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International Journal of Ventilation

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjov20

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To cite this article: Gert-Jan Braun & Wim Zeiler (2021) CO_2-concentration of the surrounding air of sleeping infants inside a crib, International Journal of Ventilation, 20:3-4, 161-171, DOI: 10.1080/14733315.2020.1777003

To link to this article: https://doi.org/10.1080/14733315.2020.1777003

Published online: 01 Jul 2020.

INTERNATIONAL JOURNAL OF VENTILATION
2021, VOL. 20, NOS. 3–4, 161–171
https://doi.org/10.1080/14733315.2020.1777003

CO_2-concentration of the surrounding air of sleeping infants inside a crib

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ABSTRACT

The indoor air quality is important for the well-being of humans, especially in the case of young babies. This research focuses on the air qualityinside a crib with sleeping infants. The effects of different sleeping positions of the baby on the air quality within the crib were studied by measurements on modelled setup. The breathing of an infant was simulated by means of a baby doll which had a breathing device: a intermitted supply of air mixed with CO_2 through a tube in the lips of the baby doll. For different sleeping positions, the effects on the CO_2 concentration inside the baby bed were measured and compared with the background CO_2-level in the sleeping quarter. The results showed an increased CO_2 concentration (up to 4 times) depending on the sleeping position of the infant.

ARTICLE HISTORY
Received 20 February 2020
Accepted 20 May 2020

KEYWORDS
Carbon dioxide; concentration; crib; infants; ventilation; sleeping position

1. Introduction

Good Indoor Air Quality is important for human in relation to their health. This is especially the case for babies as they are by far the most vulnerable human beings as their lungs are still in full development. Furthermore, there might even be a relation with the Sudden Infant death Syndrome (Corbyn, 2000; De La Iglesia et al., 2018; Sakai et al., 2008). The sleep microenvironment of baby beds is the predominant indoor space for babies where they spend most of their time. Babies often spent up to 11 h in a day-care centre during the working days. During the first period of life, infants (<1 year of age) and toddlers (1–3 years of age) sleep a considerable amount of time, on average 13.3 h/day in the first year of life, 12.6 h/day in the second year and 12.1 h/day in the third year (Boor et al., 2017; Iglowstein et al., 2003). Because of their low body weight, babies and toddlers inhale considerably more air per kg of body weight as they sleep compared to adolescents and adults. The volume of air inhaled/kg day can be estimated with the U.S. EPA EFH data set by taking the product of the mean normalised volumetric breathing rate in the sleep or nap activity (L/h kg) and the mean duration of time spent in the sleep or nap activity (h/day). The normalised inhaled air volumes, V*Sleep, are categorised by age group and gender and presented in Figure 1 (Boor et al., 2017).

Mattress dust is found to contain a diverse spectrum of biological particles and particle-bound chemical contaminants and their concentrations in dust can span many orders of magnitude among bed samples (Boor et al., 2014). Furthermore, mattress foam and covers, pillows, and bed frames can emit a variety of volatile and semi-volatile organic compounds, and emission rates can increase due to localised elevations in surface temperature and moisture near the bed due

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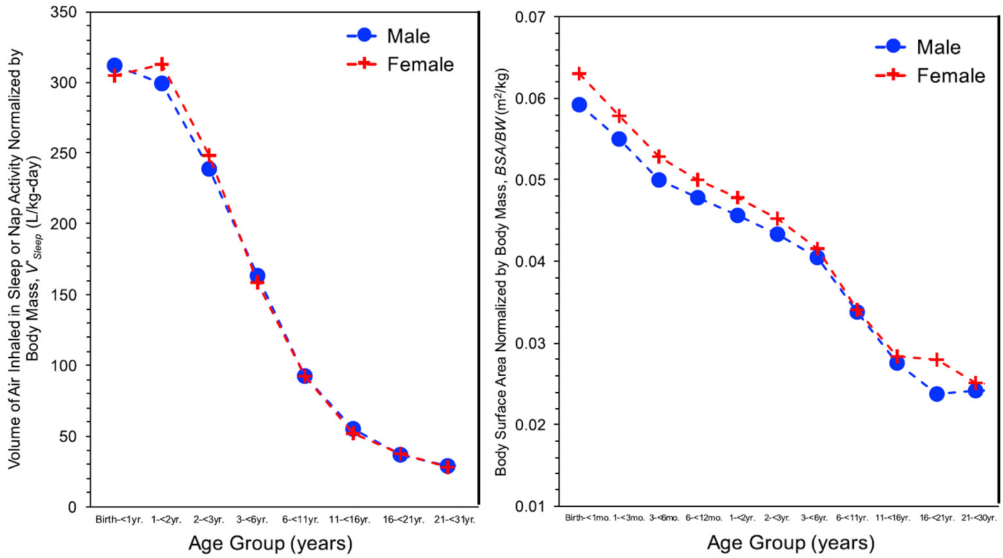


Figure 1. Volume of air inhaled during sleep or nap activity per day and Infant dermal exposure dose considerations in the sleep microenvironment: normalised by body mass for each age group and gender (calculated using U.S. EPA EFH data set (2009) by Boor et al., 2017).

Figure 2. Examples baby bunk beds (BBB) (Kinderdagverblijf-Gouda, 2016; Versteeg, 2012) and a bedstead.

to close contact with the human body (Boor et al., 2014). Therefore, good ventilation levels inside the baby beds is of extreme importance to remove the pollutants and create a healthy sleep microenvironment for the babies.

In previous research carbon dioxide (CO_2) concentrations were measured inside baby cribs in practical conditions (Braun & Zeiler, 2019; de Waard, 2014; de Waard & Zeiler, 2015; Kruisselbrink, 2015). Different types of baby beds were used: crib, bedstead and bottom and top bunk bed. Beside the type of baby cot also their position is of importance. The top of the bottom bed is then a closed surface as well as both sides and the wall facing side of the bunk bed, thus restricting the ventilation inside the bed to a large extent.

Previous research showed that when a baby was placed in the bottom bunk bed it led to higher CO_2 concentrations compared to a baby in the top bunk bed or bed stead (de Waard, 2014). Bonk beds are sometimes placed in a row of three next to each other as well as two above each other, see Figure 2.

This research focussed on the situation of the bottom bunk bed (BBB) compared to that of a bed stead (BS)with Due to movements of the babies in their beds there was a difference in the measured CO_2 concentrations at different time periods at the measurement positions (de Waard, 2014). Therefore, in the new research the effects of the position of the baby on the measured CO_2 concentrations were compared to the measurement positions.

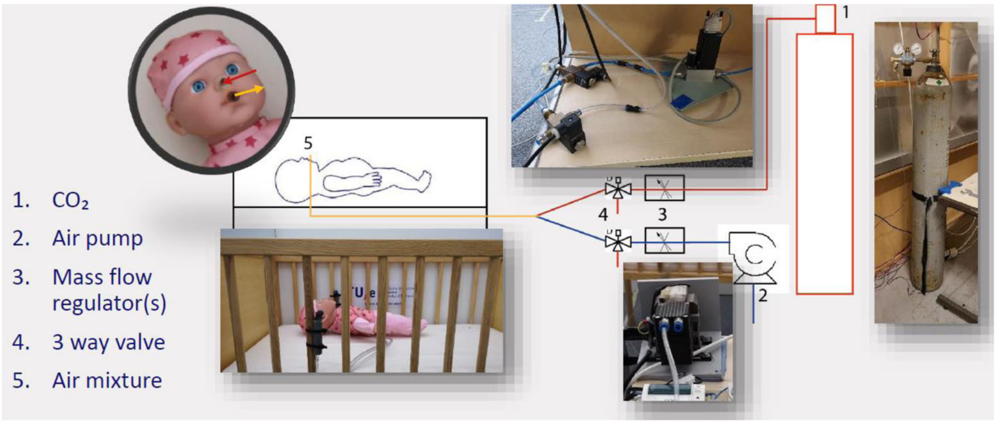
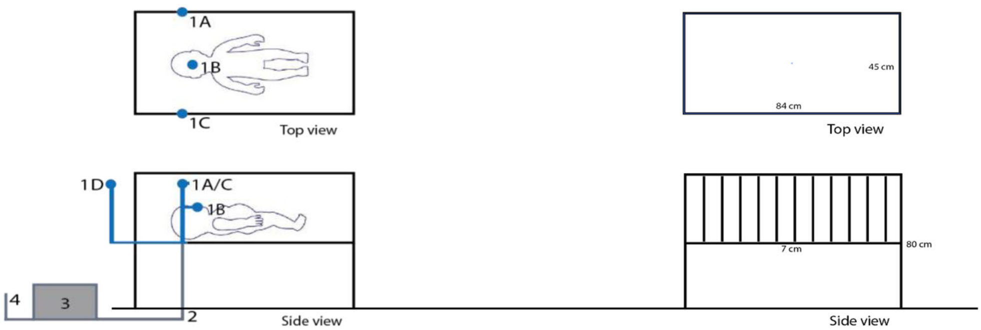


Figure 3. Breathing simulator, hose, CO_2 sensor (hose) and baby doll in test crib at TU/e.



Where: 1.Four CO_2 sensors (1A/B/C/D) 2. Cable bundler 3. Central box and 4. Mains supply

Figure 4. General measurement setup.

2. Method

To determine the effects of the closed surfaces and the breathing position of the baby on the different measurement positions, a baby doll was used with a breathing simulator, see Figure 3, as it was not possible to measure this with real babies in a real day-care centre.

2.1. Measurement setup

The general measurement setup can be seen in Figure 4.

Where 1: Four CO_2 sensors (1 A/B/C/D); 2: Cable bundler; 3: Central box; 4: Mains supply.

Four CO_2 sensors were used to measure the concentrations around the nose, bars on the wall side as well as the room side, and also the background level. The room sensor that measured the background CO_2 concentrations was placed at the same height as the sensors at the crib. The baby doll was placed in the test crib at the TU/e laboratory, more details on the type of sensors that were used can be found in Table 1.

2.2. Exhaled air simulation

To simulate the practical condition, the amount of CO_2 that a baby doll connected to a regulated supply hose has to insert into the crib was determined. An infant has a lung volume of

Table 1. Measurement equipment information.

Measurement	Device	Interval	Inaccuracy
CO_2	SBA-% CO_2 Analyser	1 s	<1%
Data logging	Squirrel 2020 series	1 s	±0.075%
Mass flow controller	Brooks model 0152	–	–
Mass flow controller	Brooks model 5850S	0–15 [ln/min]	±1%

10–15% compared to an adult and a breathing volume of 1.39 L/min (Kosch & Stark, 1984). On average an infant has a respiratory rate of 30–60 breaths/min, an adult has 12–20 breaths/min (Deboer, 2004). The increased exhaled volume of CO_2 is around 4–5%, this is about a 100-fold increase over the inhaled air (Dhami et al., 2015). Exact values for babies could not be found in the literature, therefore the lower region of the exhaled volume was chosen, the amount of exhaled CO_2 was set at 4%:

$$V_{E.CO_2} = V_{E.Air} * 4\% \tag{1}$$

where $V_{E.CO2}$: volume exhaled CO_2 [L]; $V_{E.air}$: volume exhaled air [L]; 4%: percentage of CO_2 in exhaled air.

Therefore the 'baby' has to deliver a constant volume of CO_2 of 0.06 [L/min], calculated with formula 1. This comparable with for example the data given by Persily and de Jonge (2017), 0.0009 L/s or 0.054 L/min. The schematics of the setup that was used to simulate the breathing pattern of an infant s presented in Figure 3. A CO_2 tank connected to a mass flow controller regulated the flow to 0.13 [L/min]. The Air pump also connected to a mass flow controller regulated the flow to 2.6 [L/min]. Both regulated flows then went through a three-way valve, set to a timer with an interval of 1 s. The three-way valve in combination with the timer creating the wanted air mixture thus simulating the respiratory rate of 30 breaths/min. The air mixture was inserted into the crib by a hose connected to the mouth off the baby doll, see the bottom arrow (orange) in Figure 3. The control setup, see Figure 5, was put 1 cm in front of the hose in the nose (top-red) where one of the CO_2 sensors was attached, this to prevent a short cut between the sensor in front of the extract and the air mixture supplied.

2.3. Baby positions

To see the effects of the position of the baby doll on the CO_2 concentrations inside the crib, the baby doll was placed and measured in four different positions inside the BBB, that can be seen in Figure 6.

3. Results

As an example, the results of three measured prone position inside the BBB is given in Figure 7.

3.1. Average CO_2 levels

An overview of the average CO_2 concentrations for each measurement is given in Table 3. The colouring is based on the quality standard values for ventilation in schools and child day cares (GGD Nederland, 2006), see Table 2.

3.2. Comparison between bed types

The effects off the different cribs on the CO_2 concentrations are displayed in this paragraph. The bottom bunk bed and bedstead where tested at the TU/e laboratory. The average measured CO_2

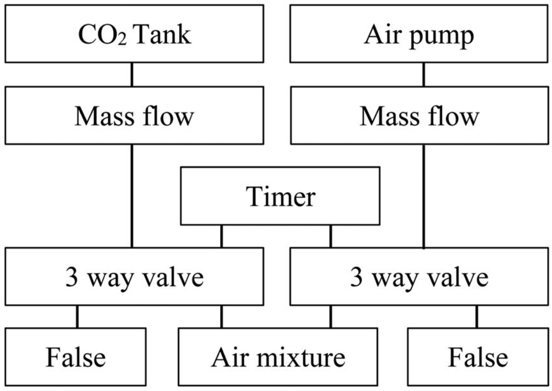


Figure 5. Schematically overview breathing.

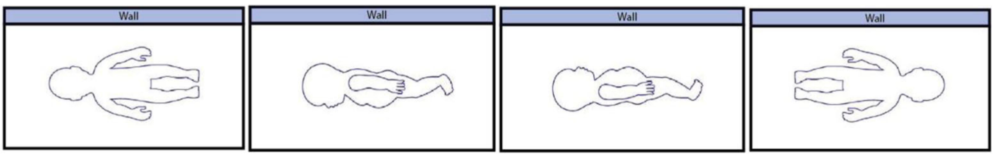


Figure 6. Measurement positions for the baby doll inside the cribs: supine, lateral facing room, lateral facing wall and prone.

concentration for each sensor position in the BBB or BS is displayed in Figure 8, where it can be seen that the CO_2 concentrations are higher for each measurement position in the bottom bunk bed and therefore lower in the bedstead.

This comparison is again made in Figure 9 where the CO_2 concentration inside the BBB and BS were made relatively to the background concentration and were lower in the BS.

3.3. Comparison between baby position

The effects off the different position, in which the baby was placed, on the CO_2 concentrations are displayed in this paragraph. The average results for each sensor position at the BBB as well as the back ground level in the room are displayed in Figure 10, the results for the BS are displayed in Figure 11.

These values where again made relative to the background in Figures 12 and 13.

The high concentration value at the mouth of the baby doll in the BS, when facing the wall is disturbing the overview of the results, therefore this value is excluded in Figure 14.

The overall results of the measurements relative to the background level are displayed in Figures 15 and 16. It can be seen that that the values at the position of the mouth reached the highest concentration, it can also be seen that, when the baby is facing a more open surface the concentration reaches less high values.

4. Discussion

The size of the crib is that of a privately owned crib, i0nstead of the slightly bigger ones used at day-care centres. Therefore, it can be expected that the values inside a bigger crib, as in day-care centres, will not reach the same increase in concentrations. All measurements were done in a laboratory situation with an extremely good background level of CO_2 of around 480 ppm. As it was not possible to do measurements with real babies, we used a baby doll with nearly the same dimensions and integrated a mechanism to represent the breathing of a baby. This led to

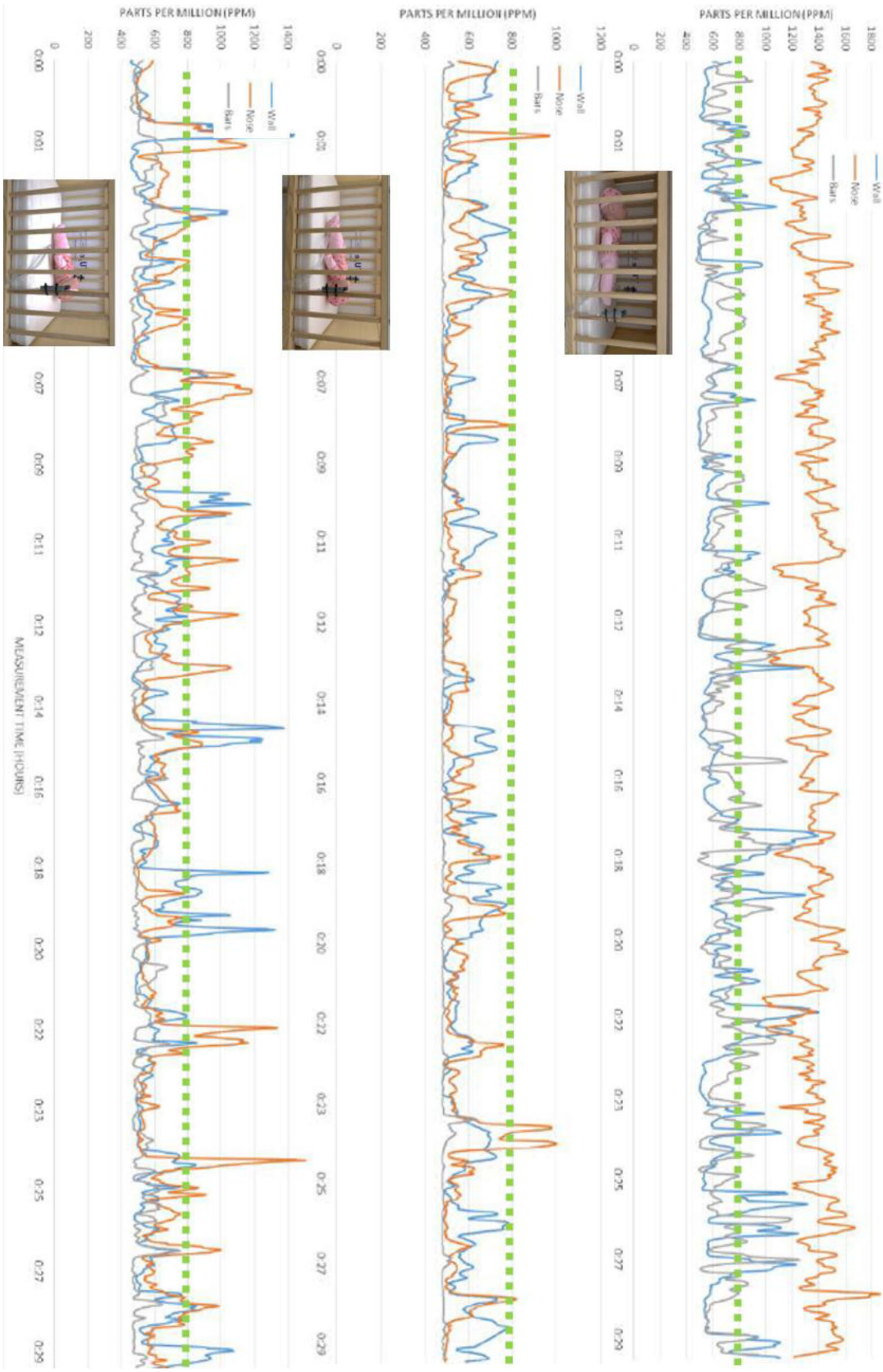


Figure 7. Measurement data of three different prone orientation, limit of 800 ppm CO_2 marked with dotted line.

Table 2. GGD classes for CO_2 [ppm] concentrations.

Class	A: Very good	B: Good	C: Acceptable	D: Insufficient	E: Very poor
CO_2 [ppm]	<650	650–800	800–1000	1000–1400	>1400

Table 3. Overview of the average CO_2 concentrations of all the measurements.

Class	A Very good	B Good	C Acceptable	D Insufficient	E Very poor
CO_2 [ppm]	< 650	650-800	800-1000	1000-1400	>1400

Table 3: Overview of the average CO_2 concentrations of all the measurements.

	Bottom bunk bed											
	Facing roof			Facing wall			Facing room			Rotated position		
	01BBB1AM_190115	02BBB1AHWW_190109	03BBB1AHWB_190109	07BBB2M_190110	08BBB2HWW_190111	09BBB2HWB_190111	10BBB3M_190110	11BBB3HWW_190111	12BBB3HWB_190114	13BBB4M_190110	14BBB4HWW_190114	15BBB4HWB_190114
Wall	886	1157	1257	854	2992	1688	489	465	480	950	597	667
Middle	1376	1492	1417	1725	2271	1696	516	516	510	1263	1344	1361
Bars	843	944	817	537	724	617	502	867	487	729	576	684
Background	490	474	469	495	473	466	501	487	471	488	468	466

	Bedstead											
	Facing roof			Facing wall			Facing room			Rotated position		
	16BS1M_190110	17BS1HWW_190114	18BS1HWB_190114	22BS2M_190110	23BS2HWW_190114	24BS2HWB_190114	25BS3M_190110	26BS3HWW_190115	27BS3HWB_190115	28BS4M_190111	29BS4HWW_190115	30BS4HWB_190115
Wall	575	621	582	1086	530	1167	495	597	469	660	658	618
Middle	556	660	730	1770	2452	1530	595	597	917	866	980	564
Bars	489	516	534	580	597	545	568	1282	573	561	515	481
Background	486	460	467	484	462	466	491	495	497	481	473	472

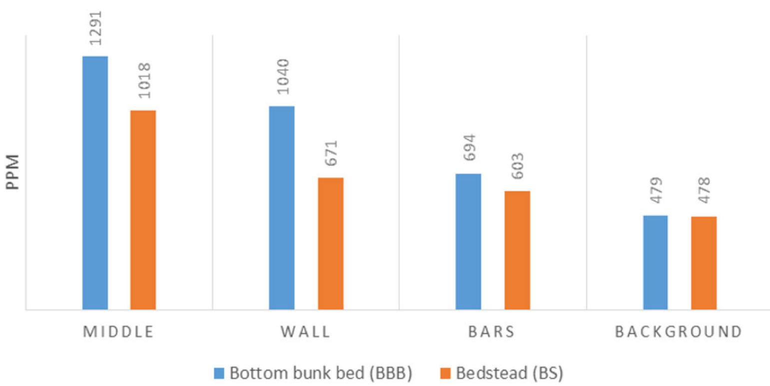


Figure 8. Bottom bunk bed versus bedstead, average CO_2 concentrations.

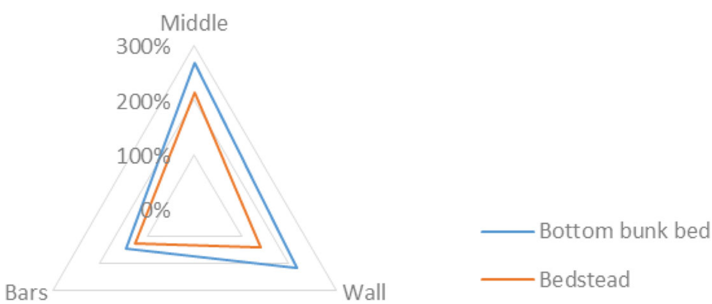


Figure 9. BBB versus BS relative to background CO_2 concentration.

simplified representation of the breathing which therefor might differ from the real baby's breathing.

The concentrations were determined by measuring at the edges of the baby crib, this due to necessary safety precautions that no sensors could be touched by the babies. This led to a

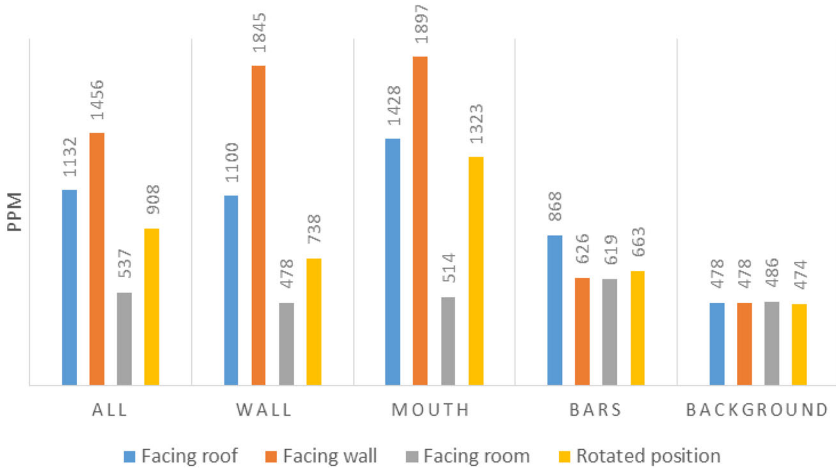


Figure 10. Average BBB CO_2 concentrations.

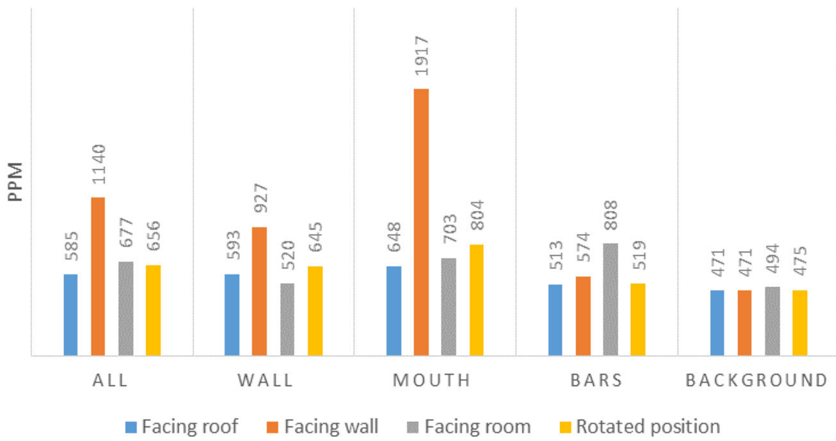


Figure 11. Average BS CO_2 concentrations.

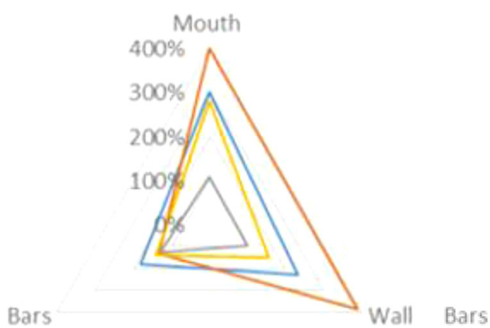


Figure 12. BBB CO_2 relative to the background.

variable distance from the exhaled air (mouth) till the measured air depending on the position of the baby within the crib. The free breathing zone of an infant was determined to be 0.3 m (de Waard, 2014). However, due to the variable distance between 0.1 and 0.4 m, this was not met in all practical measurement conditions.

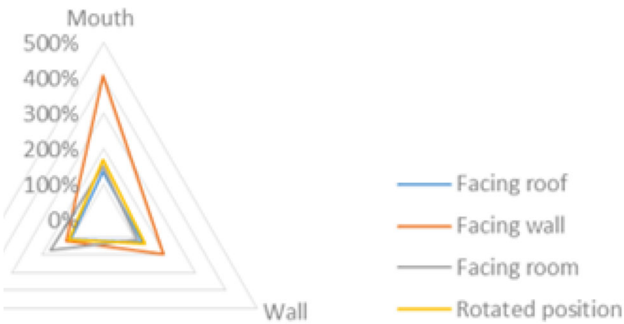


Figure 13. BS CO_2 relative to the background.

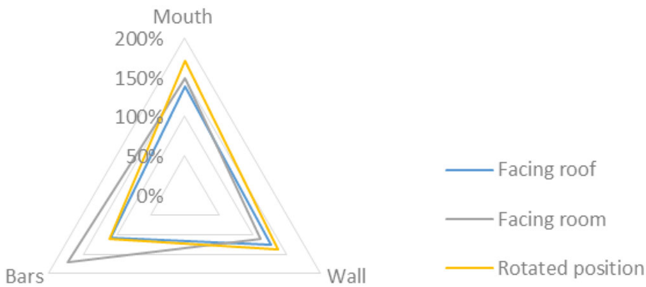


Figure 14. BS, CO_2 concentrations relative to the background (wall excluded).

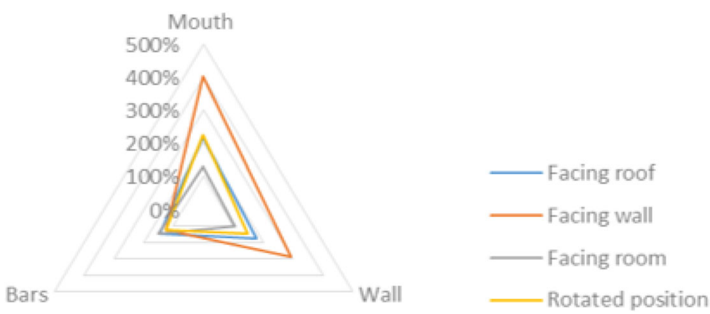


Figure 15. Average CO_2 BBB and BS combined.

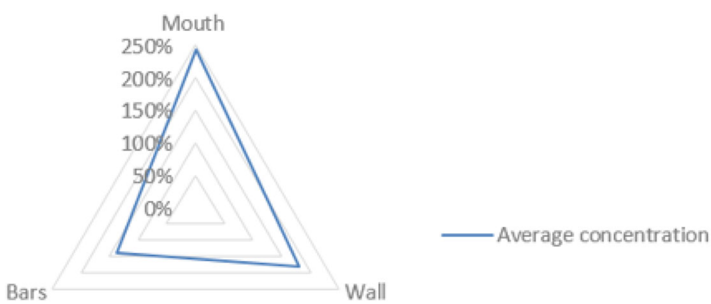


Figure 16. Average CO_2 concentrations.

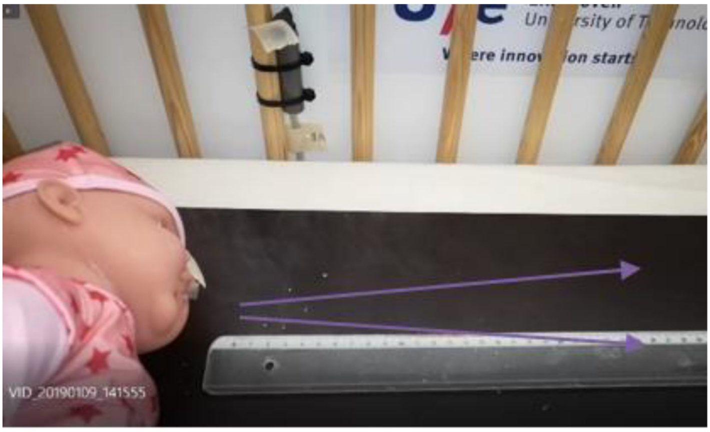


Figure 17. Breathing pattern, smoke-test.

The workings of the breathing simulation were based on data from literature and the flow pattern of the exhaled air was investigated with a smoke-test. The smoke-test enabled to check if there was a possible major short cut between the exhaled air and the nose sensor. Figure 17 shows one of these measurements, where it can be seen that the exhaled air effected the inserted smoke up to a distance of 23 cm and spread according the arrows in the figure. The air was not visually affected by the sensor in the nose of the baby doll.

5. Conclusion

This research was performed to measure the effects of the position of the baby on the measured CO_2 concentrations and also the difference between the CO_2 concentrations at the mouth of the baby doll compared to the measurement position. It was found that the bottom bunk bed with more closed surroundings led to an average increase of around 220% relative to the background level, compared to the bedstead where the increase was 160%. In both situations the increases are significant and even more significant for the measurements at the wall side, here the increase in the bottom bunk bed was on average around 270% and for the bedstead it was around 210%. Therefore, it can be concluded that the more closed the surroundings of a crib are, the higher the CO_2 concentrations will be.

The position of the baby doll also had a significant effect on the measurements. For example, with the bottom bunk bed when the baby is facing the wall the rise in the average CO_2 concentrations was around 270%, however when the baby was facing the room (bars) the CO_2 concentrations only rose by nearly 30%. Facing the roof led to an average increase of around 80%. Therefore, it is concluded that the position of the baby has a significant effect on the measured values. When the mouth of the baby is facing an open surrounding the average CO_2 concentrations of the inhaled air decreased significantly compared to when a baby was facing a more closed surrounding. Therefore, it is concluded that it is not sufficient to only measure the CO_2 concentrations in the sleeping room as the conditions will significantly deviate from those in a crib.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Gert-Jan Braun In 2016 Gert-Jan Braun did his bachelor Building Technology at HAN Arnhem after which he did his master Building Physics and Services at University of Technology Eindhoven. In 2018 he, together with a fellow student, started his own Building Physics & Services consulting company Schouenberg & Braun. Currently he works as Trainee MEP at Ballast Nedam Civil Engineering.

Wim Zeiler started in Building Services industry in 1983 and is since 2001 full professor Building Services at the faculty of the Built Environment at the Eindhoven University of Technology (TU/e). In addition Zeiler is still part time building services technology specialist at Kropman Building Services contracting. In 2014 he received the professional science award of REHVA, the European federation for Heating-, Ventilation and Air-Conditioning. His current research is on Healthy ventilation in day care centres & schools, Intelligent buildings and Flexible Smart Grid integration.

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