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Aeration Properties of a New Sleeping Surface for Infants

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Summary. Background: Prone sleeping position, use of soft mattresses and head covering by bedclothes are known risk factors for sudden infant death syndrome (SIDS). Rebreathing carbon dioxide (CO_2) may be a possible mechanism or a confounding factor of SIDS. Objective: To compare the aeration properties of a new concept of infant sleeping surface (Net) to three commercial mattresses advertised to improve aeration and to two standard infant mattresses. Design: Two experiments were performed: (I) A container (head box), filled with 7% CO_2 mixture, was opened to the mattress to allow gas mixture to passively diffuse outside and equilibrate with the surrounding room air. (II) Simulation of normal breathing of an infant, using a unidirectional reciprocal syringe, to determine CO_2 accumulation within the head box. Methods: CO_2 concentrations in the head box were continuously measured until CO_2 levels fell below 1% or for 5 min (experiment I), or until CO_2 accumulation levels plateaued or for 6 min (experiment II). Results: The Net had a significantly faster rate of CO_2 elimination (88.5 ± 4.6 and 91.9 ± 0.9 sec, Net alone and when covered with a sheet, respectively) compared to 238.3 ± 14.2 sec to 387.8 ± 7.9 sec for the other mattresses ($P < 0.001$). Only the Net was able to prevent CO_2 accumulation with maximal CO_2 levels (0.56 ± 0.03% and 1.16 ± 0.05%; Net alone and when covered with a sheet, respectively) significantly lower than the range of 4.6–6.3% for the other mattresses ($P < 0.001$). Conclusions: The new sleeping surface exhibited significantly better aeration properties in dispersing CO_2 and in preventing its accumulation. **Pediatr Pulmonol. 2011; 46:193–198.** © 2011 Wiley-Liss, Inc.

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INTRODUCTION

Sudden infant death syndrome (SIDS) is still a leading cause of death for infants aged 1 month–1 year in developed countries, despite a significant decline in its prevalence stemming from the ‘‘Back to Sleep’’ campaign.[1,2] Extrinsic risk factors that have been identified in epidemiological studies include prone and side-sleeping positions, soft bedding and sleep surfaces, bedclothes that cover the head, bed sharing, and a high ambient temperature in the sleeping environment.[1,2] A possible explanation for the relatively high incidence of SIDS in infants is rebreathing of exhaled carbon dioxide (CO_2), which is trapped in small unventilated compartments (air pockets) near a sleeping infant.[3–7]

Over the years, numerous commercial attempts have been made to improve aeration in the infant's sleep environment in order to decrease the risk of suffocation but few have been formally tested. In a study that examined the rebreathing potential of six sleeping surfaces that were advertised to reduce rebreathing of CO_2 all but one which was equipped with a powered fan, exhibited the potential for CO_2 accumulation.[8] In a recent study, researchers found that increasing room ventilation by the use of a fan was associated with a 72% reduction of SIDS, and that this reduction was more prominent in unfavorable sleeping environments such as overheated rooms.[9] The researchers speculated that their results were consistent with the hypothesis that reducing rebreathing may decrease the risk of SIDS.

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A new concept of a sleeping surface has recently been re-introduced. This is based on the use of a polyester net stretched over an open frame that enables free air flow from below. We hypothesized that the physical properties of the new sleeping surface would reduce the possibility of CO_2 accumulation. We present here preliminary results of an in vitro study aimed at evaluating the aeration and ventilation properties of this netted mattress.

EQUIPTMENT AND METHODS

Equipment

Static and simulated rebreathing experiments within a container placed on top of mattresses were performed in a pulmonary laboratory. A new netted infant sleeping surface (Net) was compared to three commercial mattresses advertised to improve airflow through the sleep surface and to two standard infant mattresses.

The Net (AirNettress®, Lizron—The Child Development Company Ltd., Pardes-Hanna, Israel) consists of a nontoxic polyester net (Sefar AG Filtration Solutions, Heiden, Switzerland) which is stretched over a wooden or aluminum frame. The net is made of 200 μm diameter fibers at a density of 15 fibers/cm^2, which attains air to fiber ratio of approximately 1:1.

The three mattresses advertised to improve airflow were:

- Aminach Air® (Aminach Ltd., Nir-Zvi, Israel): a foamed polyurethane mattress with a 5 mm honeycombed polyester upper surface.
- AeroSleep® (AeroSleep NV, Ninove, Belgiu): a 5 mm honeycombed surface placed on a standard infant mattress.
- Polyron Diamond® (Polyron Ltd., Zikim, Israel): polyurethane mattress covered with "three dimensional" (3D) cloth.

The two standard infant mattresses were:

- Pang® (Baby Feng®, Mandelbaum Brothers Ltd., Tel Aviv, Israel): a standard foamed polyurethane mattress with a lone layered polyester covering.
- Baby Shilav 3000® (Shilav Group Ltd., Bnei Brak, Israel): foamed polyurethane with a three layered polyester coating.

Each experiment was repeated at least twice for each of the mattresses. The Net was studied uncovered and with a fenestrated sheet made of cotton fibers with 0.1 mm round fenestrations at a density of 20/cm^2 (air to fiber ratio of approximately 2:1).

Two setups were investigated:

Setup I

Measuring the rate of CO_2 elimination from a plastic container (head box), which was placed with its open base on top of the mattress (Fig. 1a). The cubic shaped closed head box, with side measurements of 12.6 cm (volume of 2,000 cm^3) was filled with 7% CO_2 mixture. Once stable CO_2 levels were achieved, the bottom cover between the head box and the mattress was removed and the gas mixture within the head box was allowed to passively diffuse through the mattress and equilibrate with the surrounding room air. CO_2 concentrations were continuously measured until CO_2 levels fell below 1% or for 5 min (V_{max}, Sensormedics, Yorba Linda, CA).

Setup II

Measuring the rate of CO_2 accumulation in the head box (Fig. 1b). Air flowed into the head box from a cylinder containing 7% CO_2 in air, through an elastic reservoir and unidirectional valves. A reciprocal syringe was pumped at a rate of 30/min at a stroke volume of 50 cc, thus simulating the normal breathing rate and tidal volume of an average 6-month-old infant. As in Setup I, each experiment was repeated two to three times for each of the mattresses. The Net was also studied covered with sheet.

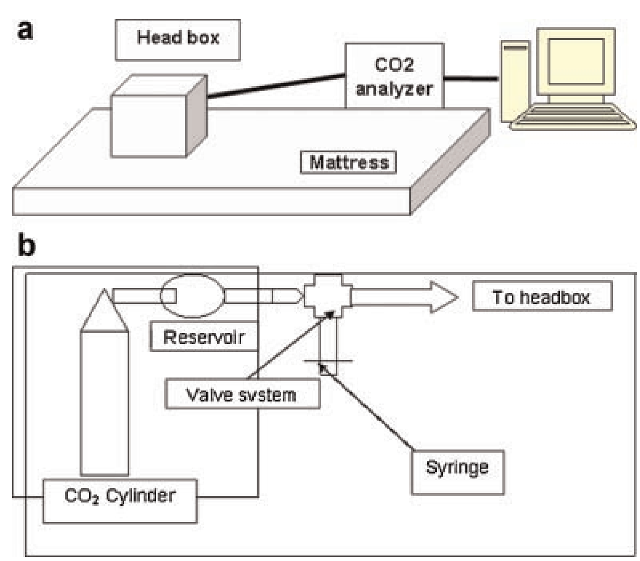

Fig. 1. a: Schematic representation of the diffusion setup. The basic setup consisted of a 2 L cubic head box with specially designed openings for a gas line, a sampling line, and a pumping port, a CO_2 analyzer and a computer for sampling, storing, and analyzing the data. b: Schematic representation of the accumulation setup. For breathing simulation, a 50 ml syringe with two one-way valves allowed for unidirectional flow. Air flowed in from the cylinder which was filled with 7% CO_2 into the syringe which was pumped at a rate of 30/min at a stroke volume of 50 ml, into the head box. CO_2 was then measured as shown in (a).

Quality Assurance

All experiments were carried out in the same laboratory which was kept air conditioned at 20–23°C, 55–60% relative humidity, and barometric pressure of 754–764 mmHg. In order to assure proper control conditions, the head box was tested for absence of leakage by monitoring a gas mixture of 7% CO_2 in the blocked head box with the plastic sheet in place. CO_2 levels were found to remain constant for at least 5 min.

The CO_2 concentration profile along the axis vertical to the mattress surface was also measured. CO_2 levels were fairly constant along the axis and were not affected by the point of measurement.

Data Analysis and Statistics

Since any diffusion process is controlled by the concentration gradient of the gas across the barrier (CO_2 in our case), it is expected to disappear from the head box and through the mattress in an exponential decay fashion. Hence, the average rate of CO_2 elimination through the mattress was defined as the time constant which is measured as the slope of Ln CO_2 concentration over time: the longer the time constant is, the slower the diffusion process.

Accumulation of CO_2 in a perfectly closed head box rises logarithmically reaching a stable plateau (max CO_2 level) with a concentration equaling that of the incoming air mixture, 7% CO_2 in the present study. The time to reach this level and CO_2 accumulation rate, are uniquely determined by the ratio of the incoming amount of CO_2 to the volume of the head box. When one face of the head box is open to the mattress, as CO_2 is introduced, CO_2 accumulation rise time is attenuated, reaching lower plateau levels which are determined by the balance between the rate of CO_2 intake (CO_2 production into the head box) and the mattress aeration ability (CO_2 diffusion out of the head box). In the CO_2 accumulation tests, CO_2 levels were found to rapidly increase within the head box at the onset and thereafter the rate of CO_2 accumulation leveled off. When plateaus were reached, mean CO_2 level over the last 150 sec of the plateau are reported. In the experiments where CO_2 accumulation did not reach a plateau within the 5 min recording time, peak CO_2 values are reported.

Results are expressed as the mean ± SD. Comparisons between parameters derived from both experiments were made by ANOVA: two-factor without replication with Tukey–Kramer multiple comparison tests. Results were considered to be significant if $P < 0.05$.

Ethics Review

The study is laboratory based with no subjects participating in it and was not submitted for approval by any Institutional Review Board.

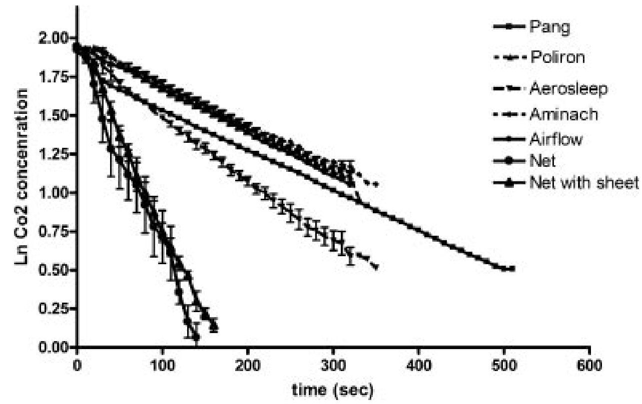

Fig. 2. The rate of CO_2 elimination from the head box, which was placed with its open base on top of the mattress. As CO_2 disappeared from the head box and through the mattress in an exponential decay fashion, natural logarithm of CO_2 is plotted against time. The CO_2 time constant is measured as the slope of Ln[CO_2] over time. Each plot represents the mean of 2–3 experiments with ±SE bars.

RESULTS

Passive elimination of CO_2 from the head box through the different mattresses are presented in Figure 2 and time constants (mean ± SD), calculated from the rate of CO_2 elimination as described above, are summarized in Table 1. As can be seen in the table, the time constants for the Net with and without a sheet were significantly shorter than for the other five commercial mattresses ($P < 0.0001$). The time constants for the Net were two to four times shorter than those measured for the other mattresses. The time constant of CO_2 elimination for the Net did not statistically change when covered by sheet.

The accumulation of CO_2 over the 6 min measuring time is shown in Figure 3 and highest CO_2 levels (mean ± SD) are presented in Table 2. Maximal CO_2 levels of the Net were significantly lower than the other five commercial mattresses (Table 2; $P < 0.0001$). Moreover, while CO_2 levels reached a plateau rapidly with the Net, it kept accumulating through the sampling period

TABLE 1—Mean Values (±SD) of Time Constants, τ, for CO_2 Elimination From the Mattresses

Name of mattress	Number of experiments	τ (sec)
Net (AirNettress)	2	88.5 ± 4.6
Net + Sheet	3	91.9 ± 0.9
Pang	2	372.2 ± 4.5[1]
Shilav	3	355.9 ± 4.5[1]
Polyron	4	359.5 ± 13.3[1]
AeroSleep	3	238.3 ± 14.2[1]
Aminach Air	2	387.8 ± 7.9[1]

[1]Values significantly different from Net + Sheet at $P \leq 0.001$ (Tukey–Kramer test).

TABLE 2— Mean Values (±SD) of CO_2 Accumulation for Each Mattress

Name of mattress	Peak CO_2 (%)
Net (AirNettress)*	0.56 ± 0.03[1]
Net + Sheet*	1.16 ± 0.05
Pang**	5.20 ± 0.04[2]
Shilav**	4.51 ± 0.10[2]
Polyron**	4.56 ± 0.04[2]
AeroSleep**	6.25 ± 0.28[2]
Aminach Air**	5.15 ± 0.19[2]

When a steady plateau in CO_2 levels was reached (*) values reported are the mean over the last 150 sec of the plateau. When a steady plateau was not reached (**) peak CO_2 levels are reported.
[1]Values significantly different from Net + Sheet at $P \leq 0.05$.
[2]Values significantly different from Net + Sheet at $P \leq 0.001$.

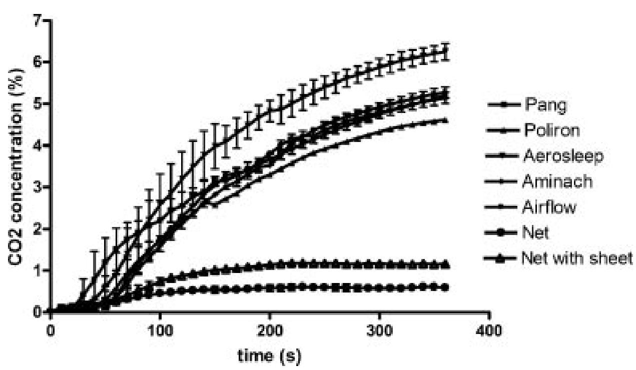

Fig. 3. CO_2 accumulation within the head box opened to six different mattresses. Accumulation is due to the balance between simulated CO_2 rebreathing and CO_2 diffusion from the head box through the mattresses. The netted sleeping surface was studied alone and covered with a sheet (F and G). Each plot represents the mean of 2–3 experiments with ±SE bars. A—Pang; B—Polyron Diamond; C—AeroSleep; D—Aminach Air; E—Baby Shilav 3000.

with all the other mattresses. In three of the mattresses CO_2 concentrations seemed to reach plateau levels towards the end of the sampling period but in two, AeroSleep and Shilav, CO_2 levels kept on rising reaching dangerous levels as high as 6% in one mattress.

DISCUSSION

Our results show that in a mechanical model of infant breathing the Net was superior to the other commercial mattresses examined due to free air movement through the mattress surface with a rapid rate of CO_2 elimination and insignificant CO_2 accumulation. These characteristics are important for infants during their first months of life, mainly in situations when breathing is possible only through the mattress as in prone sleep or when the face is covered by a blanket or pillow and in high-risk infants. The fast rate of CO_2 elimination through the new mattress, combined with insignificant resistance to air flow may prevent rebreathing of increased CO_2 levels. In spite of the fact that in the present model the breathing rate and volume were kept fixed (in contrast to infants that respond to rising CO_2 by increasing the rate and volume of respiration), the results represent the relative rebreathing potential which is dictated by the physical properties of the bedding (mattress and sheets).

In the static diffusion experiments, the time constant, which is customarily used to characterize this process, was found to be extremely short (approximately 90 sec) for the Net. The time constants for the three mattresses advertised to improve airflow were significantly prolonged and did not differ from the standard mattresses. Colditz et al.[10] performed a similar study in which CO_2 was allowed to disperse through different mattresses and the time for CO_2 decline from 5% to 1% was measured. The time ranged from 5.5 to 18.7 min, or 3.5–12.5 times longer than the results of the Net in our report.

In the dynamic diffusion experiments, the maximal CO_2 level was significantly lower for the Net compared to the other mattresses. Colditz et al.[10] used an in vivo model in which a prone sleeping infant's head was covered by a head box comparing five different mattresses and bed-covers. They observed a final steady-state CO_2 accumulation of 2.2–3% for all standard infant mattresses and bedcovers studied. Their low CO_2 level measured with the open mesh mattress (0.6%) is similar to that of the Net in the present study.

In another study an infant mannequin was employed to evaluate how CO_2 dispersal was affected by use of a conventional infant mattress and five mattresses marketed under the claim that they prevent rebreathing.[8] Three of the mattresses were passive devices and two were active devices using a fan or pump to move air in and around the mattress. The results showed that four of five experimental sleep surfaces in addition to the control mattress had reduced CO_2 dispersal, and the only sleep surface that allowed for efficient CO_2 dispersal was an active one. The reduction in CO_2 dispersal has been shown to cause lethal CO_2 retention in an animal model.[11]

In our experiments, maximal CO_2 concentrations for the mattress alone and the mattress covered with the net sheet were below the 1.2% limit. These CO_2 levels are considered safe environmental conditions according to the National Institute for Occupational Safety and Health (NIOSH) guidelines.[12] Moreover, while CO_2 levels reached a plateau rapidly with the netted sleeping surface, it kept accumulating throughout the sampling period with all other mattresses. Three of the mattresses seem to reach plateau levels towards the end of the sampling period but with two of the commercial mattresses CO_2 levels kept on rising reaching dangerous levels as high as 6% in one mattress.

An additional experiment was performed in order to measure the resistance to air flow through the Net and the possible build up of back pressure upstream from the mattress. Air was pumped in and out through a flow meter and flow rates and pressure were continuously measured. The Net offered negligible resistance of 0.06 and 0.15 cmH_2O/l/sec with the addition of a sheet covering. According to recommendations of the European Task Force, resistance of measuring devices should not exceed 1.2 kPa/l/sec (=12.3 cmH_2O/l/sec) for premature infants and 0.7 kPa/l/sec (=7.2 cmH_2O/l/sec) for term neonates.[13] The resistance of the Net was found to be well beneath these recommendations at flow rates of 50 and 100 ml/sec, respectively.

In order to assure proper control conditions, the head box was tested for absence of leakage by monitoring a gas mixture with CO_2 in the blocked head box with a plastic sheet in place. CO_2 levels were observed and found to remain constant for at least 5 min.

Within the ''sleep practices and infant sleep environment'' category, well documented risk factors for SIDS include: prone and side-sleeping positions, soft bedding and surfaces, thermal stress due to overheating or infections with fever, bed sharing between infants and adults, and exposure to tobacco smoke.[1,2,14,15] Factors that are shown to reduce the risk of SIDS in the same category include the use of a pacifier at bed time,[16] and breastfeeding.[17,18] The leading hypothesis that explains significant risk factors for SIDS in the sleeping environment is the rebreathing hypothesis. According to this hypothesis, sleeping in an environment which is characterized by limited dispersion of exhaled gas, such as the prone position, soft bedding, and with facial covering, causes rebreathing of exhaled air and may bring about hypercarbia, hypoxemia, and death.[19] In a mechanical model of infant rebreathing it has been reported that an increase in air turbulence by a fan can reduce CO_2 inhalation.[20]

Additional support for the rebreathing hypothesis comes from two recently published works. In the first, Coleman-Phox et al.[9] carried out a population-based case control study in 11 California counties comparing 185 documented SIDS cases with 312 control infants. It was demonstrated that fan use was associated with a 72% reduction in SIDS. They also showed that the reduction of SIDS was more pronounced in adverse sleep environments such as high room temperature, prone sleep position, closed windows, bed sharing, and lack of pacifier use. The authors suggested that increasing room ventilation by using a fan helps to disperse accumulated CO_2 in the dead air space around the nose and mouth of infants in sleep environments that heighten the risk of rebreathing. Consequently the use of a fan may be an effective intervention for lowering the risk of SIDS in sleeping environments that facilitate rebreathing. The second study is that of Sakai et al.[21] who tested gas dispersal potential of mattresses used by 14 infants diagnosed with SIDS at autopsy by breathing simulation with an infant mannequin and a respirator. They found eight of the mattresses to exhibit $FiCO_2$ values greater than 10% within 2.5 min of simulated breathing.

Study limitations stem from the preliminary nature of the study which does not encompass a fuller set of tests. These might be in the nature of changing the proportions of opening area to volume of the head box as well as further breathing simulations with different tidal volume and/or breathing frequencies. In addition, the present investigation did not directly investigate the importance of temperature effect on CO_2 elimination. In the course of testing, we measured the temperature within the head box and found it to be substantially lower with the Net mattress due to faster heat dissipation compared to all other mattresses. We believe that this preliminary finding strengthens our conclusions of better aeration and less CO_2 accumulation of rebreathed air.

In summary, we re-introduced here an infant sleeping surface which is made of permeable netting thus allowing free air movement through it. The special characteristics of aeration, ventilation, and resistive properties, aimed to decrease the likelihood of significant CO_2 rebreathing, may decrease important risk factors for SIDS especially in high-risk populations. Further studies to evaluate the potential benefit of products that reduce the rebreathing of CO_2 are needed.

AT A GLANCE COMMENTARY

Scientific Knowledge on the Subject

Rebreathing CO_2 trapped in small unventilated compartments (air pockets) near a sleeping infant, may be a possible mechanism or a confounding factor of sudden infant death syndrome (SIDS).

Increasing room ventilation is associated with a reduction of SIDS, and it is more prominent in unfavorable sleeping environments.

What This Study Adds to the Field

A new concept of infant sleeping surfaces—a netted mesh stretched over an aluminum frame (Net) has a significantly faster rate of CO_2 elimination compared to five commercially available mattresses. Only the Net was able to prevent CO_2 accumulation with maximal CO_2 levels being significantly lower than those found for the other mattresses.

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