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Report

A new Mattress for Infants- Aeration, Ventilation, and Resistive Properties

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August 28, 2007

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Abstract

The aim of this project was to measure and define the mechanical properties of a new mattress manufactured by Lizron- Child Development Company Ltd. (Lizron mattress). According to company's claim, this new mattress allows for free aeration and ventilation, thus lowering the risk of suffocation.

Three sets of experiments were conducted. Two were aimed to measure the aeration properties of the mattress and the third, to measuring the resistive properties to air flow through the mattress. All tests were performed on two separate mattresses, and each experiment was conducted on the mattress itself as well as when covered with company supplied sheet (net sheet) and compared to a commercially available cotton sheet (cotton sheet).

Results:

1. The average rate of CO_2 elimination was found to be 62.8±0.1 Sec (mean±SD) for the mattress. This was only slightly prolonged when the mattress was covered by the net sheet (12%), and by 45% with the cotton sheet.
2. The rate of CO_2 accumulation (time constant) was 39.9±7.0 Sec when one side of the headbox was open to the mattress. This was significantly shorter compared to a closed headbox (110.2±18.7 Sec). The rate was the same with the net sheet (33.0±0.2 Sec.), and somewhat higher with the cotton sheet (50.7±0.1 Sec).
3. Simulating a breathing infant within the headbox, the maximal attainable CO_2 levels were 0.70±0.01%, very low compared to 4.75±0.08% in an airtight chamber. This level did not change much by the addition of the net sheet (0.77±0.03%), but increased markedly by the cotton sheet (1.23±0.03%).
4. Resistance to air flow through the mattress was very low- 0.09±0.03 cmH2O/l/sec and only 4% of that of the measuring device, considered to be within the physiologically safe range. Resistance grew somewhat with the addition of the net sheet to 0.19±0.01 cmH2O/l/sec (9% of control), and substantially with the addition of the cotton sheet to 2.35±0.06 cmH2O/l/sec (107%).

Conclusions and Summary:

The new mattress of the Lizron- Child Development Company was found to have superior properties compared to known values of regularly used mattresses and bedding materials as published in the literature. The new mattress was found to have:

- A fast rate of CO_2 elimination
- The ability to clear away any CO_2 accumulation, keeping the maximal attainable CO_2 level below 1%
- An insignificant resistance to air flow.

Methods

Two sets of experiments are based on the basic laws of passive diffusion. It is obvious that the rate of diffusion is directly related to the size (cross-sectional area) of the pathway for diffusion—the larger the opening, the faster the rate. It is also known that the rate of diffusion is inversely related to the resistance to molecular motion along the diffusion pathway-- the greater the resistance, the slower the rate of diffusion. Hence, my model is based on the assumption that given a varying size of the opening, the better the aeration properties of the mattress at question, the faster will be the rate of CO_2 clearance through it.

To this end, the following sets of experiments were conducted:

1. Measuring the rate of CO_2 elimination from a container with a known volume (headbox) and open on one side to the mattress- static diffusion.
2. Measuring the rate of CO_2 accumulation in the headbox due to CO_2 production by the quiet breathing of an average infant- dynamic diffusion.

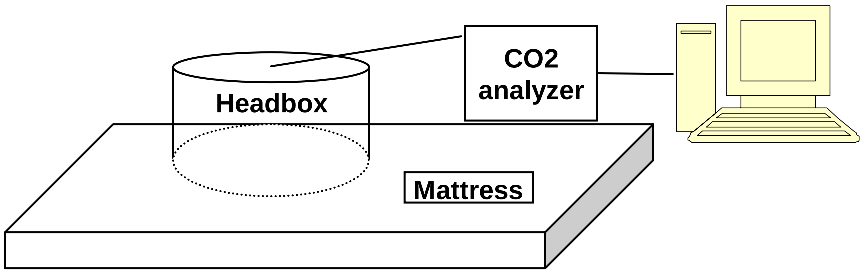
In each set the following experiments were performed:

1. All tests were performed on two separate mattresses.
2. For each mattress, each experiment was conducted on the mattress itself as well as when covered with company supplied sheet (net sheet). For comparison, each experiment was conducted on the mattress covered with a commercially available cotton sheet (cotton sheet).
3. All experiments were repeated at least three times. Results are presented as averages (±SD, standard deviation) of all technically acceptable results.
4. When applicable, control tests were performed.

An additional experiment was performed in order to measure the resistance to air flow through the mattress. The aim of this experiment was to determine the level of back pressure needed to overcome the resistive properties of the mattress. The greater this resistance is, the higher will be the pressure which is needed to be generated by the infant breathing above it, causing an increase in the work of breathing.

Design and Experimental setup

Figure 1



The basic setup consisted of the following components:

1. A square container (headbox) 15X15 cm and 10 cm high with one face open, yielding a constant volume of 2.25 liter. The headbox was built to specifications with specially designed openings for gas line, sampling line and pumping port.
2. CO_2 analyzer (Microcup plus, Oridion Corp., Israel)
3. A computer for sampling, storing and analyzing the data.
4. An interface between the analyzer and computer (A/D card, kiethley Corp., USA)

Sampling and analysis were performed using Testpoint and Matlab software packages and specially written software programs for this project.

Experiment No. 1:

Measuring the rate of CO_2 elimination from a container with a known volume (headbox) and open on one side to the mattress- static diffusion.

In this experiment, the headbox was placed with its open face on the mattress. This opening was blocked by a thin plastic sheet and an air mixture containing 4.8% CO_2 was flushed into the headbox. Once stable CO_2 levels were achieved, the plastic sheet was removed and the gas mixture within the headbox was allowed to statically diffuse through the mattress and equilibrate with the surrounding room air.

CO_2 concentrations were continuously measured until CO_2 levels fell below 1%. Since any diffusion process is controlled by the concentration differential of the gas at question across the barrier (CO_2 in our case), CO_2 is expected to disappear from the headbox and through the mattress in an exponential decay fashion, and not in a linear fashion. The average rate of CO_2 elimination through the mattress was defined as the time constant which is measured as the slope of log CO_2 concentration over time. Obviously, the longer the time constant is, the slower the diffusion process. Or in other words, a mattress having a short time constant is a mattress which lets CO_2 disperse fast.

As mentioned above, two different mattresses were studied and for each, the experiment was conducted on the mattress itself as well as when covered with company supplied sheet (net sheet) and to a commercially available cotton sheet (cotton sheet).

In order to assure proper control conditions, the headbox was tested for absence of leakage by monitoring a gas mixture of 4.8% CO_2 in the enclosed headbox with the plastic sheet in place. CO_2 levels were observed and found to remain constant for at least 5 min. (Appendix 1)

In this experiment, we also measured the CO_2 concentration profile along the axis vertical to the mattress surface. Because we chose for our experiments a fairly flat container, CO_2 levels were fairly constant and were not affected by the point of measurement.

Experiment No. 2:

Measuring the rate of CO_2 accumulation in the headbox due to CO_2 production by the quiet breathing of an average infant- dynamic diffusion.

In this experiment, CO_2 was introduced into the headbox at a rate similar to the CO_2 production of a normal infant. Accumulation of CO_2 in a perfectly closed headbox has the characteristics of a logarithmic function reaching a stable plateau (max CO_2 level) with a concentration of CO_2 equaling that of the incoming air mixture. In this case (control study), the plateau level is 4.8% CO_2. The time to reach this level and the rate of CO_2 accumulation, the time constant of the system, are uniquely determined by the ratio of incoming amount of CO2 to the volume of the headbox.

In this experiment, a valve system was devised to simulate the environment of a breathing infant. That is, CO_2 production during breathing simulation by the quiet breathing of an average infant. As CO_2 is introduced to the headbox, CO_2 levels start to rise reaching a plateau level (max CO_2 concentration) which represents the balance of CO_2 production less CO_2 diffusion out of the headbox and through the mattress- dynamic diffusion.

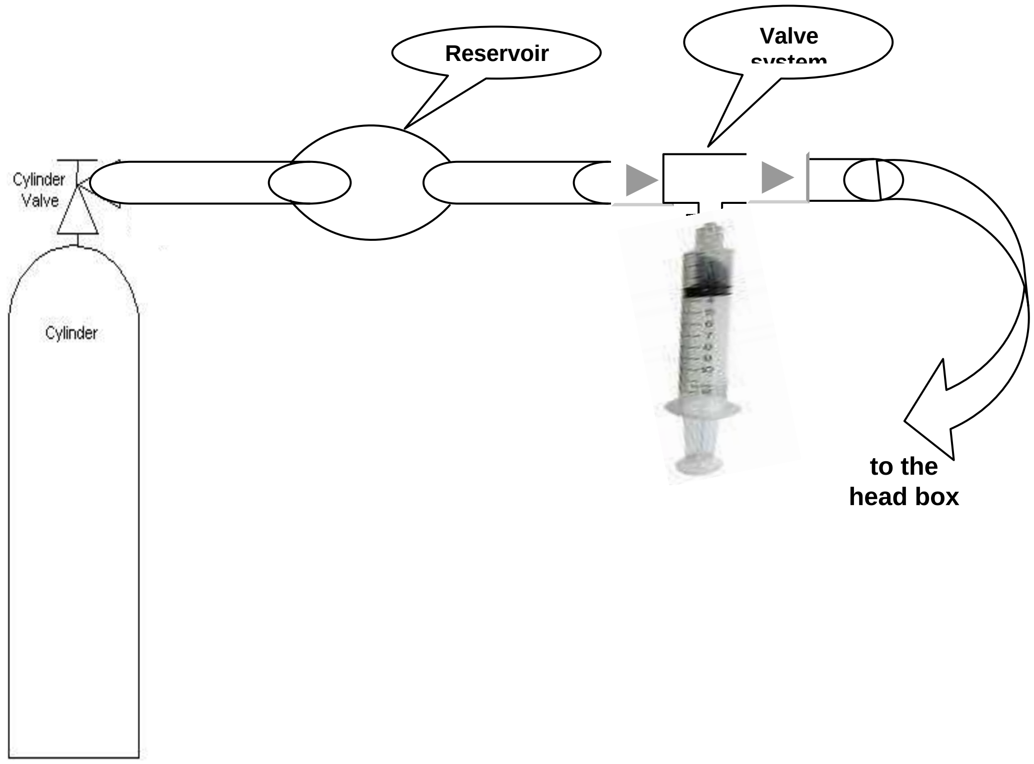
When one face of the headbox is open to the mattress, the differences between these values and these of the control case depend on the mattress aeration ability and CO_2 diffusion through it. In this case, the time to reach max CO_2 concentration and the time constant of the system, are determined by the balance of on the mattress aeration ability and CO_2 diffusion as well as the ratio of incoming amount of CO_2 to the volume of the headbox.

max CO_2 level will be lower. the time to reach max level will be longer, the rate of CO_2 accumulation slower, and.

Design and Experimental setup

The basic setup as described above was used.

Figure 2



The valve system was constructed of two one-way valves arranged in a way to allow unidirectional flow, left-to-right in this case (Fig.2). Air always came in from the reservoir (on the left) which was continuously filled with a gas mixture of known CO_2 concentration (4.8% was chosen because it is similar to expired CO_2 levels in human beings). Air out (to the right) was directed into the headbox.

The pumping sequence was always at 30 times per min with a stroke volume of 50 cc. This mimics quiet breathing of an average infant, half a year old, and the appropriate amount of CO_2 production into the headbox.

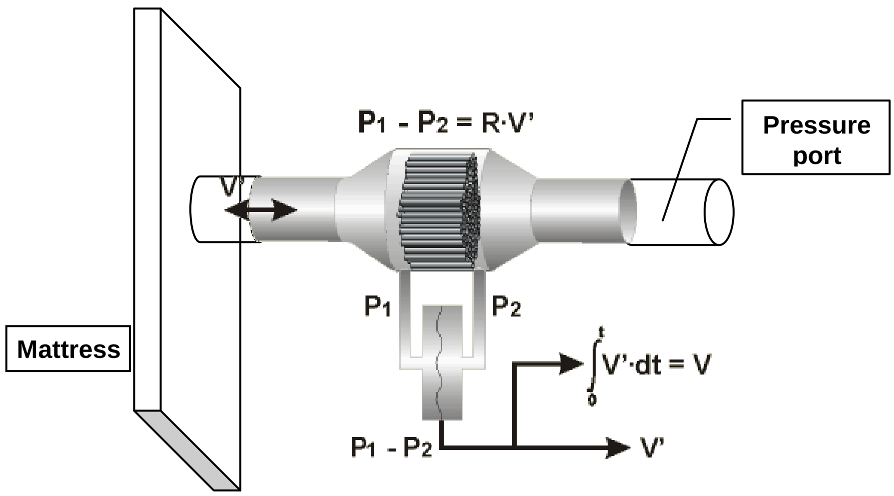
As in experiment 1, CO_2 concentrations were continuously measured until steady state levels were observed. Again, two different mattresses were studied and for each, the experiment was conducted on the mattress itself and with net and cotton sheets.

Experiment No. 3:

Measuring the resistance to air flow through the mattress.

The measuring apparatus consisted of a flow meter (Pneumotachograph model 3500, Hans Rudolph Inc., USA) attached to the mattress, a connector with a side port for pressure measurement, and a calibrate syringe.

Figure 3



In this experiment, air was pumped in and out through the measuring apparatus as in the previous experiment. That is, with a calibrating syringe (50cc) at a rate of 30/min. Flow rates and pressure were continuously measured. Resistance to flow is defined as the ratio of the two:

$$\text{Resistance} = \frac{\Delta p}{\text{flow}} \quad \{cmH2O/l/sec\}$$

Results

Experiment No. 1:

Mean ±SD values of CO_2 elimination through the mattress are presented in Appendix 2 for each mattress separately (panels a-c and Table 2a), for the three experiments carried out, and summarized in Table below.

The average rate of CO_2 elimination (time constant) was found to be 62.78± 0.06 Sec. The average rate of CO_2 elimination through the mattress when it was covered by the net sheet was only slightly prolonged (by 12%), as compared to a substantial prolongation of 45% when it was covered by the cotton sheet.

Table 1

Time constant for CO_2 elimination

	Mattress alone	Mattress + net sheet	Mattress + cotton sheet
Average of the two mattresses			
Time constant (sec)	**62.78**	**70.11**	**91.10**
change from mattress		112%	145%
Mattress #1			
Time constant (sec)	**56.70**	**68.52**	**93.24**
change from mattress		121%	164%
Mattress #2			
Time constant (sec)	**68.85**	**71.69**	**88.96**
change from mattress		104%	129%

Experiment No. 2:

In this experiment CO_2 was introduced to the headbox at a rate similar to that of CO_2 production of an average infant half a year old, as explained earlier in the methodology section. In the control experiment (Appendix 3, panel a), the headbox was isolated from the mattress by a thin plastic sheet in the same fashion as in experiment no. 1.

The mean ±SD values of max CO_2 level (plateau) was 0.70±0.01% when one side of the headbox was open to the mattress (Appendix 3, Table 3a). This was very significantly lower compared to a closed headbox (4.75±0.08%; 15% of control). Max CO_2 level was roughly the same with the mattress covered by the net sheet, and somewhat increased with the cotton sheet (Appendix 3, panels b-d).

Table 2

CO_2 accumulation during breathing simulation

	Control-closed headbox	**Mattress alone**	**Mattress + net sheet**	**Mattress + cotton sheet**
Average of the two mattresses				
Max CO_2 concentration	**4.75**	**0.70**	**0.77**	**1.23**
% of control		14.8%	16.2%	25.9%
Mattress #1				
Max CO_2 concentration	**4.75**	**0.69**	**0.69**	**1.35**
% of control		14.6%	14.6%	28.3%
Mattress #2				
Max CO_2 concentration	**4.75**	**0.72**	**0.85**	**1.12**
% of control		15.1%	17.9%	23.6%

Obviously, CO_2 accumulated in the headbox and reached a steady level of that in the gas tank in 276.5±33.2 Sec. (Table 3 and Appendix 3- Table 3b). When the headbox was open to the mattress, it can be seen that max CO_2 levels reached a much lower plateau level much quicker (69.1±4.4 sec; 25% of control). Max CO_2 plateau levels were higher with the mattress covered by the net sheet and took longer to reach (93.2±24.7 sec; 34% of control). With the mattress covered with the cotton sheet, time to reach the plateau was further increased (116.1±9.8 sec; 42% of control).

Table 3

Time to maximal CO2 concentration (plateau, sec)

	Control-closed headbox	**Mattress alone**	**Mattress + net sheet**	**Mattress + cotton sheet**
Average of the two mattresses				
Time to plateau	**276.47**	**69.08**	**93.23**	**116.05**
% of control		25.0%	33.7%	42.0%
Mattress #1				
Time to plateau	**276.47**	**65.97**	**59.50**	**116.63**
% of control		23.9%	21.5%	42.2%
Mattress #2				
Time to plateau	**276.45**	**72.20**	**77.50**	**115.47**
% of control		26.1%	28.0%	41.8%

Similarly, the average rate of CO_2 production (time constant) was found to be 110.2± 18.7 Sec for the control case (airtight headbox), (Table 4 and Appendix 3-Table 3c). The time constant when the headbox was open to the mattress alone was substantially shorter (39.9±7.0 sec; 36% of control).

The average rate of CO_2 production through the mattress when it was covered by the net sheet was roughly the same with the mattress covered by the net sheet (33.0±0.2 sec; 30% of control), and somewhat increased with the cotton sheet (50.7±0.1 sec; 46% of control). In all three situations, time constants when the headbox was open were significantly shorter than that of the airtight headbox.

Table 4

Time constant of CO2 accumulation (sec)

	Control-closed headbox	**Mattress alone**	**Mattress + net sheet**	**Mattress + cotton sheet**
Average of the two mattresses				
Time constant (sec)	**110.22**	**39.90**	**33.04**	**50.68**
% of control		36.2%	30.0%	46.0%
Mattress #1				
Time constant (sec)	**110.22**	**35.97**	**37.45**	**44.75**
% of control		32.6%	34.0%	40.6%
Mattress #2				
Time constant (sec)	**110.22**	**43.83**	**28.63**	**56.60**
% of control		39.8%	26.0%	51.4%

Experiment No. 3:

Mean ±SD values of resistance to air flow are presented in Appendix 4 for each mattress separately and summarized in Table 5 below. The resistance to flow of the mattress was very low, 0.06±0.02 cmH2O/l/sec on average. Resistance grew somewhat with the addition of the net sheet to 0.15±0.02 cmH2O/l/sec, and grew substantially with the addition of the cotton sheet to 2.30±0.03 cmH2O/l/sec.

Table 5

Resistance to air flow (cmH2O/l/sec)

	Mattress alone	Mattress + net sheet	Mattress + cotton sheet	net sheet	cotton sheet
Average					
mean	0.058	0.152	2.298	0.09	2.24
SD	0.023	0.019	0.030	0.00	0.02
Mattress #1					
mean	0.095	0.189	2.347	0.09	2.25
SD	0.031	0.010	0.059		
Mattress #2					
mean	0.022	0.116	2.249	0.09	2.23
SD	0.015	0.028	0.001		

Discussion

The new Lizron mattress utilizes a unique concept unlike any of the regular mattresses in the market- for infants or adults. Its design is quite simple in that it is simply a net (made of synthetic material with fine mesh) stretched over a wooden frame. As such, it was not surprising to find out the obvious namely, that air can move freely across the mesh and with very little resistance to air flow.

I performed three sets of experiments and the results of it helped me reach this conclusion. In the first set of experiments, an air mixture with a known concentration of CO_2 (as a marker) was allowed to passively diffuse across the mesh of the Lizron mattress until full equilibration with room air i.e., CO_2 concentration falling to roughly 0%. The time constant which is customarily used to characterize this diffusion process was found to be extremely short, of the order of magnitude of 1 min. For comparison, Colditz et al [J. Paediatr. Child Health 2002; 38:192–195] performed a similar study in which CO_2 was allowed to disperse through different mattresses and reported that the time taken for 5% CO_2 to disperse to 1% CO_2 ranged from 5.5 to 18.7 min depending on the mattress studied (open mesh to foam). Comparing just the results of the test with similar experimental conditions, the time reported by the authors of this report are more than five times longer that that found by me in the Lizron mattress. The authors reported on the time for CO_2 to disperse to 1% rather than the customary time constant. Converting my results to this criteria yield a value of roughly 90 sec which is still at least three times faster than that previously reported by Colditz. This can be explained by either the mechanical properties of the mattress (type and size of mesh) or by the size and dimensions of the headbox- volume versus the open face to the mattress.

In the same study [Colditz et al 2002], the authors also reported their findings on the rate of CO_2 diffusion through different bedding materials (cotton sheet, and various doonas and blankets) and reported that the time taken for 5% CO_2 to disperse to 1% CO_2 ranged from 3.2 to 6.5 min with the cotton sheet being the fastest. In my experiments, the addition of the cotton sheet attributed to an increase of only 30 sec to the time constant for passive diffusion. As before, this can be explained by either the properties of the sheet used (type and size of mesh) or by the size and dimensions of the headbox.

In the second set of experiments, the steady state level of CO_2 is the result of the balance between CO_2 input (from breathing) and CO_2 output (by diffusion through the mattress). Hence, steady state levels can range from a maximum of 4.8%CO2 at one end (when the headbox is completely blocked as in our control test—full CO_2 input but no CO_2 out). At the other end of the scale, steady state levels can theoretically reach a minimum level of 0% CO_2 (when there is no CO_2 input or when CO_2 input is so much lower than CO_2 output). Hence, the lower the steady state level, the higher the rate of CO_2 diffusion through the mattress. In my experiments, the max CO_2 concentration was very low for the mattress alone and even when covered with a cotton sheet (0.7-1.2% compared to 4.8% in the control). These low CO_2 levels are considered safe environmental conditions. It is well known that:

- At 1% concentration of CO_2 and under continuous exposure at that level, such as in an auditorium filled with occupants and poor fresh air ventilation, some occupants are likely to feel drowsy.
- The concentration of CO_2 must be over about 2% before most people are aware of its presence unless the odor of an associated material (auto exhaust or fermenting yeast, for instance) is present at lower concentrations.
- Above 2%, CO_2 may cause a feeling of heaviness in the chest and/or more frequent and deeper respirations.
- If exposure continues at that level for several hours, minimal "acidosis" (an acid condition of the blood) may occur but more frequently is absent.
- Breathing rate doubles at 3% CO_2 and is four times the normal rate at 5% CO_2.
- At levels above 5%, concentration CO_2 is directly toxic.

According to U.S. Department of Labor Occupational Safety & Health Administration (OSHA), OSHA Permissible Exposure Limits for CO_2 in workplace atmospheres are 1% for long exposure durations, 3% for Short-Term Exposure

Limit, and reaching as high as 5% for Transitional Limit. Similarly, according to the U.S. National Institute for Occupational Safety and Health (NIOSH publication 76-194): "Employee exposure to CO_2 shall be controlled so that environmental limit does not exceed 1% concentration for up to 10-hour work shift with a ceiling concentration of 3% not to exceed 10 min."

In the study mentioned above [Colditz et al, 2002], the authors also reported their findings on the rate of CO_2 diffusion through different bedding materials (cotton sheet, and various doonas and blankets) and showed that CO_2 accumulated to relatively high levels (range 1.2–4.8%) with a single bedcover. In my experiments, only with the cotton sheet max CO_2 concentration barely exceeded the 1% limit, and max CO_2 concentration for the mattress alone or with the net sheet were below the 1% limit.

The third set of experiments namely, measuring the resistive properties of the mattress, was conducted in order to answer the question of whether or not the tested mattress offers a substantial resistance to breathing through it and by that increasing the work of breathing to overcome this added resistance. This is an important issue since the favorable physical properties of the mattress may not be of use under physiological conditions. In other words, given the excellent aeration properties of the mattress, it is quite possible that these could be achieved at a cost of a significant back pressure needed to overcome the resistance to air flow brought about by the mattress it self.

In this set of experiments, control values represent the resistance of the measuring apparatus (basically, the flow measuring device). The mean±SD value in this case was found to be 2.19±0.02 cmH2O/l/sec. This value is considered well within the safe range allowed by any measuring devices designed for infants. The resistance of adult-type screen pneumotachograph and of antibacterial filters are in the range of 0.6 - 0.8 cmH2O/l/sec at a much higher flow range.

Compared to control values, the tested mattress offers negligible resistance (less than 5% of control). The addition of the net sheet increased total resistance but only to levels of 5-10% of control. The resistance to flow of the cotton sheet is substantially greater than that of the tested mattress and the net sheet. However, even in this case, the total resistance is well within the international recommendations for safe limits.

Even though the resistive properties of the tested mattress are impressive, it should be noted that substantial differences were observed between the two mattresses which were tested- a four-fold difference. Since the resistive properties of either of the sheets tested were consistent regardless of the mattress used, I am sure that the difference between the two mattresses is real. I can only speculate that this difference is the result of different tension applied to the mesh when constructing the mattress.

In terms of the quality of experimental design and data collection, it is noted that both within and between mattress variabilities were reasonably low, less than 10%, when measuring CO_2 concentrations (experiments 1 and 2). Variability between the two mattresses remained at a 10% level even for the technically demanding time-constant measurement, with within-mattress variability increasing somewhat but not exceeding 20%.

It is concluded that the new Lizron mattress has superior properties compared to known values of regularly used mattresses and bedding materials in that it has a fast rate of CO_2 elimination, the ability to clear away any CO_2 accumulation, keeping the maximal attainable CO_2 level below 1%, and an insignificant resistance to air flow.