Comparing indoor air quality in naturally ventilated and air-conditioned hospitals in the tropics

Ben M. Roberts*[1], Raymond Kasei[2], Samuel N.A. Codjoe[3], Ebenezer F. Amankwaa[4], Katherine V. Gough[5], Karim Abdullah[6], Peter Mensah[4], and Kevin J. Lomas[1]

1 Building Energy Research Group,
School of Architecture, Building and Civil Engineering
Loughborough University
Loughborough, Leicestershire, UK
**Corresponding author: b.m.roberts@lboro.ac.uk*
Presenting author

2 Department of Environment, Water and Waste Engineering
University for Development Studies
Tamale, Ghana

3 Regional Institute for Population Studies
University of Ghana
Legon, Accra, Ghana

4 Department of Geography and Resource Development
University of Ghana
Legon, Accra, Ghana

5 Department of Geography and Environment
Loughborough University
Loughborough, Leicestershire, UK

6 Department of Food Security and Climate Change
University for Development Studies
Tamale, Ghana

ABSTRACT

Occupant exposure to airborne pathogens in buildings can be reduced by a variety of means, including adequate provision of outdoor air by ventilation. This is particularly important in buildings, such as hospitals, which may house a higher number of infected individuals relative to the wider population. In tropical Africa, however, there is evidence that new hospitals built with air-conditioning to cope with the extreme heat are poorly ventilated compared to existing hospitals that were designed to be naturally ventilated. As a proxy for indoor air quality, the carbon dioxide concentrations in two hospitals in Ghana were monitored over a period of one week. All wards were naturally ventilated, but some also had mechanical ventilation or recirculating air-conditioning. Air-conditioned wards generally had the poorest indoor air quality, with measured maximum CO_2 concentrations of 3286 ppm indicating insufficient ventilation relative to occupancy levels. Staff reported keeping windows closed in these wards to prevent mosquitoes from entering and to provide thermal comfort for the patients. Recommendations are that staff working in air-conditioned rooms should regularly open windows to allow outdoor air to enter. Mosquito netting should be installed on all windows to encourage staff to open the windows. Future hospital design should better consider the interplay between thermal comfort, ventilation, and indoor air quality.

KEYWORDS

Hospitals; Tropics, Indoor air quality; Ventilation; Thermal comfort; CO_2 measurement.

1 INTRODUCTION

Hospital acquired (nosocomial) infections are widespread across tropical Africa (Rothe et al., 2013). Scarce data, however, means that these infections are likely to be underestimated (Allegranzi et al., 2011), since many microorganisms remain viable in the aerosolised state, even though they are non-culturable (Beggs, 2003). Airborne transmission is the main route for infection by pathogens, such as, tuberculosis, measles, chicken pox, SARS (J. W. Tang et al., 2006), and SARS-CoV-2 (S. Tang et al., 2020). Several routes for airborne transmission exist, including short-range airborne (droplet) and long-range airborne (aerosols) (Ribaric et al., 2022). Aerosol transmission of pathogens occurs in tropical hospitals even where healthcare workers do not have close contact with infected patients (Lee et al., 2003; Wong et al., 2004). SARS-CoV-2, for example, has been found in the air in Indian and Singaporean hospitals between 3 and 5 m away from infected patients (Ang et al., 2022; Dubey et al., 2021).

Respiratory viruses (and other pathogens) are known to be highly transmissible within healthcare settings in tropical Africa (Rothe et al., 2013) and other tropical regions. Airborne transmitted infections are common (Wang et al., 2021), with lower respiratory tract infections being responsible for between 8% and 14.5% of all nosocomial infections in tropical Africa (Rothe et al., 2013). Nosocomial airborne transmitted infections include tuberculosis as found in Cote d'Ivoire (Kassim et al., 2000), Zimbabwe (Corbett et al., 2007), South Africa (Matuka et al., 2021; Naidoo & Jinabhai, 2006; O'Donnell et al., 2010; Tudor et al., 2014), Uganda (Kayanja et al., 2005) and Malawi (Harries et al., 2002), as well as in Vietnam (Lien et al., 2009). Additionally, nosocomial rubella and measles were reported in Uganda (Lewis et al., 2006), SARS-CoV-2[1] in India (Dubey et al., 2021) and Singapore (Ang et al., 2022), and respiratory syncytial virus (RSV), e.g. in South Africa (Madhi et al., 2004; Visser et al., 2008). RSV is a leading cause of lower respiratory tract infection in children worldwide (Rose et al., 2021). Hospital-acquired pneumonia was among the most common nosocomial infection in a review of papers from ten developing countries in Africa (Nejad et al., 2011). In Ghana, 16.3% of nosocomial infections in a study representing 32.9% of all acute care beds in government hospitals, were respiratory (Labi et al., 2019).

Adequate ventilation provision is needed to dilute and remove airborne viruses and other pathogens contained in aerosols (Dai & Zhao, 2020; di Gilio et al., 2021; Morawska & Cao, 2020). This is especially important in healthcare buildings, where both a high number of infected individuals are likely to congregate, and where the building occupants are likely to be vulnerable, e.g., neonates, pregnant women, and the immunocompromised. Ventilation design in hospitals should consider three key factors: ventilation rate (dilution), ventilation direction (from clean zones to dirty zones and not moving air from one patient to another), and air flow distribution (mixing) to ensure all the air in a space is replaced (Eames et al., 2009; J. W. Tang et al., 2006).

There are limited data on indoor air quality in hospitals in tropical Africa. However, a study of operating theatres in Ghana with positively-pressurised non-laminar ventilation with high-efficiency particulate air (HEPA) filters found that air samples taken during surgical procedures contained substantial microbial contamination due to excessive door opening and the high numbers of people present (Stauning et al., 2018). Also in Ghana, high airborne bacterial and fungal loads were found in the outpatients' department and theatre ward, with high loads of bioaerosols found in most wards, due to overcrowding (Larrey et al., 2020). Similar results have been obtained in hospitals in Ethiopia (Fekadu & Getachewu, 2015) and Nigeria (Ekhaise & Blessing, 2012; Okolo et al., 2020).

Dust transported on winds from the Sahara Desert presents a health risk due to the particulates (PM_{10}) entering the airways and causing nontransmissible respiratory diseases, such as asthma and bronchitis (de Longueville et al., 2013; Marone et al., 2020). Inhaled dust particulates

[1] It is believed that 11-15% of SARS-CoV-2 infection is acquired in hospitals (Ribaric et al., 2022).

expose the throat to infection from other airborne disease, such as bacterial meningitis (Codjoe & Nabie, 2014). The Saharan dust itself may also harbour bacteria and fungi that can have negative health impacts if inhaled (Marone et al., 2020). Some authors, therefore, have recommended that mechanical ventilation is used in tropical African hospitals to prevent outdoor dust from entering (Larrey et al., 2020). Alongside dust, mosquito entry is also a concern for such hospitals (Mohammed et al., 2013).

Concerns around supplying adequate ventilation whilst considering dust (the inherent particulates and the associated pathogens) and mosquito entry might make mechanical ventilation systems an attractive option. Indeed, because hospitals in tropical regions are increasingly exposed to extreme heat (Codjoe et al., 2020), which is being exacerbated by climate change (Wilby et al., 2021), incorporating cooling into mechanical ventilation systems may also be desirable. Mechanical ventilation systems, however, may transport pathogens including viruses like SARS-CoV-2 (Correia et al., 2020). For example, in Hong Kong, 50 healthcare workers were infected with the SARS virus (Lee et al., 2003); this nosocomial transmission was partly attributed to the hospital ventilation system, which mixed incoming outdoor air with potentially infected indoor air (70% recirculation) (Wong et al., 2004). Mechanical ventilation systems, which were old and poorly maintained, were also identified as a bacterial transport mechanism at a hospital in Jordan (Qudiesat et al., 2009). Futhermore, SARS-CoV-2 RNA was detected in 25% of samples taken from 10 air-handling units in hospitals in the USA, although the samples were not evaluated for viral infectivity (Horve et al., 2021). Dust on air-conditioning filters was a significant source of airborne bacteria and fungi in Egyptian hospitals (Osman et al., 2017).

Ventilation and cooling systems, however, may be beneficial, as demonstrated in Iranian hospitals where ductless (recirculating) air-conditioners had filters that reduced bioaerosols (Eslami et al., 2016). Ductless (recirculating) air-conditioning systems are used to ensure thermal comfort and reduce patient heat stress. Their use is likely to increase worldwide due to climate change (Davis & Gertler, 2015). If windows are closed and recirculating air-conditioning systems are relied on for cooling, indoor air quality may deteriorate, potentially increasing the transmission of airborne infectious diseases (Lu et al., 2020; Zhou et al., 2015).

The foregoing review points to a tension between natural ventilation, mechanical ventilation, and ductless air-conditioning. The low cost and high ventilation rates that are possible with natural ventilation may dilute airborne pathogens, whilst allowing dust and mosquitoes to enter. The higher cost ductless air-conditioning may ensure thermal comfort at the expense of indoor air quality. Mechanical ventilation systems may ensure satisfactory indoor air quality, thermal comfort, and prevent dust and mosquito ingress but are the highest cost, difficult to retrofit, and if not properly maintained may be a pathogen transmission pathway.

Therefore, the aim of this paper is to examine whether the ventilation of two hospitals located in tropical climates is adequate to ensure good indoor air quality and reduce the transmission of airborne pathogens, and to identify how the indoor air quality can be improved. To achieve this aim, the air quality in 14 wards and waiting rooms in two hospitals in Ghana were measured; four of the wards had re-circulating air-conditioning and two had air-conditioning supplied by a central ventilation system. Carbon dioxide (CO_2) concentration was measured as a proxy for exposure to exhaled breath, which potentially contains virus-laden aerosols.

2 METHODS

2.1 Location and context

Ghana was selected as the location for this research because it is located in a region of sub-Saharan Africa that experiences a high number of extreme heat days, which are predicted to rise in future (Garland et al., 2015; Wilby et al., 2021). To cope with the temperature increase, greater air-conditioning uptake is likely in hospitals (Codjoe et al., 2020), which may reduce indoor air quality if recirculating systems are installed.

Two hospitals are the focus of this study, located in the cities of Accra and Tamale. Accra, in the south of Ghana, near the coast, is the capital and largest city (population 2.4 million); whilst Tamale is a rapidly growing intermediate-size city in northern Ghana (Gough et al., 2019), with a population of 701,171 in 2022. The climate of Accra is coastal savannah with local mean daily maximum temperatures ranging from 33°C in March (peak of the dry season) to 28°C in July-September (the rainy season); in Tamale mean daily maximum temperatures are 38°C in March and 30°C in July-September (Gough et al., 2019).

2.2 Case study hospitals

Data were collected from Accra Hospital (AH) and Tamale Hospital (TH)[2]. Both hospitals treat inpatients and outpatients. Accra Hospital is a 74-bed bed hospital that was built in 1928, with later additions, and serves the most critically ill neonates and children of Accra, Ghana (Figure 1a). Tamale Hospital is an 800-bed hospital that was built in 1974, with later additions, and serves patients of all ages from across the Northern Region of Ghana (Figure 1b). It is used to treat adults, children, and neonates.

The monitoring took place during the rainy season in Ghana. Outside AH, the mean outdoor dry bulb temperature was 28.8°C (min = 24.3°C; max = 34.6°C). Outside TH, the mean outdoor dry bulb temperature was 28.5°C (min = 25.8°C; max = 31.8°C).

(a) Accra Hospital (AH) (b) Tamale Hospital (TH)

Figure 1: Exterior photographs of the case study hospitals.

[2] The hospital names have been changed to maintain anonymity.

2.3 Spaces monitored

Wards of interest were identified in collaboration with the hospital staff who were asked to highlight wards that were prone to high temperatures, low temperatures, or olfactory sensations of stuffiness. This ensured a variety of indoor environments were captured to allow for comparison. Additionally, hospital staff were asked to recommend wards which would be frequently or continuously occupied, where particularly vulnerable patients would be, or where crowding would occur (e.g., in waiting rooms).

Table 1: AH – wards monitored, patient type, dimensions, natural ventilation type, presence of mechanical ventilation, and presence of air-conditioning (A/C), height of sensor from floor.

Space monitored	Patient type	Floor area (m^2)	Volume (m^3)	Natural vent.	Mech. vent.	A/C	Ceiling fans	Sensor height (m)
Physiotherapy (Physio)	Child (outpatients)	29	79	Adjustable louvres	No	No	2	1.6
Outpatients' department waiting room (OPD)	Child (outpatients)	-	-	Semi-outdoor	No	No	3	2.2
Paediatrics 1	Child (inpatient)	47	138	Adjustable louvres	No	No	4	1.9
Paediatrics 2	Child (inpatient)	47	138	Adjustable louvres	No	No	4	1.6
Malnutrition	Malnourished child	65	215	Adjustable louvres	No	No	4	1.6
Neonatal Intensive Care Unit (NICU)	Neonatal (premature unstable)	23	75	Sliding panes	No	Ductless	2	1.6
Emergency	Child	45	125	Sliding panes	No	Ductless	2	1.6

Table 2: TH – wards monitored, patient type, dimensions, natural ventilation type, presence of mechanical ventilation, and presence of air-conditioning (A/C), height of sensor from floor.

Space monitored	Patient type	Floor area (m^2)	Volume (m^3)	Natural vent.	Mech. vent.	A/C	Ceiling fans	Sensor height (m)
Neonatal Intensive Care Unit (NICU)	Neonatal (premature unstable)	33	89	Sliding panes	Yes	Ducted	0	2.2
Kangaroo	Neonatal (premature stable)	39	104	Adjustable louvres	Yes	Ducted	0	1.6
Pre-natal	Pregnant women	63	206	Adjustable and fixed open louvres	Yes	No	4	1.6
Post-natal	New mothers and neonatal (full-term stable)	46	153	Adjustable and fixed open louvres	Yes	No	4	1.6
Maternity waiting room	Pregnant women and neonatal	133	379	Fire exit door	Yes	Portable	4	2.2
Emergency	All	105	283	Sliding panes and bottom-hung casement	No	No	6	1.6
Paediatrics U6m	Children under 6 months	34	113	Adjustable and fixed open louvres	No	Ductless	2	1.6

2.4 Ventilation and cooling of wards

All wards had the ability to be naturally ventilated, i.e., there were openings present. A variety of ventilation openings were observed in the wards: sliding panes, adjustable louvres, fixed louvres, bottom-hung casements, and doors (Table 1, Table 2, Figure 2, and Figure 3). Mechanical ventilation was supplied to some wards in TH (Table 2) but staff reported that this did not provide climate control, except in the NICU and Kangaroo wards (ducted air-conditioning). Staff had no control over the operation of the ducted mechanical ventilation. There was one portable (recirculating) floor-mounted air-conditioning unit in the TH Maternity waiting room and one ductless (recirculating) wall-mounted air-conditioning unit in the TH Paediatrics U6m ward. In AH there were two ductless units in the Emergency ward and two in the NICU (all wall-mounted). In all cases, staff were responsible for the control and operation (i.e., setting the temperature and duration of use) of the ductless air-conditioning, often in response to requests from patients or their carers.

Ceiling fans were installed in most, but not all, wards (Table 1 and Table 2) and were generally observed switched on when researchers visited to download the data, except in the TH Post-natal ward, the TH Pre-natal ward, and the AH NICU. In the TH Emergency ward, three ceiling fans were switched on above the staff areas but three fans above the patients were switched off. In the AH Malnutrition ward, three of the four fans were switched on, two of these close to where the staff congregated.

Mosquito nets were observed installed in most ventilation openings in AH, but generally not in TH. Many windows at TH had external shading systems as is visible in Figure 1, which may influence the ventilation rate. Within wards and around beds there were no privacy curtains (medical screens), except in the TH Emergency ward (and these were observed open and tied up). Therefore, it can be assumed that air should move unimpeded around the ward.

(a) Ventilation openings in the TH Emergency ward. Sliding windows and bottom-hung casement windows.

(b) Ventilation openings in the TH Post-natal ward. Adjustable glass louvre blades in lower portion with open fixed metal louvres in upper portion.

Figure 2: Ventilation openings in TH.

Figure 3: Ventilation openings and air-conditioning unit in the TH Paediatrics U6m ward. Sliding windows in lower portion and fixed glazed units in upper. External shading to windows is visible.

2.5 Installing sensors

Poorly ventilated indoor environments are likely to enable greater transmission of airborne viruses such as SARS-CoV-2 (Jones et al., 2021) and other airborne pathogens. The measurement of CO_2 concentration is useful because it is a proxy for exhaled breath, which may contain suspended aerosols containing pathogenic particles (Peng & Jimenez, 2021). High concentrations of CO_2 in a space indicate low levels of ventilation, high occupancy relative to the space volume, or a combination of both (Malki-Epshtein et al., 2022).

Combined temperature, relative humidity, and carbon dioxide sensors were placed in seven wards in each hospital (Table 1 and Table 2) and one was installed outside of each hospital to measure the local ambient conditions (Table 3). The sensors were battery-powered and logged data to the internal memory on each device. Calibration of the sensors was performed by the manufacturer in the month prior to the installation. The outdoor sensors were placed in locations that were protected from direct solar radiation, rain, away from external air-conditioning units, and where security staff could monitor them.

Table 3: Sensors installed

Sensor	Variable	Logging interval (mins)	Units	Range	Resolution	Accuracy
Eltek MS47B	Temperature	15	°C	-30 to +65	0.1	±0.4 (+5 to +40) ±1.0 (-20 to +65) ±1.5 (-30 to -20)
	Relative humidity	15	%	0 to 100	0.1	±2 (10 to 90) ±4 (0 to 100)
	Carbon dioxide (CO_2)	15	ppm	0 to 5000	3	±50

One sensor was placed in each ward of interest, where possible in a central location. All of the sensors were wall mounted and affixed to the wall using adhesive wall hanging strips, except in the TH Maternity waiting room, the AH OPD waiting room, and the outdoor sensors, which were nailed or screwed to walls using metal brackets for security reasons. The sensors in each ward were generally placed at a height of 1.6 m from the floor, however, in some instances they were placed higher (1.9 – 2.2 m, see Table 1 and Table 2) due to concerns regarding potential tampering by patients and visitors. In the TH Neonatal Intensive Care Unit, there was a shiny painted wall coating to allow for effective cleaning, hence the sensor was placed above this at a height of 2.2 m to avoid risk of dislodging the adhesive fixing. Sensors were placed away from direct sunlight, doors, windows, sources of heat (e.g., medical equipment), and outlets of mechanical ventilation and air-conditioning units.

In AH, data were analysed from 13/06/2022 at 12:15 to 17/06/2022 at 09:15 (3 days and 21 hours). In TH, data were analysed from 10/06/2022 at 12:00 to 12/06/2022 at 10:15 (1 day, 22 hours, and 15 minutes). Further monitoring is ongoing and will continue for at least one year.

2.6 Air quality classification

Concerning transmission of airborne viruses, The Scientific Advisory Group for Emergencies for the UK Government (SAGE-EMG) recommended that spaces frequently reaching CO_2 levels above 1500 ppm should be improved (SAGE-EMG and SPI-B, 2021). Similarly, BS EN 16798[3] (BSI, 2017) states that occupants with a need for high indoor environmental quality, such as hospital patients, should occupy spaces with indoor CO_2 levels of 950 ppm[4] or less. Importantly, cognitive function may be impaired at higher CO_2 concentrations, for example, there is a 15% lower cognitive function at ~945 ppm and 50% lower at ~1400 ppm against a baseline of 550 ppm (Allen et al., 2016). Air quality in this paper will be classified according to the BS EN 16798 Category I target.

[3] BS EN = British Standards European Norm.
[4] Strictly, this is 550 ppm in addition the outdoor concentration, assumed for simplicity to be 400 ppm.

2.7 Informal discussions with staff

It was important to understand ventilation behaviours and how the staff used the ductless air-conditioning systems that they had control over. These data are vital for interpreting the CO_2 measurements in the context of the use of the ventilation and cooling systems. When the researchers visited to install sensors and returned 2-4 days later to download the data, conversations were held with staff working in each ward. These comprised explanations of how the sensors worked, seeking advice on convenient and unobtrusive placement of the sensors, and briefly explaining the data gathered. During these conversations, staff were asked about their experiences of the indoor environment and how they operated the windows, doors, and ductless air-conditioning systems.

3 RESULTS

3.1 CO_2 monitoring

In both hospitals, a range of CO_2 concentrations were observed between spaces. The maximum CO_2 concentrations ranged from values expected of near ambient conditions (400-500 ppm) to the highest concentration of 3286 ppm in the AH Emergency ward (Figure 4 and Figure 5). Consequently, three wards[5] had mean CO_2 concentrations that exceed the BS EN 16798 (BSI, 2017) concentration guideline of 950 ppm, indicating consistently poor indoor air quality (Figure 6 and Figure 7).

Wards with ductless air-conditioning installed (see Table 1 and Table 2) generally had higher mean and maximum CO_2 concentrations, indicating poor ventilation relative to the occupancy levels. Naturally ventilated and mechanically ventilated wards without ductless air-conditioning generally had lower CO_2 concentrations indicating better indoor air quality (Figure 4, Figure 5, Figure 6, and Figure 7).

Occupancy is a clear driver of CO_2 concentration. The large difference between mean and maximum CO_2 concentration in the TH Maternity waiting room occurred because it was densely occupied (estimated 100 adults and 75 neonates in a 379 m^3 space) on weekdays only. The data were captured on Friday, Saturday, and part of Sunday (Figure 7). Lack of natural ventilation increased the CO_2 concentration, as although outdoor air could be brought in via a glazed push-bar fire exit at one end of the room, this was closed and blocked with chairs during the researchers' visit, and air delivered by the mechanical ventilation was insufficient.

3.2 Understanding ventilation practices

In the TH Paediatrics U6m ward, staff reported closing the windows when the air-conditioning was switched on to allow for effective cooling. Similarly, windows were reported to be often closed during the rainy season in Ghana, as parents claim that their children are feeling cold. When the windows were opened at 06:00 in the morning, the CO_2 concentration reduced from ~2000 ppm to ~500 ppm, indicating that there was an adequate supply of fresh outdoor air for satisfactory indoor air quality, when windows were open (see Paediatrics U6m ward in Figure 7).

The TH Kangaroo ward is where premature babies are placed on their mothers' chest with direct skin-to-skin contact to keep the babies warm because there are not enough incubators in

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[5] The AH NICU, the AH Emergency ward, and the TH Paediatrics U6m ward.

the hospital. Here windows are also frequently closed, even when the mothers' thermal comfort is compromised, to keep the babies warm. Yet, because air was supplied to the ward via a central mechanical ventilation system, and the occupants limited in number, satisfactory air quality was maintained even without supplementary window opening.

In the AH NICU, the staff close all the windows and doors to keep mosquitoes from entering and to ensure the room remains sterile. The air-conditioning is often switched on because the incubators emit heat which makes it uncomfortably hot for staff. At night, two staff are present in the room with the doors and windows closed. During the day, frequent entry and exit through the ward doors increases the ventilation rate, even though windows are likely to remain closed, and this day/night cycle is observable in the CO_2 profiles (Figure 6).

In the AH Emergency ward, which had high and varying CO_2 concentrations, three large peaks in CO_2 concentration coincide with 09:00, 13:00, and 00:00 over the almost 4-day monitoring period (Figure 6). Staff did not offer any reasons for the time-varying peaks, hence this warrants further investigation. It was observed that windows were always shut in this ward, which has ductless air-conditioning.

Staff reported that there are privacy concerns in the TH Pre-natal ward. The families of pregnant women try to look through the louvred windows if they are open, so they are generally shut as the frosted glass helps maintain privacy. Here, mechanical ventilation supplies outdoor air and CO_2 concentrations remained low (Figure 5 and Figure 7).

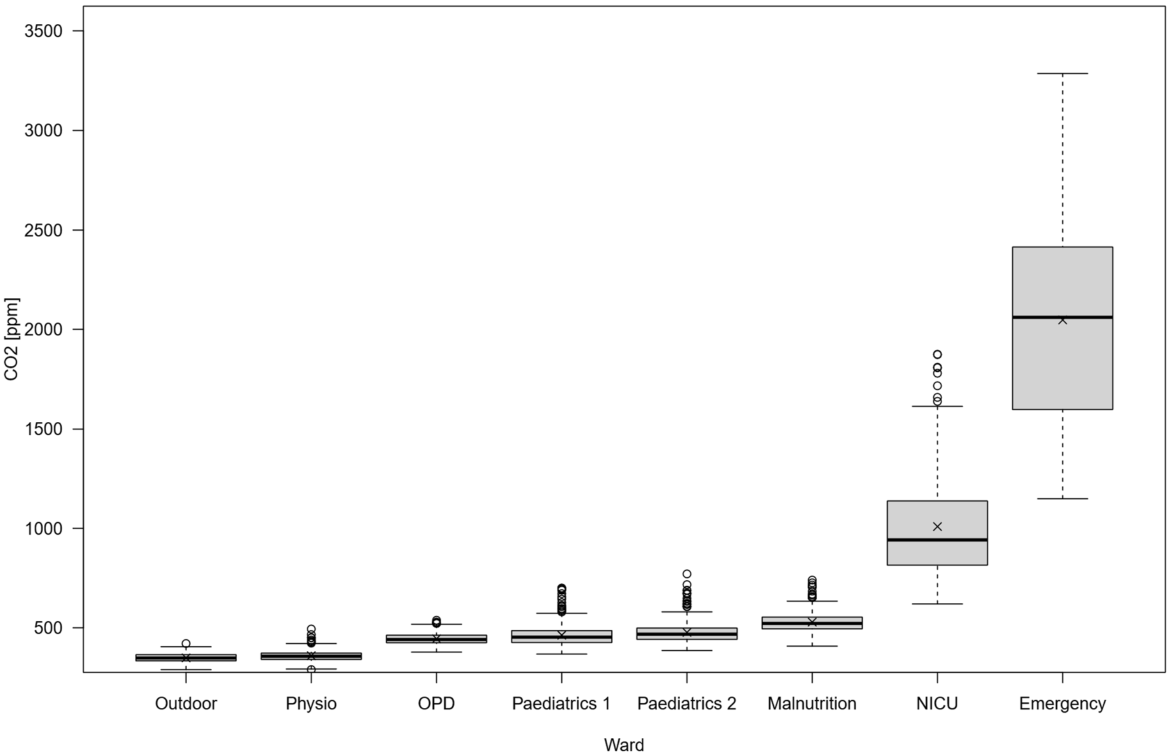

Figure 4: Boxplot of CO_2 concentration in AH. Arranged by the smallest to greatest mean concentration. Y-axis minimum is 400 ppm.

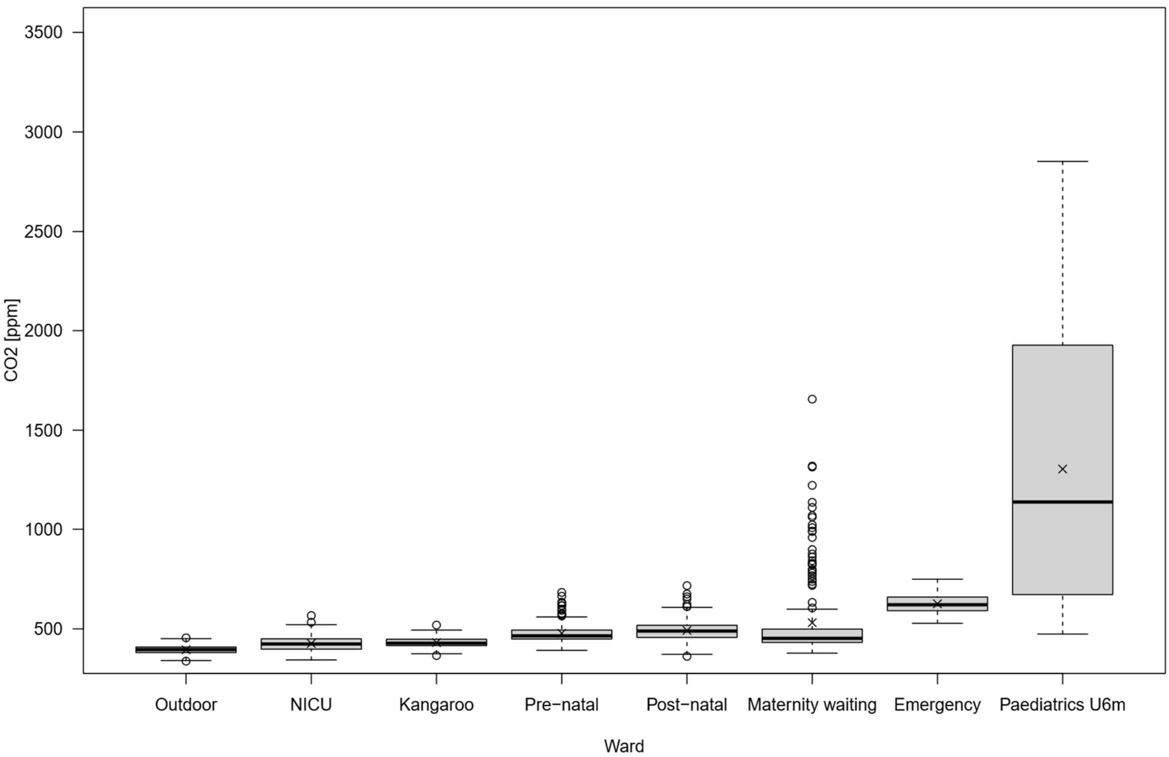

Figure 5: Boxplot of CO_2 concentration in TH. Arranged by the smallest to greatest mean concentration. Y-axis minimum is 400 ppm.

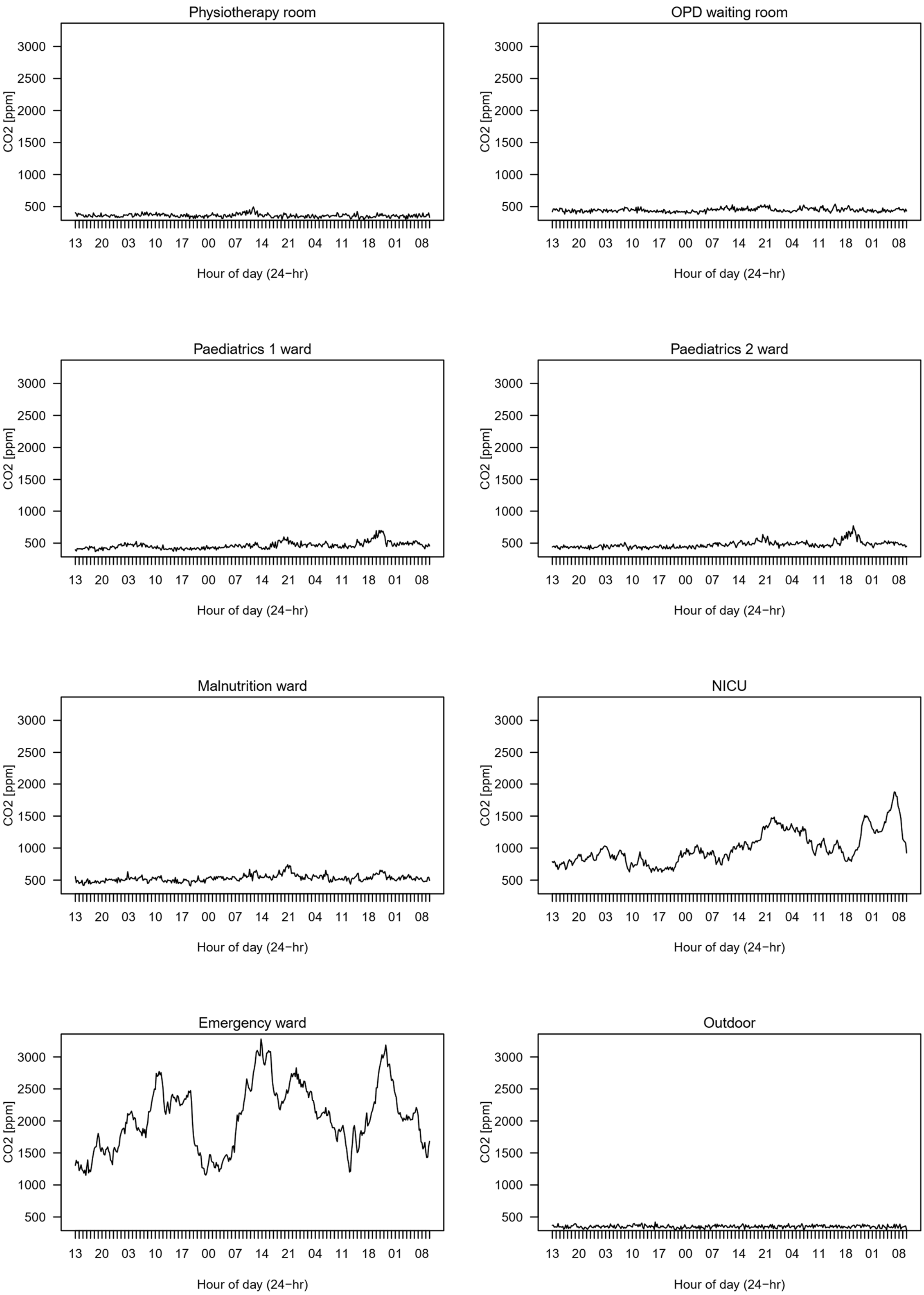

Figure 6: CO_2 profiles in the wards and outside at AH. Y-axis minimum is 400 ppm.

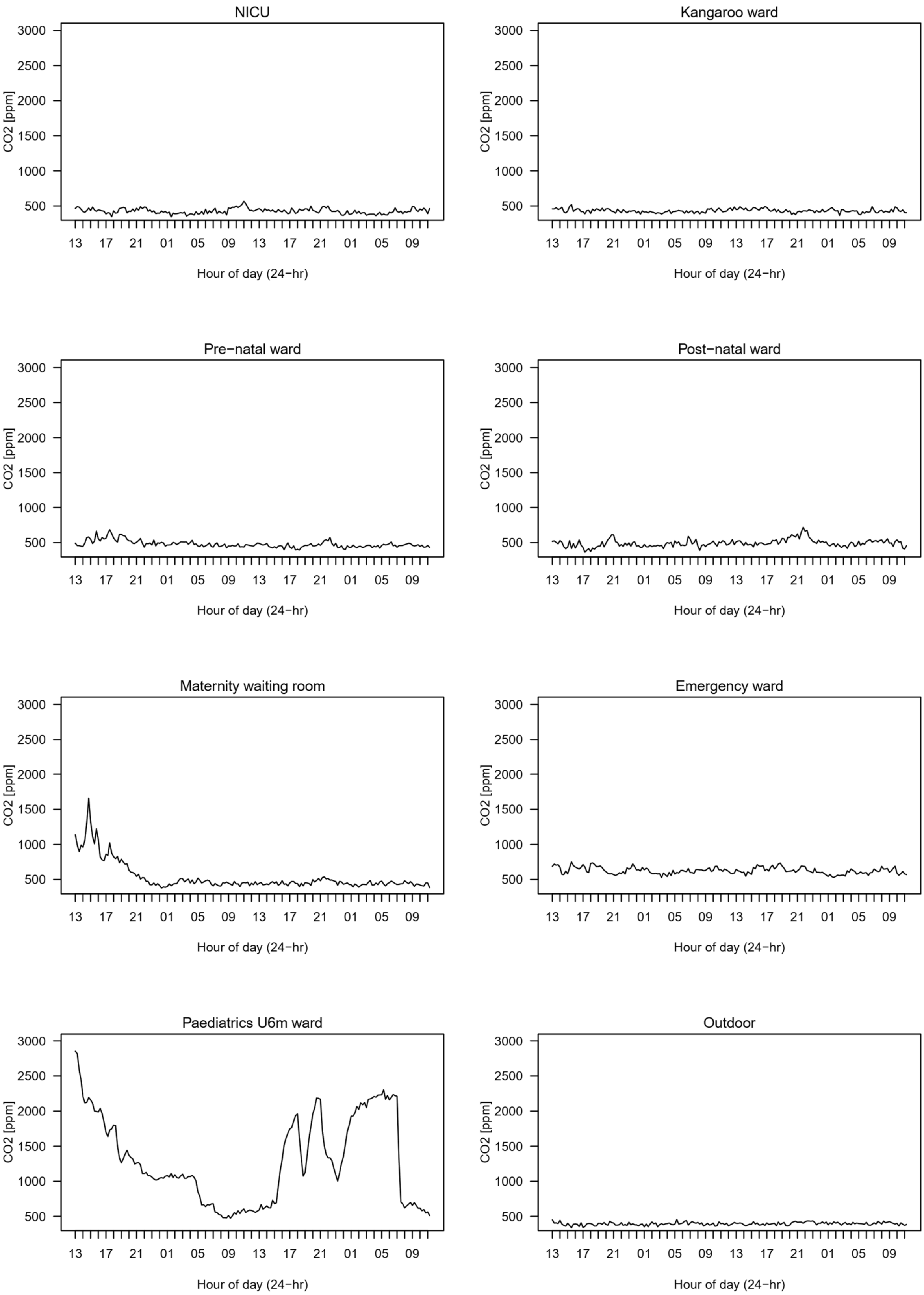

Figure 7: CO_2 profiles in the wards and outside at TH. Y-axis minimum is 400 ppm.

4 DISCUSSION

The monitoring of CO_2 concentration, as a proxy for indoor air quality, in 14 wards in two hospitals in Ghana revealed that mechanically ventilated wards generally have the best indoor air quality, as do most naturally ventilated wards when the windows are open. Wards with ductless air-conditioning, where overcrowding occurs, or where there is inoperable natural ventilation, have the poorest indoor air quality. Studies of nosocomial respiratory infections in Africa frequently report dense occupancy as a contributing issue, but rarely mention ventilation (e.g., Madhi et al., (2004). Overcrowding itself does not necessarily cause poor indoor air quality if there is adequate ventilation provision. The two waiting rooms monitored were both densely occupied during weekdays, but the TH Maternity waiting room had considerably higher CO_2 concentrations due to lack of ventilation compared to the AH OPD waiting room, which was a semi-outdoor structure with large openings on one side and in the roof.

Mechanical ventilation, which supplies outdoor air to wards, was effective at maintaining good indoor air quality where windows may be closed for privacy reasons, such as the TH Pre-natal ward, or where spaces must be kept sterile, as in the TH NICU and Kangaroo ward. However, it was insufficient in the crowded TH Maternity waiting room which also had limited options for supplemental natural ventilation. In contrast, mechanical ventilation alone was sufficient in the sparsely occupied TH NICU where emission of respiratory CO_2 is likely to be lower in intensive care wards containing neonates, as staff and visitors are restricted for hygiene reasons and the neonates themselves exhale much smaller quantities of CO_2 than adults. One of the lowest CO_2 concentrations was observed in the AH Physiotherapy room where natural ventilation openings were large and located on opposite sides of the room, allowing for cross-ventilation. This is important in such a room where high levels of physical activity take place, which increases the emission of potentially virus-laden aerosols compared to wards where patients are confined to beds and are less active (Blocken et al., 2021). At the other extreme, the TH Emergency ward was located in an older part of the hospital, with small, single-sided window openings (Figure 2a). This ward is almost continually occupied hence mean CO_2 concentrations were consistently higher here than most other wards, perhaps due to the suboptimal natural ventilation provision.

In wards without mechanical ventilation, where windows were closed to provide thermal comfort, the CO_2 concentrations often exceeded the BS EN 16798 (BSI, 2017) limits. A similar trend was found in Chinese hospitals where CO_2 concentrations increased in wards when windows were closed to keep patients warm (Zhou et al., 2015). When the windows were open in the TH Paediatrics U6m ward, the CO_2 levels indicated good indoor air quality, suggesting that staff should be encouraged to intermittently ventilate the ward whilst using the ductless air-conditioner to improve the indoor air quality. In four wards, CO_2 concentrations also exceeded levels that can impair cognitive function (Allen et al., 2016) which may be detrimental to the quality of patient care offered.

Seasonal differences in indoor air quality may occur due to the way natural ventilation and air-conditioning are operated in response to the thermal comfort demands of patients and staff. Indoor air quality may improve as windows are opened to provide cooling, however, increased ductless air-conditioning use may be detrimental to indoor air quality if windows are closed. Monitoring will continue for one year to investigate this. It will also be important to investigate the impact of inconsistent electricity supply (Codjoe et al., 2020; Tabiri et al., 2018) on the indoor air quality in hospitals. Whilst no power cuts were reported during the short monitoring period reported here, these are likely to occur in the future (Kayaga et al.,

2020) and indoor air quality may be affected in wards where mechanical ventilation fails to operate.

Thermal comfort and hygiene drives ventilation and air-conditioning use in the case study hospitals. Cultural and societal practices may also be influential, however, and future research should address and ultimately improve practices through education and awareness creation.

Infection risk can be inferred from CO_2 concentration (Rudnick & Milton, 2003), however, more sophisticated relative exposure models, such as the one proposed by Jones et al., (2021) are required to make an assessment of airborne virus transmission risk. Further work is also required to explore this.

The attributes of wards identified with good indoor air quality are that they are sufficiently ventilated, either via natural or mechanical means, with low occupancy rates. Consequently, some recommendations are:

1. Identify and prioritise the most densely crowded spaces and increase the ventilation. For example, use semi-outdoor spaces if privacy and thermal comfort requirements allow.
2. In rooms where windows cannot be opened for reasons of thermal comfort, mosquito entry, and/or sterility, mechanical ventilation should be installed. Extractor fans could be retrofitted to existing hospitals, which would have the benefit of negatively pressurising the ward to reduce the risk of aerosols escaping to other wards (WHO, 2021).
3. Ductless (recirculating) air-conditioning units should not replace other natural or mechanical ventilation systems (WHO, 2021).

5 CONCLUSIONS

To assess the indoor air quality in 14 wards in two hospitals exposed to a tropical climate, a CO_2 monitoring campaign was initiated during the rainy season in Ghana. This was combined with informal discussions with staff about their experiences of the indoor environment and the ways they operate the ward ventilation and air-conditioning. Most wards were naturally ventilated, but some were also supplemented by mechanical systems. Ductless air-conditioning was used in some wards, where staff reported closing windows and using air-conditioning to provide comfort and sterility.

The key conclusions are:

1. Indoor air quality was satisfactory in most wards.
2. Air-conditioned wards suffered from poor indoor air quality due to recirculating air without additional outdoor air input.
3. Semi-outdoor spaces ensured good air quality for densely crowded waiting rooms, compared to those without adequate ventilation provision.
4. Staff concerns about patient thermal comfort and mosquito entry were drivers of window opening (and closing) and subsequent ventilation provision. Windows were much more likely to be closed in air-conditioned wards.

Future research will analyse CO_2 data over a longer time period in Ghana, including during the dry season. This will allow for deeper understanding of the factors causing variation in indoor air quality and result in more nuanced policy recommendations.

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