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A silent cloud of CO_2 in the safe space of the crib - understanding SIDS: a model simulation

Łukasz Derkacz [1] - A,B,C,D,E,F,G,H,I,K,L,M,N,O. ORCID www.orcid.org/0009-0000-8025-1456
Łukasz Styś [1] - B,C,E,F,G,N,O. ORCID www.orcid.org/0009-0008-8076-8453
Krystian Lech [1] - D,F,G,H,N,O. ORCID www.orcid.org/0009-0007-3871-7313
Ireneusz Barziej [1] - C,E,F,G,J,K,N,O. ORCID www.orcid.org/0009-0008-8531-4282

[1] *National Academy of Applied Sciences in Nysa, Health Care Unit, Nysa, Poland.*

Address for correspondence:
Łukasz Derkacz. *National Academy of Applied Sciences in Nysa, Nysa (Medical College, Building D). Armii Krajowej Street 7, 48-300 Nysa, Poland; e-mail: derkacz@zoznysa.pl; tel: +48 725511403*

Author Contributions (CRediTTaxonomy):

Conceptualization - **A**
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Formal Analysis - **C**
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Methodology - **F**
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Resources - **H**
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Supervision - **J**
Validation - **K**
Visualization - **L**
Writing (Draft Preparation) - **M**
Writing (Review & Editing) – **N**
Approved the final version - **O**

ABSTRACT

INTRODUCTION: Sudden Infant Death Syndrome (SIDS) is a disease syndrome with an as yet unexplained cause, resulting in the sudden death of an infant commonly considered healthy/healthy developing, occurring during sleep. Due to the lack of detection of a direct cause of sudden infant death syndrome in infants, many theories, suspicions, and risk factors have emerged, but no research method has confirmed an absolute cause of this syndrome. The purpose of this study was to assess the dynamics of CO_2 accumulation in crib volume under model conditions, taking into account the influence of crib design, season, and environmental parameters.

MATERIALS AND METHODS: The study was carried out in a room replicating the conditions of a child's bedroom, using two types of cribs (home and medical) and infant mannequins heated to 37 ° C. Ventilation of a 4-month-old infant (VE < 2 l/min) was simulated by introducing technical CO_2 (1 l/min) in 15-minute cycles. The gas concentration was monitored with sensors placed around the head, chest, and lower extremities. Furthermore, the effects of atmospheric pressure, humidity, and temperature were analysed.

RESULTS: In the home crib, significant CO_2 accumulation was observed in the head and chest zone, with peak values of >2000 ppm, particularly in the evening. In the medical crib, no significant increases in concentrations were observed. A positive correlation between humidity and CO_2 concentration was observed, as well as destabilisation of the gas cloud at atmospheric pressure >990 hPa. Fluorescence visualisation confirmed the presence of a stable CO_2 layer over the chest and neck.

CONCLUSIONS: The accumulation in the CO2 crib space is not uniform – the gas forms a local cloud in the respiratory zone, which can lead to hypercapnia and ventilation disorders. Crib design and environmental conditions play a key role in modulating the risk of SIDS. The results obtained highlight the importance of environmental factors in the pathogenesis of SIDS and suggest directions for further research on the prevention of this phenomenon.

KEY WORDS: SIDS, CO_2 cloud, crib volume, breathing disorders.

INTRODUCTION

Sudden Infant Death Syndrome (SIDS) is a disease syndrome with an as yet unexplained cause, resulting in the sudden death of an infant commonly considered healthy/healthy developing, occurring during sleep. Due to the lack of detection of a direct cause of sudden infant death syndrome in infants, many theories, suspicions, and risk factors have emerged, but no research method has confirmed an absolute cause of this syndrome. In the field of medicine, one can boldly term it a "phenomenon." The problem lies in the methodology of the research on the cause, as statistically, the group of SIDS represents a very small research group, and pathological examinations do not provide any answers regarding causality.

According to the definition of 1969 and the report of the expert team from San Diego in 2004 - classification of death as SIDS - must differentiate all other causes of infant death, particularly accidental suffocation by having a pillow, blanket, or other covering element pulled over the infant's face, positioning on the stomach (specific suffocation), hidden developmental and genetic defects, including defects detected in utero or other abnormalities; prematurity, other birth complications; accidental aspiration of food contents due to regurgitation, excessive flexion of the head toward the chest - improper use of a pillow, or factors related to a large occiput and a tendency to flex the head - mechanical spontaneous closure of the airways, homicide, as well as accidents and other pathologically identifiable causes [1,8,9].

In conclusion, SIDS is the sudden unexpected death of an infant (syn. Crib death, death without pathology, silent death) that occurs during sleep, and the causes are not explained by the medical history, circumstances of death, including the examination of the death—or a comprehensive postmortem investigation. SUDI is the sudden, unexpected death of an infant that occurs during sleep or not, including all causes that can lead to this death, such as adverse health circumstances, developmental defects, prematurity and complications, accidental suffocation, effective choking/asphyxia. A clear cause of death is identified in the pathomorphological examination. ALTE is a clearly life-threatening condition in an infant. The symptoms of ALTE are usually associated with broadly defined respiratory disturbances and primarily involve the appearance of apnea, choking, changes in skin colour, and loss of muscle tone. The restoration of normal vital functions occurs spontaneously or as a result of cardiopulmonary resuscitation. Currently, ALTE is believed that has a clinical cause, and if the baby dies, it is classified as SUDI rather than SIDS, as the direct cause of death is known [16].

In 2004, a team of experts in San Diego proposed an appropriate classification of the differential diagnosis of SIDS, issuing the following recommendations:

SIDS Category 1A - This is a set of certain deaths – based on clinical data, history, and execution of all possible differential causes of death, and findings of postmortem examination – where no direct cause of the infant's death is identified, such deaths should be classified as SIDS 1A [16].

SIDS Category 1B - This is a set of deaths that meet the criteria or premises for SIDS, but without all possible postmortem examinations and differential diagnosis conducted for a potential direct cause, or failure to perform all recommended diagnostic tests, for which the history absolutely directs toward SIDS. [16]

SIDS Category 2 - In this category, we classify cases that can be attributed to the SIDS picture, but there are other less or more significant deviations not from the classical image of the aforementioned unit, but for example the age of the child itself, which by definition does not fall within the traditionally established norms, i.e., a child up to 21 days of life or before 2 months of life; infants over 9 months old; unclear situations without evidence of a clear crime, e.g., a similar pattern of death of other infants under the care of the same caregiver, or of a similar context of events; other health problems that occurred during the perinatal or neonatal period but subsided by the time of death; also, if during the analysis of the circumstances of death, it was possible that accidental suffocation occurred, but the mechanism was not confirmed by evidence of this act or accidental situation; if the postmortem examination indicates developmental defects that did not affect the process of the aforementioned death; other inflammatory changes that are not the direct cause of death.[16]

Sudden infant death syndrome (SIDS) remains a phenomenon whose ethics is not fully understood. Among the proposed mechanisms, environmental factors, including the accumulation of carbon dioxide (CO_2) in the infant's sleep space, are increasingly important [1,8,9,12]. The purpose of this study was to assess the dynamics of CO_2 accumulation in crib volume under model conditions, taking into account the influence of crib design, season, and environmental parameters.

MATERIALS AND METHODS

MATERIALS

The measurement study was carried out during two seasons, the summer period on 26 June 2024 and the winter period on 23 January 2025. For each season, based on an environmental and obstetric interview, the statistically most common sleep/nap periods of the babies were taken into account. Three daily time intervals were selected:

morning: 7:00–10:00

midday: 12:00–14:00

evening/night: 19:00–22:00.

The study was carried out in a room of the National Academy of Applied Sciences in Nysa, Building D, arranged to most accurately reproduce the environment of the bedroom of an infant.

Room dimensions:

- Length: **3.35 m**
- Width: **3.023 m**
- Height: **3.65 m**
- Volume: **36.9637325 m³**

In the study, two types of crib were used in the study: a classic home crib and a medical university crib.

Home crib dimensions:

- Length: **1.2 m**
- Width: **0.65 m**
- Height: **0.74 m**
- Mattress base height: **0.1 m**
- Mattress height: **0.1 m**
- Volume: **0.5772 m³**
- Volume of the crib: **0.234 m³**

Medical crib dimensions:

- Length: **0.75 m**
- Width: **0.4 m**
- Height: **1.2–1.4 m**
- Mattress base height: **0.85 m**
- Mattress height: **0.08 m**
- Volume: **0.075 m³**
- Volume of the crib: **0.075 m³**

Additional room equipment:

- measurement and data recording station,
- two cylinders (5 kg each) of technical CO_2,
- tube routed into the crib near the mouth–nose area,
- infant mannequins,
- four thermal heaters mounted on mannequins, maintaining 37°C,
- crib accessories: mattresses; the home crib also had a canopy, curtains, quilt, and pillow (Attachment 1 - specification).

Two adult researchers (85 kg and 80 kg) were present inside the room.

Measurement equipment:

Benetech sensors (series 1021220149911, ZigBee Wi-Fi, rechargeable battery, weight 0.18 kg, IJUY201, CE-certified, EAN 4006430394449), measuring:

- CO_2 concentration [ppm],
- formaldehyde (HCHO) concentration [mg/m³],
- TVOC concentration [mg/m³],
- indoor humidity [%],
- indoor temperature [°C],
- air quality indicator with alarm (green/yellow/orange/red).

Additional devices:

Digital thermometer and barometer connected to a CUBOT KING KONG STAR smartphone, measuring:

- outdoor temperature [°C],
- atmospheric pressure [hPa],
- outdoor humidity [%].

A clock and a 15-minute interval matrix were also used. Specification of the technical CO_2 gas (Attachment 2 - technical data).

METHODS

Several statistical assumptions were made to model the scenario:

- SIDS affects babies aged 2 to 9 months,
- The highest incidence occurs around the 4th month,
- expected body weight at 4 months: 3 kg + (0.5 kg × 4 months) = 5 kg.

Minute ventilation (VE)

$$VE = mc \times V_t \times f = 5\,kg \times 10\,ml/kg \times 40 = 500\,ml \times 40 = 2000\,ml/min$$

In the model, the tidal volume was treated as constant to set the gas flow. According to the literature, ventilation can vary by ±50%, giving a physiological range of 1000–2000 ml/min. The minimum value was adopted. Since continuous inhalation–exhalation simulation was not possible, only minute flow could be modelled. The goal was to determine whether exhaled CO_2 accumulates evenly within the crib ("crib volume") and how quickly.

CO_2 introduction protocol:

- CO_2 was introduced at **1 L/min** for each 15-minute session.
- After each session, the gas was turned off and retention was monitored until the values returned to atmospheric baseline **400–550 ppm**.
- Average decay time between sessions: **2 minutes**.
- Then, gas introduction was resumed.

Use of UV-reactive dye

An additional technique involved the use of “Brilliant Coolant”**,** an automotive dye used to detect CO_2 leakage from engine cylinder heads. Under UV light, it fluoresces in the presence of CO_2 (Figure 1). Illumination of the crib revealed a bright glow in the chest area, indicating a higher CO_2 concentration. A bright glow around the head, neck, and chest region clearly indicates the pattern of CO_2 cloud accumulation (CO_2 CLOUD).

Figure 1. UV lamp analysis - identification of CO_2 location in the crib volume.

RESULTS

Analysis and Interpretation of CO_2 Accumulation in the Crib Volume During the Summer Period

<u>Medical crib</u>

Table 1 presents the measurements obtained in the medical crib, where a greater accumulation was initially expected. The crib was inclined approximately 30% downward from the head side; constructed of plastic, without ventilation openings.

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Table 1. Results of the measurement in the summer period (medical crib).

medical_crib

measurable unit	results	time of measure- 7:00-10:00													attentions
		07:00:00	07:15:00	07:30:00	07:45:00	08:00:00	08:15:00	08:30:00	08:45:00	09:00:00	09:15:00	09:30:00	09:45:00	10:00:00	10:07:00
CO2 [ppm] nr1	421	438	438	434	432	432	465	462	472	464	474	468	564	462	496
CO2 [ppm] nr2	426	462	462	447	429	440	460	473	499	430	522	460	705	434	478
CO2 [ppm] nr3															
CO2 [ppm] nr4															
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.003	0.002	0.001	0.002	0.003	0.001	0.002
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.001	0.002	0.002	0.001	0.002
TEMP. internal.- [oC]	22	22	23	24	24	25	25	25	25	25	25	25	25	25	25
TEMP. external.- [oC]	17	17	17	19	19	19	21	20	22	22	23	23	24	24	24
air humidity-internal[%]	62	62	63	63	62	63	63	63	63	63	63	63	63	64	64
air humidity external[%]	77	77	77	75	74	72	73	73	66	66	65	64	62	61	61
air pressure [Hpa]	993	993	993	993	993	993	993	993	993	993	993	993	993	993	993

measurable unit	results	time of measure- 12:00-2:00pm												
		12:00:00	12:15:00	12:30:00	12:45:00	13:00:00	13:15:00	13:30:00	13:45:00	14:00:00	15:15:00	15:30:00	15:45:00	16:00:00
CO2 [ppm] nr1	412	412	480	451	452	445	482	468	465	445				
CO2 [ppm] nr2	423	423	520	520	467	454	441	440	445	465				
CO2 [ppm] nr3														
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.002	0.011	0.008	0.001	0.001	0.001	0.001	0.001				
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001				
TEMP. internal.- [oC]	22	22	24	25	25	26	26	26	26	26				
TEMP. external.- [oC]	28	28	28	28	28	28	29	29	29	26				
air humidity-internal[%]	65	65	67	67	66	66	66	66	67	67				
air humidity external[%]	52	52	51	52	50	48	47	48	48	49				
air pressure [Hpa]	992	992	992	992	992	991	992	991	991	991				

measurable unit	results	time of measure 7:00-10:00pm												
		19:00:00	19:15:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00	20:45:00	21:00:00	21:15:00	21:30:00	21:45:00	22:00:00
CO2 [ppm] nr1	430	430	410	440	427	440	447	437	422	440	442	441	420	438
CO2 [ppm] nr2	428	428	480	488	490	464	460	430	430	426	445	427	433	437
CO2 [ppm] nr3														
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.02	0.005	0.001	0.007	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.003
HCHO- FORMALDEHYD [mg/m^3]	0.001		0.003	0.002	0.002	0.002	0.006	0.001	0.001	0.001	0.001	0.001	0.002	0.002
TEMP. internal.- [oC]	22	22	24	25	25	26	26	26	26	26	25	26	26	26
TEMP. external.- [oC]	29	29	27	28	27	27	27	25	25	24	24	24	23	23
air humidity-internal[%]	77	77	71	70	69	69	70	69	69	69	70	71	72	72
air humidity external[%]	54	54	56	54	57	57	55	63	69	66	66	68	71	71
air pressure [Hpa]	989	989	989	989	989	990	989	989	989	990	990	990	990	990

[CO_2-1] HEAD

Morning period

- **Lowest value:** 432 ppm at 7:45
  Atmospheric pressure: 993 hPa
  Temperature: 25°C
  Humidity: 63%

- **Highest value:** 564 ppm at 9:45
  Atmospheric pressure: 993 hPa
  Temperature: 25°C
  Humidity: 63%

During the midday period, the highest reading occurred at 13:15 - 482 ppm, with atmospheric pressure 992 hPa, temperature 26 ° C and humidity 66%. The lowest reading: 12:00 - baseline value, pressure 992 hPa, temperature 22°C, humidity 65%.

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Night period

- **Lowest value:**
  410 ppm at 19:15
  Pressure: 989 hPa
  Temperature: 22°C
  Humidity: 77%
- **Highest value:** 447 ppm at 20:15
  Atmospheric pressure: 992 hPa
  Temperature: 26°C
  Humidity: 65%

[CO_2-2] LOWER LIMBS

Morning period

- **Lowest value:**
  429 ppm at 7:45
  Pressure: 993 hPa
  Temperature: 24°C
  Humidity: 62%
- **Highest value:**
  705 ppm at 9:45
  Pressure: 993 hPa
  Temperature: 25°C
  Humidity: 63%

Midday period

- **Lowest:**
  423 ppm at 12:00
  Pressure: 992 hPa
  Temperature: 22°C
  Humidity: 65%
- **Highest:**
  520 ppm at 12:15 and 12:30
  Pressure: 992 hPa
  Temperature: 24-25°C
  Humidity: 67%

Night period

- **Lowest:**
  428 ppm at 19:00
  Pressure: 989 hPa
  Temperature: 22°C
  Humidity: 77%

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- **Highest:**
  490 ppm at 19:45
  Pressure: 989 hPa
  Temperature: 25°C
  Humidity: 69%

<u>Classic home crib</u>

Table 2 presents results from the classic home crib, equipped with a canopy, curtains, mesh sides, a pillow, and a quilt, all items capable of influencing airflow.

Table 2. Results of the measurement in the summer period (home crib)

home crib

measurable unit	results					time of measuare- 7:00-10:00									attentions
		07:00:00	07:15:00	07:30:00	07:45:00	08:00:00	08:15:00	08:30:00	08:45:00	09:00:00	09:15:00	09:30:00	09:45:00	10:00:00	10:07:00
CO2 [ppm] nr1	416	416	427	434	425	445	445	452	462	450	425	434	536	434	600
CO2 [ppm] nr2	428	428	490	420	423	432	442	444	471	443	424	447	524	426	430
CO2 [ppm] nr3															
CO2 [ppm] nr4															
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.017
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001
TEMP. internal.- [oC]	22	23	23	23	24	24	24	24	24	24	24	24	24	24	24
TEMP. external.- [oC]	17	17	17	19	19	19	21	20	22	22	23	24	24	24	24
air humidity-internal[%]	63	63	63	63	63	63	64	64	64	64	64	64	64	64	64
air humidity external[%]	77	77	77	75	74	72	73	73	66	66	65	64	62	61	61
air pressure [Hpa]	993	993	993	993	993	993	993	993	993	993	993	993	993	993	993

measurable unit	results					time of measure 12:00-2:00pm								
		12:00:00	12:15:00	12:30:00	12:45:00	13:00:00	13:15:00	13:30:00	13:45:00	14:00:00	15:15:00	15:30:00	15:45:00	16:00:00
CO2 [ppm] nr1	411	411	419	437	442	445	443	452	465	466				
CO2 [ppm] nr2	421	421	430	442	432	438	437	428	432	428				
CO2 [ppm] nr3														
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0,001				
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0,001				
TEMP. internal.- [oC]	22	22	23	24	24	25	25	25	25	25				
TEMP. external.- [oC]	28	28	28	28	28	28	29	29	29	29				
air humidity-internal[%]	67	67	67	67	67	66	66	66	68	67				
air humidity external[%]	52	52	51	52	50	48	47	48	48	49				
air pressure [Hpa]	992	992	992	992	992	991	992	991	991	991				

measurable unit	resluts					time of measure- 7:00pm- 10:00pm								
		19:00:00	19:15:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00	20:45:00	21:00:00	21:15:00	21:30:00	21:45:00	22:00:00
CO2 [ppm] nr1	415	415	455	460	451	449	430	436	426	440	440	427	433	421
CO2 [ppm] nr2	428	428	447	451	453	452	432	435	417	438	460	438	460	440
CO2 [ppm] nr3														
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.02	0.003	0.003	0.001	0.004	0.001	0.002	0.001	0.002	0.005	0.001
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.002	0.002	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.002	0.001
TEMP. internal.- [oC]	22	22	24	24	25	25	25	25	25	25	25	25	25	25
TEMP. external.- [oC]	29	29	27	28	27	27	27	25	25	24	24	24	23	23
air humidity-internal[%]	71	71	70	70	68	69	68	70	69	70	71	71	72	72
air humidity external[%]	54	54	56	54	57	57	55	63	63	66	66	68	71	71
air pressure [Hpa]	989	989	989	989	989	990	989	989	989	990	990	990	990	990

chest sensor

measurable unit	1170	1160	1248	1205	1184	964	865	1170	1065	1110	761	583
	455	451	453	430	430	436	426					
CO2 [ppm] nr1												
CO2 [ppm] nr2												
CO2 [ppm] nr3	0.049	0.070	0.001	0.006	0.006	0.040	0.033	0.068	0.080	0.138	0.053	0.017
CO2 [ppm] nr4	0.005	0.007	0.001	0.065	0.065	0.004	0.004	0.006	0.008	0.013	0.005	0.003
TVOC-volatile organic compounds [mg/m^3]	24	25	26	25	25	25	26	25	25	25	26	25
HCHO- FORMALDEHYD [mg/m^3]	27	28	27	27	27	25	25	24	24	24	23	23
TEMP. internal.- [oC]	70	69	69	69	69	69	68	70	70	71	72	72
TEMP. external.- [oC]	56	54	57	55	55	63	63	66	66	68	71	71
air humidity-internal[%]	989	989	990	989	989	989	989	990	990	990	990	990
air humidity external[%]												
air pressure [Hpa]												

520 PPM- 14-14:10
7:34- spadek poniż 1000ppm
14:11-2290pmm chest
13:10- 1519- measure results after Łukasz Styś is coming out of the room

[CO_2-1] HEAD

Morning period

- **Lowest value:**
  416 ppm at 7:00
  Pressure: 992 hPa
  Temperature: 23°C
  Humidity: 63%

- **Highest value:**
  536 ppm at 9:45
  Pressure: 993 hPa
  Temperature: 24°C
  Humidity: 64%

Midday period

- **Lowest:**
  411 ppm at 12:00
  Pressure: 992 hPa
  Temperature: 22°C
  Humidity: 67%
- **Highest:**
  442 ppm at 12:30
  Pressure: 992 hPa
  Temperature: 24°C
  Humidity: 67%

Evening period

- **Lowest:**
  415 ppm at 19:00
  Pressure: 989 hPa
  Temperature: 23°C
  Humidity: 71%
- **Highest:**
  460 ppm at 19:30
  Pressure: 989 hPa
  Temperature: 24°C
  Humidity: 70%

[CO_2-2] LOWER LIMBS

Morning period

- **Lowest:**
  420 ppm at 7:45
  Pressure: 993 hPa
  Temperature: 24°C
  Humidity: 63%
- **Highest:**
  524 ppm at 9:45
  Pressure: 993 hPa
  Temperature: 24°C
  Humidity: 64%

Midday period

- **Lowest:**
  421 ppm at 12:00
  Pressure: 992 hPa
  Temperature: 24°C
  Humidity: 67%
- **Highest:**
  442 ppm at 12:30
  Pressure: 992 hPa
  Temperature: 24°C
  Humidity: 67%

Important observations from the summer measurements

Observation 1

At 13:15, one of the investigators left the room, causing a disturbance in the air. Immediately afterward, the CO_2-1 sensor (head) began showing 1519 ppm - a sudden spike likely caused by turbulent mixing of the accumulated CO_2. The decision was made to place an additional sensor at the chest level, CO_2-3 (CHEST).

Observation 2

At 14:11, the CHEST sensor recorded a maximum of 2290 ppm at pressure 988 hPa and humidity 68%. The CO_2 concentration returned below 1000 ppm only after 7 min 34 s. This was one of the most important findings of the entire study.

Evening period - continued monitoring with added chest sensor

[CO_2-3] CHEST AREA

Evening period results

- **Lowest:**
  583 ppm at 22:00
  Temperature: 25°C
  Humidity: 72%
  Pressure: 990 hPa
- **Highest:**
  1248 ppm at 19:45
  Temperature: 26°C
  Humidity: 69%
  Pressure: 990 hPa

The chest level readings showed the highest increases, confirming formation of a CO_2 cloud centred around the thorax/airway zone due to limited air circulation, textile barriers, and environmental conditions.

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Analysis and Interpretation of CO_2 Accumulation in the Crib Volume During the Winter Period

Medical crib

Table 3 presents the results obtained in the medical room during the winter season. Measurements were taken using three sensors, positioned identically to the summer study:

- at the head area,
- at the lower limbs,
- at the chest/thoracic region.

Table 3. Measurement Results in Winter (Medical Crib).

medical_crib

measurable unit	results	time of measure 7:00-10:00												
		07:00:00	07:15:00	07:30:00	07:45:00	08:00:00	08:15:00	08:30:00	08:45:00	09:00:00	09:15:00	09:30:00	09:45:00	10:00:00
CO2 [ppm] nr1	412	412	432	456	551	430	735	663	421	436	428	420	450	436
CO2 [ppm] nr2	426	462	462	447	429	440	718	418	430	446	522	427	430	427
CO2 [ppm] nr3	426	462	462	447	429	440	460	418	430	436	430	420	430	427
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.001	0.007	0.002	0.004	0.001	0.002	0.002	0.001	0.002	0.003	0.002
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.002	0.001	0.088	0.005	0.039	0.002	0.011	0.003	0.006	0.002	0.002	0.017
TEMP. internal - [oC]	15	15	20	23	23	23	24	25	25	25	25	25	25	25
TEMP. external - [oC]	-2	-2	-1	-2	-2	-2	0	0	0	-2	-2	-2	-2	1
air humidity-internal[%]	50	50	20	42	43	45	42	63	44	39	39	43	43	43
air humidity external[%]	94	94	97	98	86	86	90	73	98	98	98	95	92	83
air pressure [Hpa]	984	984	984	984	984	983	984	993	983	983	983	983	983	983

measurable unit	WYNIK	time of measure 12:00-2:00pm												
		12:00:00	12:15:00	12:30:00	12:45:00	13:00:00	13:15:00	13:30:00	13:45:00	14:00:00	15:15:00	15:30:00	15:45:00	16:00:00
CO2 [ppm] nr1	410	410	417	421	426	422	425	480	438	530				
CO2 [ppm] nr2	410	415	418	433	446	430	418	477	435	457				
CO2 [ppm] nr3	410	410	417	421	426	422	425	480	438	458				
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0,001	0,001	0,001	0,001	0,002	0,002	0.001	0,002	0,002	0,003				
HCHO- FORMALDEHYD [mg/m^3]	0:001	0,001	0,001	0,001	0.002	0,002	0.001	0,002	0,003	0,003				
TEMP. internal - [oC]	22	23	24	25	25	24	24	24	24	25				
TEMP. external - [oC]	28	4	3	4	4	4	4	3	3	3				
air humidity-internal[%]	65	43	42	45	45	46	46	43	46	46				
air humidity external[%]	52	83	86	86	86	83	100	100	96	96				
air pressure [Hpa]	992	982	982	982	982	982	981	982	982	982				

chest sensor	results	time of measure 7:00-22:00												
		19:00:00	19:15:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00	20:45:00	21:00:00	21:15:00	21:30:00	21:45:00	22:00:00
CO2 [ppm] nr1	420	423	420	438	554	461	415	424	425	423	443	415	480	472
CO2 [ppm] nr2	421	418	422	413	467	453	415	427	418	410	473	428	420	438
CO2 [ppm] nr3	420	423	420	438	554	461	415	424	425	423	443	415	480	472
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0,001	0,001	0,002	0,002	0,001	0,002	0.001	0,001	0.001	0:001	0.002	0,002
HCHO- FORMALDEHYD [mg/m^3]	0:001	0,001	0,001	0,001	0.018	0.002	0,001	0,003	0.001	0,001	0.001	0.001	0.015	0.0016
TEMP. internal - [oC]	21	21	23	23	23	23	23	23	23	24	23	23	23	23
TEMP. external - [oC]	2	2	-1	-1	0	0	0	0	0	0	-1	-1	-1	-1
air humidity-internal[%]	41	41	42	41	41	42	41	40	40	40	40	40	40	40
air humidity external[%]	100	100	100	100	94	94	94	96	96	96	100	96	100	100
air pressure [Hpa]	988	988	988	988	988	989	989	989	990	990	990	990	991	991

[CO_2-1] HEAD

Morning period

- **Lowest value:**
  412 ppm at 7:00
  Temperature: 15°C
  Humidity: 50%
  Atmospheric pressure: 984 hPa

- **Highest value:**
  735 ppm at 8:15
  Temperature: 24°C
  Humidity: 42%
  Pressure: 984 hPa

Midday period

- **Lowest value:**
  410 ppm at 12:00
  Temperature: 23°C
  Humidity: 43%
  Pressure: 982 hPa
- **Highest value:**
  530 ppm at 14:00
  Temperature: 25°C
  Humidity: 46%
  Pressure: 982 hPa

Evening period

- **Lowest value:**
  415 ppm at 21:00
  Temperature: 24°C
  Humidity: 40%
  Pressure: 990 hPa
- **Highest value:**
  554 ppm at 19:45
  Temperature: 23°C
  Humidity: 41%
  Pressure: 989 hPa

[CO_2-2] LOWER LIMBS

Morning period

- **Lowest value:**
  418 ppm at 8:30
  Temperature: 25°C
  Humidity: 63%
  Pressure: 993 hPa
- **Highest value:**
  718 ppm at 8:15
  Temperature: 24°C
  Humidity: 42%
  Pressure: 984 hPa

Midday period

- **Lowest:**
  415 ppm at 12:00
  Temperature: 23°C
  Humidity: 43%
  Pressure: 982 hPa
- **Highest:**
  457 ppm at 14:00
  Temperature: 25°C
  Humidity: 46%
  Pressure: 982 hPa

Evening period

- **Lowest:**
  410 ppm at 21:00
  Temperature: 24°C
  Humidity: 40%
  Pressure: 990 hPa
- **Highest:**
  473 ppm at 21:15
  Temperature: 23°C
  Humidity: 40%
  Pressure: 990 hPa

[CO_2-3] CHEST / THORACIC REGION

Morning period

- **Lowest:**
  418 ppm at 8:30
  Temperature: 25°C
  Humidity: 63%
  Pressure: 993 hPa
- **Highest readings:**
  462 ppm were recorded at both:
  – 7:00 (15°C, humidity 50%, 984 hPa)
  – 7:15 (20°C, humidity 20%, 984 hPa)

Midday period

- **Lowest:**
  410 ppm at 12:00
  Temperature: 23°C
  Humidity: 43%
  Pressure: 982 hPa

- **Highest:**
  480 ppm at 13:30
  Temperature: 24°C
  Humidity: 43%
  Pressure: 982 hPa

Evening period

- **Lowest:**
  415 ppm at 21:30
  Temperature: 23°C
  Humidity: 40%
  Pressure: 990 hPa

- **Highest:**
  554 ppm at 20:00
  Temperature: 23°C
  Humidity: 41%
  Pressure: 988 hPa

<u>Classic home crib</u>

Table 4 summarises the results of the home crib in the winter season. Again, three sensors were used: head, lower limbs, and chest.

Table 4. Measurement Results in Winter (Home Crib).

home_crib

measurable unit	results	time of measure 7:00-10:00 am												
		07:00:00	07:15:00	07:30:00	07:45:00	08:00:00	08:15:00	08:30:00	08:45:00	09:00:00	09:15:00	09:30:00	09:45:00	10:00:00
CO2 [ppm] nr1	432	423	423	811	489	504	473	562	495	503	452	470	426	414
CO2 [ppm] nr2	436	483	483	670	436	700	560	892	465	440	421	431	412	412
CO2 [ppm] nr3	516	461	461	800	429	744	650	570	701	680	710	722	685	640
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0,005	0,005	0.001	0,003	0,002	0.001	0,003	0,009	0,004	0,004	0,003	0,002
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0,052	0,052	0.001	0,031	0,002	0,001	0,0019	0,037	0,036	0,052	0,027	0,0013
TEMP. internal.- [oC]	17	20	23	23	21	25	26	26	26	27	27	27	27	27
TEMP. external.- [oC]	-2	-1	-2	-2	-2	-2	0	0	0	-2	-2	-2	-2	1
air humidity-internal[%]	55	53	43	43	42	41	40	40	40	39	43	43	39	39
air humidity external[%]	94	97	90	90	86	86	90	90	98	98	99	95	92	83
air pressure [Hpa]	984	984	984	984	984	983	984	984	983	983	983	983	983	983

measurable unit	results	time of measure 12:00-2:00pm												
		12:00:00	12:15:00	12:30:00	12:45:00	13:00:00	13:15:00	13:30:00	13:45:00	14:00:00	15:15:00	15:30:00	15:45:00	16:00:00
CO2 [ppm] nr1	422	423	434	526	506	512	531	444	454					
CO2 [ppm] nr2	422	426	425	412	420	425	634	720	412					
CO2 [ppm] nr3	419	426	730	750	724	738	845	780	710					
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0,004	0,004	0,004	0,004	0,007	0,004	0,006					
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0,039	0,052	0,054	0,003	0,071	0,044	0,064					
TEMP. internal.- [oC]	22	24	26	26	27	27	27	27	27					
TEMP. external.- [oC]	4	4	3	4	4	4	4	3	3					
air humidity-internal[%]	39	39	40	40	39	40	40	40	40					
air humidity external[%]	83	83	86	86	86	83	100	100	96					
air pressure [Hpa]	982	982	982	982	982	982	981	982	982					

measurable unit	results	time of measure 7:00-10:00pm												
		19:00:00	19:15:00	19:30:00	19:45:00	20:00:00	20:15:00	20:30:00	20:45:00	21:00:00	21:15:00	21:30:00	21:45:00	22:00:00
CO2 [ppm] nr1	415	415	455	460	451	449	430	436	426	440	440	427	433	421
CO2 [ppm] nr2	428	428	447	451	453	452	432	435	417	438	460	438	460	440
CO2 [ppm] nr3	428	428	1170	1160	1248	1205	1184	964	865	1170	1065	1110	761	583
CO2 [ppm] nr4														
TVOC-volatile organic compounds [mg/m^3]	0.001	0.001	0.001	0.02	0.003	0.003	0.001	0.004	0.001	0.002	0.001	0.002	0.005	0.001
HCHO- FORMALDEHYD [mg/m^3]	0.001	0.001	0.002	0.002	0.002	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.002	0.001
TEMP. internal.- [oC]	23	23	24	24	25	25	26	25	25	26	25	25	25	25
TEMP. external.- [oC]	29	29	27	28	27	27	27	25	25	24	24	24	23	23
air humidity-internal[%]	71	71	70	70	68	69	68	70	69	70	71	71	72	72
air humidity external[%]	54	54	56	54	57	57	55	63	63	66	66	68	71	71
air pressure [Hpa]	989	989	989	989	989	990	989	989	989	990	990	990	990	990

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[CO_2-1] HEAD

Morning period

- **Lowest:**
  414 ppm at 10:00
  Temperature: 27°C
  Humidity: 39%
  Pressure: 983 hPa
- **Highest:**
  562 ppm at 8:30
  Temperature: 26°C
  Humidity: 40%
  Pressure: 983 hPa

Midday period

- **Lowest:**
  423 ppm at 12:00
  Temperature: 24°C
  Humidity: 39%
  Pressure: 982 hPa
- **Highest:**
  531 ppm at 13:15
  Temperature: 27°C
  Humidity: 40%
  Pressure: 981 hPa

Evening period

- **Lowest:**
  415 ppm at 19:00
  Temperature: 23°C
  Humidity: 71%
  Pressure: 989 hPa
- **Highest:**
  480 ppm at 19:30
  Temperature: 24°C
  Humidity: 70%
  Pressure: 989 hPa

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[CO_2-2] LOWER LIMBS

Morning period

- **Lowest:**
  412 ppm at 9:45 and 10:00
  Temperature: 27°C
  Humidity: 39%
  Pressure: 983 hPa
- **Highest:**
  892 ppm at 8:30
  Temperature: 26°C
  Humidity: 40%
  Pressure: 984 hPa

Midday period

- **Lowest:**
  412 ppm at 12:30 and 13:45
  Temperature: 26–27°C
  Humidity: 40%
  Pressure: 982 hPa
- **Highest:**
  720 ppm at 13:30
  Temperature: 27°C
  Humidity: 40%
  Pressure: 982 hPa

Evening period

- **Lowest:**
  417 ppm at 20:45
  Temperature: 25°C
  Humidity: 69%
  Pressure: 989 hPa
- **Highest:**
  460 ppm at 21:45
  Temperature: 25°C
  Humidity: 72%
  Pressure: 990 hPa

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[CO_2-3] CHEST / THORACIC REGION

Morning period

- **Lowest:**
  429 ppm at 7:45
  Temperature: 21°C
  Humidity: 42%
  Pressure: 984 hPa
- **Highest:**
  722 ppm at 9:30
  Temperature: 27°C
  Humidity: 43%
  Pressure: 983 hPa

Midday period

- **Lowest:**
  426 ppm at 12:00
  Temperature: 24°C
  Humidity: 39%
  Pressure: 982 hPa
- **Highest:**
  845 ppm at 13:15
  Temperature: 27°C
  Humidity: 40%
  Pressure: 982 hPa

Evening period

- **Lowest:**
  428 ppm at 19:00
  Temperature: 23°C
  Humidity: 71%
  Pressure: 989 hPa
- **Highest:**
  1248 ppm at 19:45
  Temperature: 25°C
  Humidity: 69%
  Pressure: 989 hPa

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DISCUSSION

SIDS is a situation in which a healthy, normally developing infant dies unexpectedly before one year of age. In children, the most common cause of cardiac arrest is the preceding respiratory arrest [2,8,9,16]. Child's death occurs during sleep, and the diagnosis is made only after excluding all other potential causes that could explain the fatal event [2,8,9,16]. SIDS remains an unresolved mystery for many researchers and scientists.

According to published sources, researchers at Boston Children's Hospital and Harvard Medical School collected tissue samples from infants who died from SIDS between 2004 and 2011 - focusing primarily on the brainstem. They found that in all 70 samples examined, there were changes in serotonin 5-HT2A/C receptor levels. Studies in rodents indicate that proper serotonin receptor function is responsible for maintaining an adequate oxygen concentration in the brain during sleep [8,9].

In the 2023 doctoral dissertation by Magorzata Habich, "*The Vicious Cycle Theory. Study of the compensatory mechanisms of phosphate metabolism in Sudden Infant Death Syndrome"*, the author concludes - through a series of clinical analyses — that phosphate homeostasis is disrupted, in particular resulting in hypophosphatemia [4-7]. If studies from Boston Children's Hospital and Harvard Medical School demonstrated abnormalities of the serotonin receptor in all SIDS cases examined post mortem, and the receptor in question is responsible for maintaining normal systemic oxygen levels, and if incidental hypophosphatemia correlates with hyperventilation and the development of tetany-like syndromes - and despite all performed post-mortem investigations no direct internal cause of death can be identified, - then the triggering factor must originate externally [8,9]. Furthermore, the mechanism must occur over time, since biochemical markers (serotonin, phosphate irregularities) are present; therefore, the triggering cause must be measurable and detectable, at least in theory [4-7].

Proposed External Mechanism

CO_2, being 1.5 times heavier than air, tends to accumulate under appropriate conditions, especially when:

- textile barriers (curtains, canopies),
- ventilation is poor,
- atmospheric pressure is below 989 hPa,
- humidity is elevated.

Under such conditions, CO_2 accumulates around the chest, neck, and facial region, increasing with each exhalation of the infant. A young physiologically immature organism attempts to compensate for the decrease in oxygen availability with each breath, triggering an increased respiratory drive mediated by the serotonin 5-HT2A / C receptor, consistent with Harvard and Boston [9]. Hyperventilation and accompanying biochemical markers (including those described in Habich's dissertation) emerge as secondary responses to a progressively forming CO_2 cloud within the breathing zone [4-7].

This pattern would result in the following:

- CO_2 accumulation,
- reduction of available O_2,
- a change in the oxyhemoglobin dissociation curve (Bohr effect paradox^1),
- ventilatory failure,without leaving clear anatomical lesions detectable in postmortem examination.

Thus, this mechanism constitutes an external, noninjurous, and nontraumatic cause, compatible with the clinical mystery observed in SIDS cases.

Summary

In the home crib, CO_2 accumulation in the head/neck region of the mannequin during the summer period reached its highest value between 14:00 and 14:11 - 2290 ppm. A repeated increase in CO_2 concentration was observed during the evening session, where the highest values were exclusively correlated with atmospheric pressure at or below 990 hPa. At pressures at or above 990 hPa, the CO2 concentration dropped sharply, indicating the destabilisation of the CO_2 cloud.

According to the data, several factors influenced the concentration of CO2.

- indoor humidity - higher humidity corresponded to higher CO_2 levels,
- indoor temperature - higher temperatures also correlated with increased CO_2 accumulation.

In the medical crib, no significant increases in CO_2 concentration were recorded in the head/neck area. A phenomenon of CO_2 adhesion was observed to the walls was observed — the wall temperature (14–16°C) prevented the formation of a dangerous CO_2 cloud. During the winter period, with the methodological improvement of adding a permanent chest-level CO_2 sensor, the highest concentrations were again recorded around the chest region during the evening hours.

Additionally:

- The rise in humidity corresponded to the increase in CO2 concentration in the chest region.
- Temperature did not correlate strongly with CO_2 levels; it remained stable around ~25°C.

As in the summer analysis, no dangerous CO_2 elevations occurred in the medical crib. Again, the adhesion of CO_2 to the cooler crib walls (15–18°C) prevented the formation of clouds. The authors draw attention to the Bohr effect paradox - a situation in which during hyperventilation the curve does not shift to the left, but cascades to the right, due to the continuous increase in CO2 concentration through increasingly faster ventilation – auto compensation in the bed volume, in the area indicated in the study.

CONCLUSIONS

The concentration within the crib volume does not increase uniformly, contrary to the initial hypothesis that the gas would simply fill the crib volume evenly. Under specific environmental conditions (low atmospheric pressure, limited ventilation, higher humidity), CO_2 accumulates as a localised cloud, not as a diffuse, evenly distributed gas. This CO_2 cloud forms in the infant's breathing zone, particularly around the neck and chest, creating a relatively stable barrier when ventilation is insufficient. With each exhalation, the cloud grows in density, further reducing available oxygen. This mechanism explains how an external, nontraumatic, nonmechanical, and nonobstructive factor may lead to respiratory failure without leaving postmortem evidence of airway obstruction or trauma - a pattern fully consistent with the clinical and forensic profile of SIDS.

SUPPLEMENTARY INFORMATION

Funding: *No fund was received related to this study.*
Institutional Review Statement: *The study was conducted according to the guidelines of the Declaration of Helsinki.*
Informed Consent Statement: *Informed consent was obtained from all subjects involved in the study.*
Data Availability Statement: *The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.*
Conflicts of Interest: *The authors declare no conflicts of interest.*

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