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

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## ABSTRACT

The indoor air quality is very important for the well-being of occupants, especially in the case of young babies. This research focuses on the air quality of the surrounding air inside a crib with sleeping infants. To study the effects of different sleeping positions of the baby with in the crib a measurement setup was created in the laboratory. The breathing of an infant was simulated by means of a baby doll with air supply mixed with $CO_2$ and measured at different sensor locations for different sleeping positions. The results show an enormous increase in the $CO_2$ concentration (up to 4 times) depending on the sleeping position of the infant, and also show the effect of a more open crib. The effect of the position of the baby on the $CO_2$ concentrations inside the crib are compared with the background level in the sleeping quarter.

## KEYWORDS

Carbon dioxide, concentration, Crib, Infants, ventilation, sleeping position

## 1 INTRODUCTION

Babies often spent up to 11 hours in a day care centre during the working days in modern society. 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 1$^{st}$ year of life, 12.6 h/day in the 2$^{nd}$ year, and 12.1 h/day in the 3$^{th}$ year (Iglowstein et al 2003, Boor et al 2017). The sleep microenvironment is the predominant indoor space for babies where they spends most of their time. 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 normalized 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 normalized inhaled air volumes, V*Sleep, are categorized by age group and gender and presented in Fig. 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. 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 localized elevations in surface temperature and moisture near the bed due to close contact with the human body (Boor et al 2014, 2015).
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. They are by far the most vulnerable as their lungs are still in full development. Furthermore some literature suggest even a relation with the Sudden Infant death Syndrome (Corbyn 2000, Sakai et al 2008, De La Iglesia et al 2018).

In previous research carbon dioxide ($CO_2$) concentrations were measured inside baby cribs in practical conditions (de Waard 2014, de Waard & Zeiler 2015, Kruisselbrink 2016, Zeiler 2018, Braun & Zeiler, 2019). Different types of baby beds are being used: crib, bedstead and bottom & top bunk bed. Beside the type of baby cot also there position is of importance. Sometimes they are placed in a row of three next to each other as well as two above each other, see Fig. 2. The problem is that the top is then often a closed surface as well as both sides of the bunk bed, which restricts the inside ventilation in the baby bed itself to a large extent. Previous research showed that when there is a baby placed in the crib the top bunk bed has lower $CO_2$ concentrations compared to the bottom bunk bed (BBB) ( de Waard 2014). Therefore this research focused on the bottom bunk bed and also on the bedstead (BS). The main difference between this two baby cots is the closed off surface at the top of the bottom bunk bed.

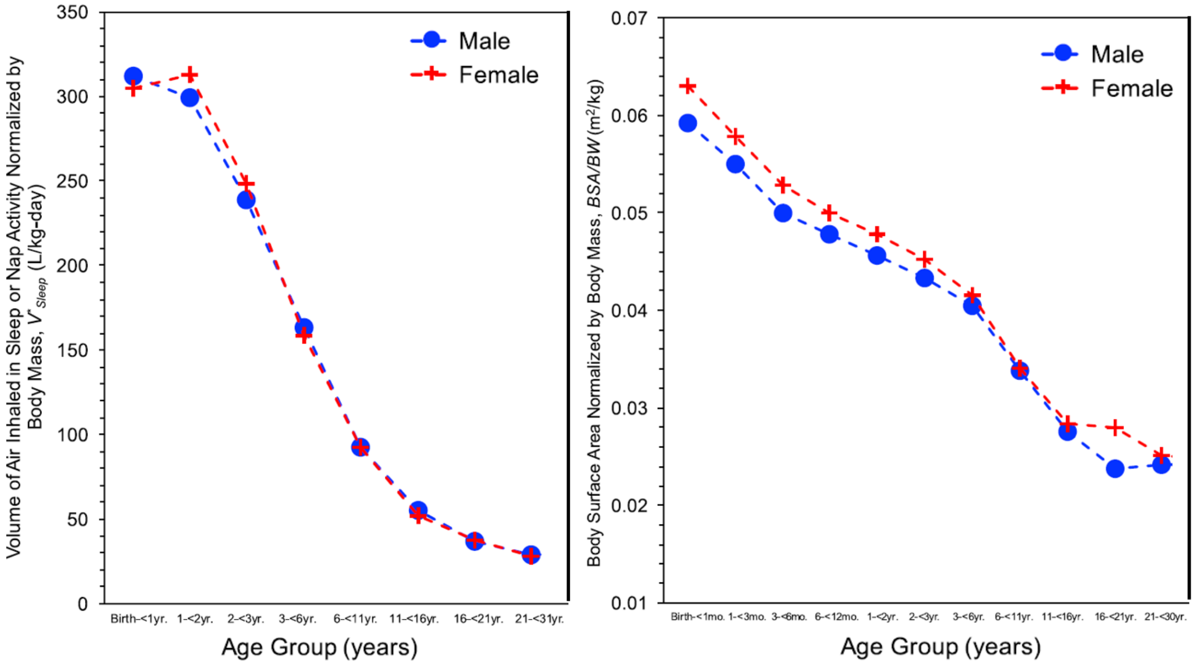



Figure 1. Volume of air inhaled during sleep or nap activity per day and Infant dermal exposure dose considerations in the sleep microenvironment: normalized by body mass for each age group and gender (calculated using U.S. EPA EFH data set (2009) by Boor et al 2017).

Figure 2. Examples baby bunk bed (Versteeg 2012, Kinderdagverblijf Gouda 2016)

It was noticed that there was a significant difference of 5.7% (Class B, GGD) in the measured $CO_2$ concentrations and a visible difference at different time periods between the measurement positions. Therefore the effects of the position of the baby on the measured $CO_2$ concentrations and also the difference between the CO2 concentrations at the mouth of the baby compared to the measurement positions are determined in this research.

# 2 METHOD

The method below is used to determine the effects of the closed surfaces and the breathing position of the baby on the different measurement positions. As it was not possible to measure on real babies a baby doll was used instead with a breathing simulator, see Fig. 3.

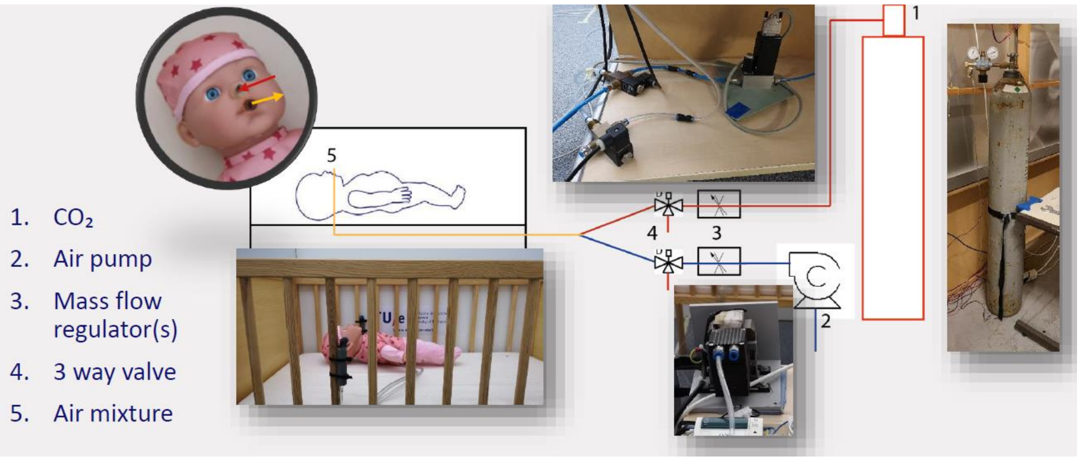
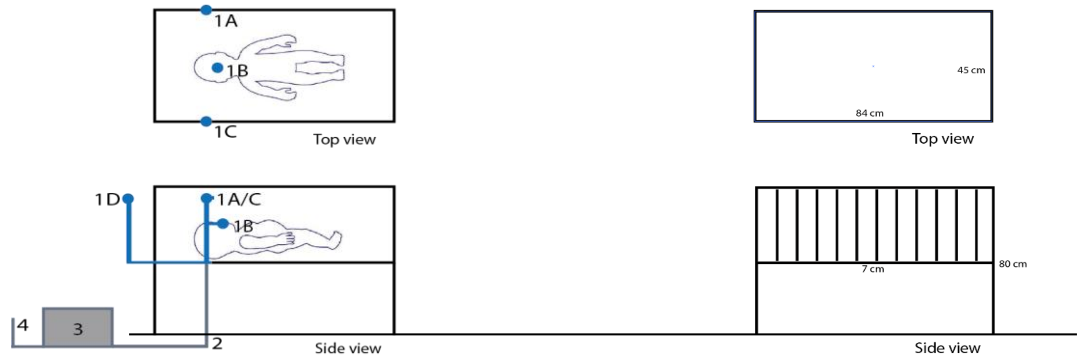



Figure 3: Breathing simulator, hose, $CO_2$ sensor (hose) and baby doll in test crib at TU/e

## 2.1 Measurement setup

The general measurement setup can be seen in Fig. 4.




Where: 1.Four CO2 sensors (1a/b/c/d) 2. Cable bundler 3. Central box and 4. Mains supply

Figure 4: General measurement setup

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 is placed in the test crib at the TU/e, more details on the type of sensors that were used can be found in Table 1.

Table 1: Measurement equipment information

| Measurement | Device | Interval | Inaccuracy |
|---|---|---|---|
| $CO_2$ | SBA-% $CO_2$ Analyser | 1 sec | < 1% |
| Data logging | Squirrel 2020 series | 1 sec | ±0,075% |
| Mass flow controller | Brooks model 0152 | - | - |
| Mass flow controller | Brooks model 5850S | 0-15 [ln/min] | ± 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 10-15% compared to an adult and a breathing volume of 1.39 litres per minute (Kosch, 1984), On average an infant has a respiratory rate of 30-60 breaths per minute, an adult has 12-20 breaths per minute. (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-1], calculated with formula 1 (for an adult it would have been 0.30 [L.min-1]). The schematics of the setup that was used to insert this $CO_2$ into the crib and to mimic the breathing pattern of an infant can be seen in Fig. 3. A $CO_2$ tank that was connected to a mass flow controller regulated the flow to 0.13 [L.min-1]. The Air pump was also connected to a mass flow controller and regulated the flow to 2.6 [L.min-1]. Both regulated flows then went through a three way valve, set to a timer with an interval of one second. The three way valve in combination with the timer mimicked the respiratory rate of 30 breaths per minute by extracting the air and $CO_2$ outside the room and by combining both and creating the wanted air mixture. 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 Fig. 3 and the control set-up in Fig. 5. This hose was put one centimetre in front of the hose in the nose (top-red) at witch one of the $CO_2$ sensors was attached, this to prevent a shortage between the sensor and the air mixture.

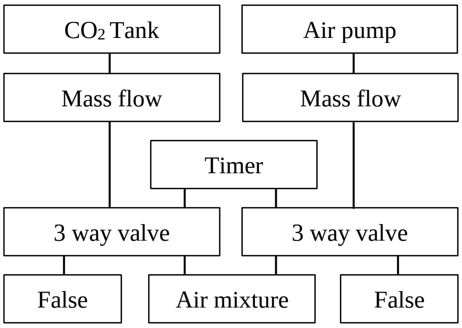



Figure 5: Schematically overview breathing

## 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 BS and BBB, that can be seen in Fig.6.

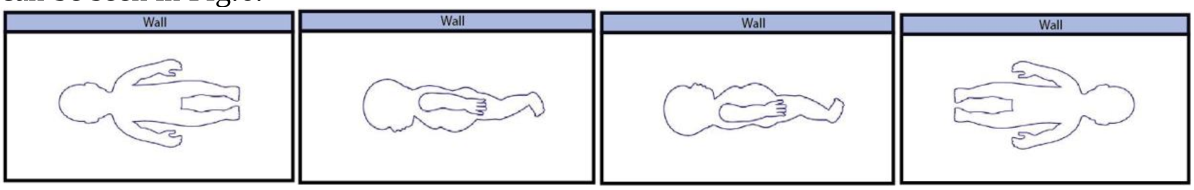



Figure 6: Measurement positions for the baby doll inside the cribs: supine, lateral facing room, lateral facing wall and prone

# 3 RESULTS

As an example the results of a series of 3 measurements prone position inside the BS is given, in Fig. 7.

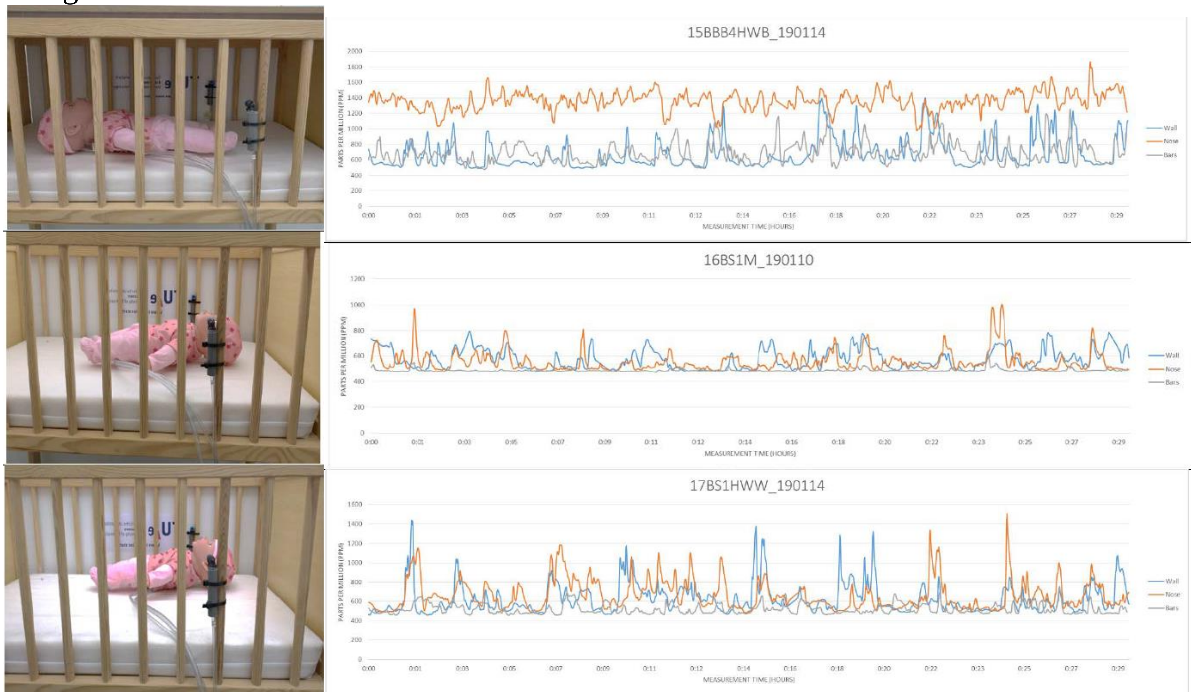



Figure 7. Actual measurement data of 3 slightly different position with prone orientation

## 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 test values for ventilation in schools and child day cares (GGD Nederland, 2006), see Table 2.

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.

| | 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 |

## 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 $CO_2$ concentration for each sensor position in the BBB or BS is displayed in Fig. 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.

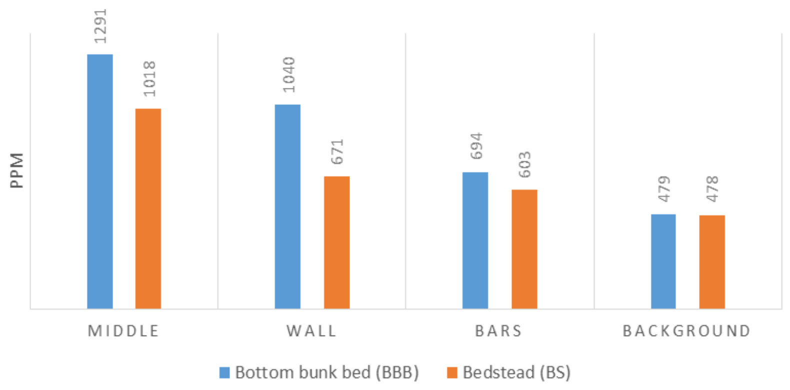



Figure 8: Bottom bunk bed vs. bedstead, average $CO_2$ concentrations

This comparison is again made in Fig. 9 where the $CO_2$ concentration inside the crib was made relatively to the background concentration. Again the results show that the $CO_2$ concentration relatively to the background concentration are lower in the bedstead.

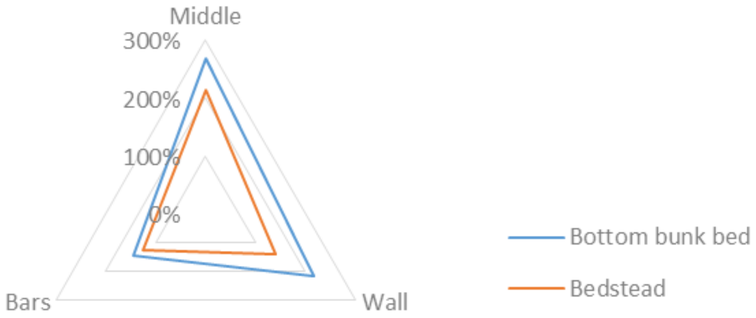



Figure 9: BBB vs. BS relative to background $CO_2$ concentration

### 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 Fig. 10, the results from the BS are displayed in Fig. 11.

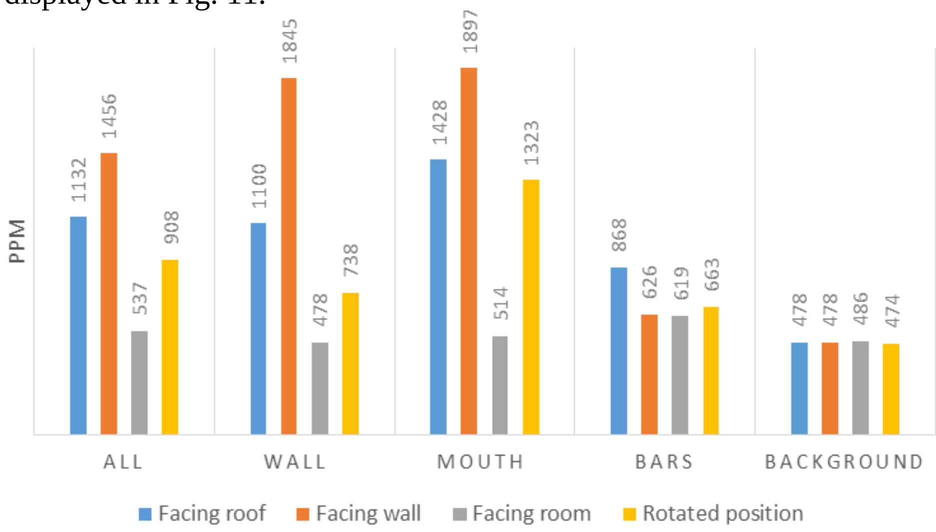



Figure 10: Average BBB $CO_2$ concentrations

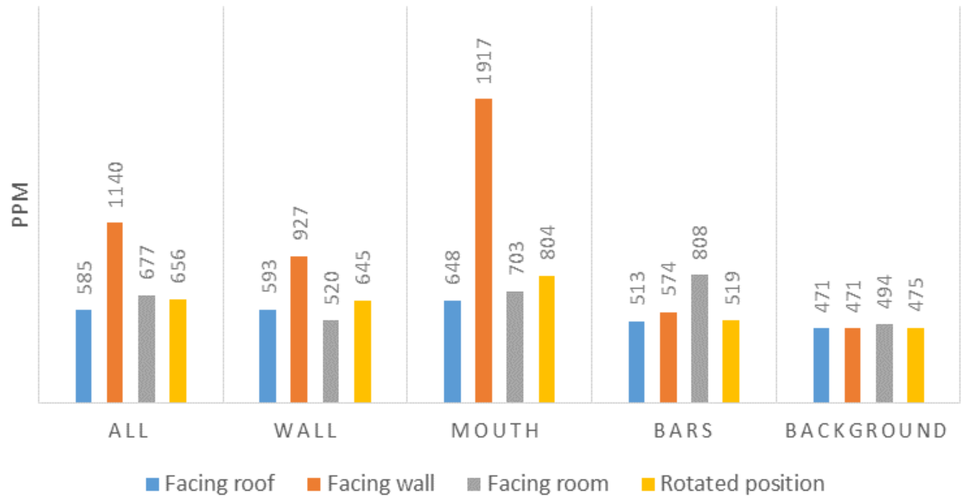



Figure 11: Average BS CO2 concentrations

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

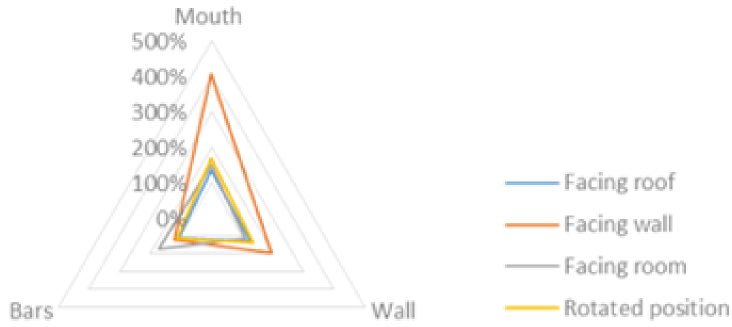




Figure 12: BBB, $CO_2$ relative to the background

Figure 13: BS, $CO_2$ relative to the background

The high concentration value at the mouth of the baby doll, when facing the wall makes is somewhere unclear to see the results, therefore this value is excluded in Fig. 14.

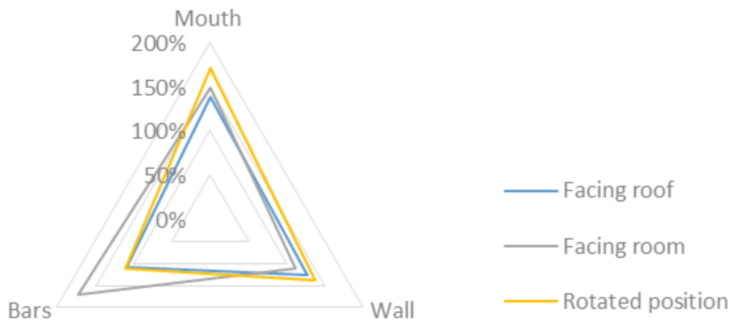



Figure 14: BS, $CO_2$ concentrations relative to the background (wall excluded)

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

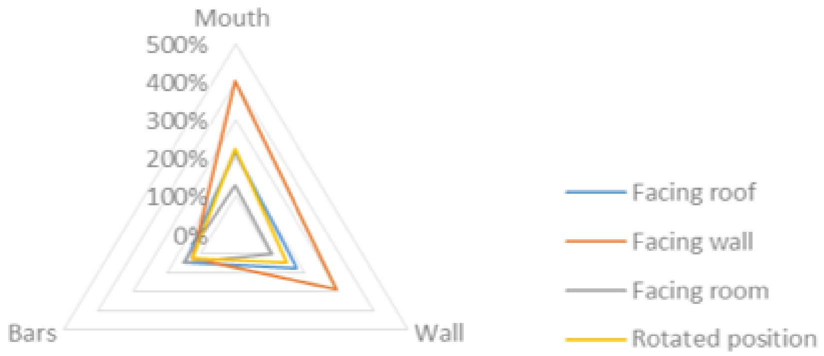



Figure 15: Average $CO_2$ BBB and BS combined

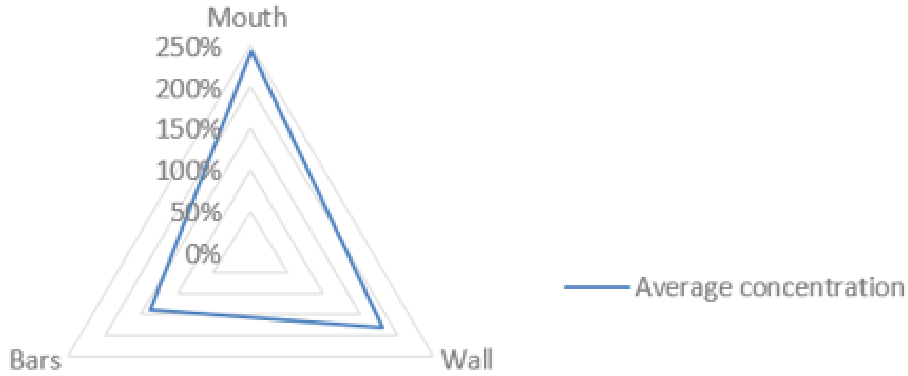



Figure 16: Average CO2 concentrations

# 4 DISCUSSION

The size of the crib is that of a privately owned crib, instead of the ones used at day-care centers. Therefore it can be expected that the values inside a bigger crib, as in daycare centers, 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. In normal buildings this would be much higher to start with. However, as our focus was on the effect of the position of the baby inside the crib on the $CO_2$ concentration of the inhaled air we choose this level to be able to detect differences more easy.  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 simplifications of representing the breathing which therefor might differ from the real baby´s breathing.
The concentrations were determined by measuring at the edge of the baby crib, this due to necessary safety precautions that no measure equipment could be reached by the babies.  This led to a 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 meters (de Waard, 2014). However, due to the variable distance between 0.1 - 0.4 meters, this was not met in all practical conditions.

The workings of the breathing simulation was not compared with a real enfant, therefore it cannot be said how accurately the breathing pattern was simulated, the flow pattern of the exhaled air was however investigated with a smoke-test. The smoke-test enabled also to check if there was a possible major short cut between the exhaled air and the sensor. Fig. 17 shows a position in time of these measurements, where it can be seen that the exhaled air effected the inserted smoke up to a distance of 23 centimetres and spread according the arrows in the figure. The air was not visually affected by the sensor in the nose of the baby doll.

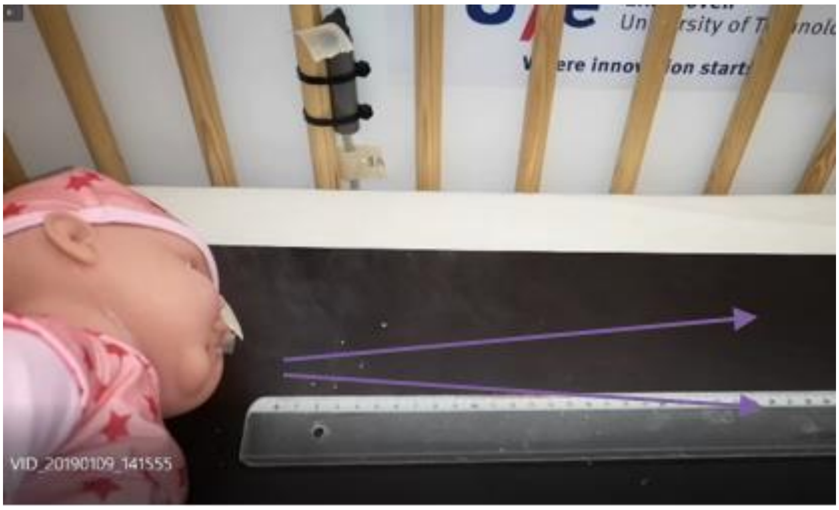



Figure 17: Breathing pattern, smoke-test

It was found that the location of the sensor had a significant effect on the measured concentrations, the mouth sensor measured an increase relative to the background level of around 140 percent higher, where the wall sensor measured 80 percent higher and the bar sensor nearly 40 percent higher.

## 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 a more closed surroundings led to an average increase of around 220 percent relative to the background level, compared to the bedstead where the increase was 160 percent. 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 percent and for the bedstead it was around 210 percent. 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 percent, however when the baby was facing the room (bars) the $CO_2$ concentrations only rose by nearly 30 percent. Facing the roof led to an average increase of around 80 percent. 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.

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