0)
Comforter/comforter/comforter/sheet/sheet‡	9.1 (0.6)
Quilt/mattress	9.1 (2.0)
Cloth diaper/changing pad	8.0 (0.8)
Quilt/mattress	6.3 (0.5)
Sheet/quilted sheet/mattress	4.5 (0.2)

Maximum % CO_2 (mean (SEM)) values shown for each set of bedding items. *Unless stated otherwise, all comforters, pillows, and the sleeping bag are infant sized, polyester fibre filled. Mattresses, bassinet pads, and the changing pad are all waterproof (enclosed in a plastic covering). †Face turned to the side (about 45°). ‡Face turned to the side (about 90°), but overlain by a decorative type pillow.

while others fell into the middle and low ranges. Of 26 infant comforters tested, 25 fell below 20.0% CO_2. Surprisingly, the only comforter which fell into the high range (above 20.0%) was of about the same thickness as most of the other infant comforters (½ to 1 inch, 1.25 to 2.5 cm, uncompressed). This item did not appear obviously different from these other comforters in any way. One infant comforter was noticeably bulkier than the others, at 1.5 to 3 inches (4 to 8 cm) uncompressed. However, this item resulted in a maximum CO_2 concentration of only about 9%, placing it in the low range. Not surprisingly, very thin items (blankets, quilts, sheets) fell into the low and middle ranges, while plastic encased (waterproof) mattresses and bassinet pads fell consistently into the low range (all items referred to in tables 1 and 3 as "mattresses" were typical infant crib mattresses with an outer covering of plastic—mattresses of other designs were not tested).

In the tests at different head angles on various bedding materials, the face down position (head angle = 0°) consistently resulted in higher CO_2 than other positions, with a decrease in maximum concentration as the head was turned more and more towards the side (table 2). The only exception to this observation was the sheepskin, which resulted in the same mean concentration (31.1%) at 15° as at 0°. In tests with the sheepskin the head had to be turned further than with other products in order to reach an equivalent reduction in CO_2. On most items, a head angle of 30° resulted in an approximately 50% reduction in CO_2 compared with the face down position. In the case of the sheepskin, however, the CO_2 did not drop below 50% of the face down value until the head was at an angle of 60°. Even at 90° the CO_2 was as high as 6.8%. This may have been because the sheepskin fibres (6.5 cm nap) extended above the height of the doll's nares, though the head was turned completely sideways.

Table 3 summarises the results of the 29 infant death scene recreations, listing the bedding materials retrieved from each death scene which were then tested using our model. For each test, bedding items are listed in order of decreasing proximity to the infant, with the topmost item listed first. The table presents the results from top to bottom in order of decreasing CO_2 concentration. Only cases in which the infants were found laying either face down or sideways with nose and mouth pressed against the bedding are reported here. As expected, recreations from cases in which the air passages were free and unimpeded showed little or no CO_2 increase; therefore these results are not included here.

Discussion

Our results show that in a mechanical model of an infant, rebreathing of air varies between different types of bedding materials and between different head positions. Because the model cannot physically respond to increased CO_2 like an infant (the model's breathing rate and volume are fixed), CO_2 rapidly equilibrates in the "trachea" at concentrations that probably exaggerate the effect an infant would experience. Nevertheless we believe that these concentrations are useful as a relative measure of rebreathing potential, which is itself determined solely by the inherent physical properties (that is, porosity, permeability, size, compressibility, and so on) of the bedding materials.

Our results show maximum rebreathing taking place in the face down position on various materials, and decreasing as the head is turned to the side. On the sheepskin this decline with increasing head angle was less pronounced, and seemed to lag behind the other items by about 30°, which suggests that sheepskins might cause hazardous rebreathing even for infants who are not directly face down. This is consistent with the results of other researchers, who previously used a mechanical infant model[15] to examine rebreathing on several bedding items at different head angles.

In the model used by Bolton *et al*,[15] inspired air was sampled just inside the nostril of a doll placed on sheepskins and four kinds of mattresses. The firmer mattresses were found to result in negligible rebreathing, while softer (natural fibre) mattresses and sheepskins resulted in 7% to greater than 10% CO_2 in the inspired air, with the doll placed face down. A limitation of their model was the inability to measure concentrations of CO_2 that exceeded 10%. By contrast, our model is capable of measuring CO_2 concentrations as high as 50% in the tracheal system, thus avoiding the ambiguities associated with exceeding the maximum range of the detector.

Results using our mechanical model show that bedding type has a direct influence on rebreathing. In the present study, single layer items (sheets, blankets) were found to have little rebreathing potential (that is, a low maximum CO_2). Items showing high rebreathing potential (that is, a high maximum CO_2) were generally composed of thin, permeable outer layers surrounding a porous filling (or of an uncovered porous material in the case of the sheepskins). In contrast, mattresses and bassinet pads with impermeable covers displayed low rebreathing potential. Similarly, when we covered high rebreathing items (sheepskin, bean bag cushion) with an impermeable plastic layer, rebreathing potential declined into the low range. This substantiates Kemp and Thach's assertion that the outer layers of bedding must possess low resistance to airflow in order for the bedding to have substantial rebreathing potential.[6] Further research into the relation between rebreathing potential and other physical characteristics of bedding might contribute to the development of design criteria for safer bedding for infants.

Consistent with the tests on individual items, the death scene recreations showed a wide range of results, with means of between 4.5% and 28.7% CO_2 for various items alone or in combination. Cases falling near the high rebreathing end of the CO_2 scale generally involved more items than those near the low end, and those near the low end tended to involve thinner or impermeable items, such as sheets or plastic encased—that is, waterproof—mattresses. Also consistent with the single item results, items fitting the description of "comforter" (< 1 inch (2.5 cm) polyester batting, encased in a woven fabric outer cover) fell widely over the range of all results.

Unfortunately, it was not always possible to obtain the complete suite of bedding items associated with each incident studied. Where very big items such as beds or couches were involved, these were usually not collected by the field investigators, and so were not included in our recreations. It is not known how these additional items would have affected the test results had we had access to them in the laboratory. The presence of a soft or permeable mattress beneath the tested items might have affected the gas dynamics and therefore the rebreathing potential of the materials tested. Also, the tests themselves should be regarded as crude approximations at best of the actual death scenes, given the many uncertainties inherent in the method used to recreate them. For these reasons it would not be appropriate to speculate on the role that rebreathing might have played in any specific case, based solely upon these results. Several possible explanations, not all of which relate to bedding,[20–22] have been proposed to explain how the prone sleeping position might act to increase the risk of SIDS. It is possible that rebreathing is one of several mechanisms which can interact to place infants at increased risk. Our results suggest that in some of the cases we examined the infants may have been exposed to a high rebreathing microenvironment at the time of death.

SUMMARY

In 1992 the American Academy of Pediatrics task force on infant positioning and SIDS recommended that "healthy infants, when being put down for sleep, be positioned on their side or back."[23] Through the development of a mechanical model, our results confirm that the face down position results in maximal rebreathing, and support the results of previous researchers who have identified bean bag cushions and sheepskins as items which may be hazardous to face down infants.[6 11] The results of 29 infant death scene recreations suggest that in some cases bedding materials presented at least the opportunity for substantial rebreathing to have taken place around the time of death. The model described in this paper establishes a way to measure and compare the rebreathing potential quantitatively in different bedding materials. This technique may be used in future efforts to develop safer bedding design criteria for infants.

We are indebted to Drs Bradley Thach MD and James Kemp MD for providing us their expertise during various phases of the project. We thank the Directorate for Epidemiology of the US CPSC for collecting the bedding materials and personal interviews from the death scene investigations, which made this study possible. We also thank Dr Suad Nakamura of the Directorate for Health Sciences, US CPSC, for providing us with her physiological expertise and feedback throughout the project.

The CPSC is a federal regulatory agency which works to prevent injury and death associated with consumer products. The opinions expressed in this article do not necessarily represent the views of the Commission or staff.

1 Ponsonby AL, Dwyer T, Gibbons LE, Cochrane JA, Wang Y. Factors potentiating the risk of sudden infant death syndrome associated with the prone position. *N Engl J Med* 1993;**329**:377–82.
2 Mitchell EA, Scragg R, Stewart AW, *et al*. Results from the first year of the New Zealand cot death study. *NZ Med J* 1991;**104**:71–6.
3 Dwyer T, Ponsonby AL, Newman NM, Gibbons LE. Prospective cohort study of prone sleeping position and sudden infant death syndrome. *Lancet* 1991;**337**:1244–7.
4 Fleming PJ, Gilbert R, Azaz Y, *et al*. Interaction between bedding and sleep position in the sudden infant death syndrome: a population based case-control study. *BMJ* 1990;**301**:85–9.
5 Beal SM, Finch CF. An overview of retrospective case-control studies investigating the relationship between prone sleeping position and SIDS. *J Paediatr Child Health* 1991;**27**:334–9.
6 Kemp JS, Thach BT. Sudden death in infants sleeping on polystyrene-filled cushions. *N Engl J Med* 1991;**324**:1858–64.
7 Kemp JS, Thach BT. A sleep position-dependent mechanism for infant death on sheepskins. *Am J Dis Child* 1993;**147**:642–6.
8 Kemp JS, Kowalski RM, Burch PM, Graham MA, Thach BT. Unintentional suffocation by rebreathing: a death scene and physiologic investigation of a possible cause of sudden infant death. *J Pediatr* 1993;**122**:874–80.
9 Ryan EL. Distribution of expired air in carry cots—a possible explanation for some sudden infant deaths. *Aust Phys Eng Sci Med* 1991;**14**:112–18.
10 Donoghue AM, Cherry GW, Carleton JN, Nakamura SW, Wind ML, Porter WK. Testing of infant bedding products to determine risk of suffocation in infants. Savannah, Georgia: Proceedings of Society for Risk Analysis, December 5–8, 1993.
11 Chiodini BA, Thach BT. Impaired ventilation in infants sleeping facedown: potential significance for sudden infant death syndrome. *J Pediatr* 1993;**123**:686–92.
12 Kinney HC, Filiano JJ, Sleeper LA, Mandell F, Valdes-Dapena M, White WF. Decreased muscarinic receptor binding in the arcuate nucleus in sudden infant death syndrome. *Science* 1995;**269**:1446–50.
13 Rognum TO, Saugstad OD. Hypoxanthine levels in vitreous humor: evidence of hypoxia in most infants who died of sudden infant death syndrome. *Pediatrics* 1991;**87**:306–10.
14 Naeye RL. Sudden infant death. *Sci Am* 1980;**242**:52–62.
15 Bolton DPG, Taylor BJ, Campbell AJ, Galland, BC, Creswell, C. Rebreathing expired gases from bedding: a cause of cot death? *Arch Dis Child* 1993;**69**:187–90.
16 Scheers NJ. *Infant suffocation project. Final report*. Washington DC: US Consumer Product Safety Commission, November 1994.
17 Cross KW. Plethysmograph for studying respiration in the newborn infant. *J Physiol* 1949;**108**:37.

18 Vaughan VC, McKay RJ, Nelson ED, eds. *Textbook of pediatrics*. 10th Ed. Philadelphia: WB Saunders, 1975.
19 Mountcastle VB, ed. *Medical physiology*. 14th Ed. St Louis: CV Mosby, 1980.
20 Kaada B. Why is there an increased risk for sudden infant death in prone sleeping? Fear paralysis and atrial stretch reflexes implicated? *Acta Paediatr* 1994;**83**:548–57.
21 Helweg-Larsen K, Lundemose JB, Bille H. Overheating and sudden infant death. Temperature regulation in relation to the prone position, the possible pathogenesis of sudden infant death. *Ugeskr Laeger* 1994;**156**:7193–6.
22 Bell S, Crawley BA, Oppenheim BA, Drucker DB, Morris JA. Sleeping position and upper airways bacterial flora: relevance to cot death. *J Clin Pathol* 1996;**49**:170–2.
23 AAP Task Force on Infant Positioning and SIDS. Positioning and SIDS. *Pediatrics* 1992;**89**:1120–6.