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Exposure to Waste Anesthetic Gases Throughout Surgical Interventions: A Case Study in a Portuguese Local Health Unit

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Abstract: The accumulation of anesthetic gas residues in surgery units can pose health risks to healthcare professionals, highlighting the need to establish effective protection measures. This study evaluated waste anesthetic gas levels in a local health unit in northern Portugal to identify high-exposure areas during surgeries using general anesthesia. Measurements of desflurane, sevoflurane, carbon dioxide, air temperature, and relative humidity were taken during 20 surgeries carried out over approximately six months. The results showed that the thermal conditions were not adequately controlled, particularly the relative humidity levels. The detected WAG concentrations fluctuated across different locations, with concerning peaks being detected in specific settings. Desflurane levels reached 8.79 ppm in the general surgery room (GSR) and averaged 3.13 ppm in the recovery room (RR), while the sevoflurane levels averaged 2.06 ppm in the RR. High concentrations exceeding the recommendations of the U.S. National Institute for Occupational Safety and Health (NIOSH) were notably observed after endotracheal tube removal. In short surgeries, anesthetic gas levels exceeded safety limits, while long surgeries caused peaks in sevoflurane levels. Longer surgeries and higher occupancy were significantly linked to increased levels of WAG and carbon dioxide, emphasizing the need to improve ventilation and environmental controls to safeguard healthcare professionals.

Keywords: indoor air; sevoflurane; desflurane; occupational safety; general anesthesia; circular anesthesia system

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1. Introduction

Healthcare services are facing increasing demand due to various health conditions within the population [1]. Anesthesia plays a crucial role in surgical interventions by suppressing pain and inducing a state of unconsciousness, enabling medical procedures to be performed safely and effectively [2]. Currently, halogenated gases such as sevoflurane, isoflurane, and desflurane are among the most frequently used volatile anesthetic agents [3]. These substances initially come in liquid form but are then vaporized, mixed with oxygen, and administered via inhalation using devices such as mechanical ventilation, endotracheal tubes, and facial masks [4,5].

Consequently, surgical professionals may be frequently exposed to waste anesthetic gases (WAGs) that are released from systems due to leaks in the piping, seals, and joints, improper practices, lack of training, inadequate ventilation, ineffective gas scavenging systems, and improper maintenance of equipment [6]. Additionally, during clinical use, volatile anesthetics are not fully metabolized by the body and are exhaled unchanged [7]. Whenever the flow of WAGs reaches the breathing zone of anyone in the area, it is considered a setting at "high risk" of exposure. The overall risk level depends on the frequency and duration of this exposure [8].

Exposure to WAGs in surgery rooms has long-term impacts on healthcare professionals, including reproductive problems, oxidative stress, DNA damage, and an increased risk of cancer [9], as well as chronic fatigue, persistent headaches, and nausea. In patients, short-term effects related to the toxicity of these gases include elevated serum bilirubin and liver enzyme levels [10]. Despite this, volatile anesthetics have been classified as Group 3 by the International Agency for Research on Cancer (IARC), which refers to substances that are not classifiable as to their carcinogenicity in humans [11]. This does not imply they are safe, but rather that the available scientific data are inconclusive or insufficient to determine their carcinogenicity. Recent research has highlighted the potential adverse health effects of occupational exposure to WAGs on healthcare professionals. Key findings include evidence of genetic instability, oxidative stress, and inflammation in exposed individuals. Silva et al. [6] reported increased buccal micronuclei and nuclear buds in professionals with higher weekly exposure, particularly among those over 30 years old, and noted gender differences in oxidative stress markers. Braz et al. [12] confirmed increased DNA damage and inflammatory risks in young doctors exposed during residency. Additionally, Amiri et al. [13] observed subtle hematological changes such as reduced hemoglobin, hematocrit, and red blood cell counts, even when exposure levels were within the recommended limits.

The U.S. National Institute for Occupational Safety and Health (NIOSH) recommends limiting occupational exposure to halogenated anesthetic agents to $\leq$2 ppm when used alone, or $\leq$0.5 ppm with nitrous oxide over a 1 h period, with effective scavenging systems used for anesthesia equipment [14]. The current guidelines from the U.S. Department of Labor, Occupational Safety, and Health Administration (OSHA) stress the need to minimize exposure to trace anesthetic gases to protect workers' health; although, no universally safe levels have been established, making most policies advisory rather than mandatory [15]. To expand occupational health surveillance, the European Union (EU) implemented Council Directive 89/391 on 12 June 1989 [16], outlining a hierarchy of prevention measures: (a) eliminate hazards, (b) substitute safer alternatives, (c) implement engineering and administrative controls, and (d) use personal protective equipment [16].

Measuring WAG concentrations is essential for identifying and maintaining the appropriate safety measures. There is also interest in evaluating the effectiveness of control measures for exposure WAGs, such as ventilation systems, protective masks, and safety protocols. Sárkány et al. [17] found that a laminar flow air conditioning system in operating rooms reduced exposure, with no significant differences seen between anesthetists who were sitting or standing. Kisielinski et al. [18] examined different masks and found that N95, surgical, and fabric masks release volatile organic compounds (VOCs), with concentrations exceeding the World Health Organization (WHO) guidelines, especially during prolonged use. Additionally, Jafari et al. [19] showed that isoflurane in urine is an effective biomarker for monitoring exposure and recommended real-time air monitoring for better control.

Despite the existing studies on anesthetic gas exposure, significant gaps remain, particularly in the understanding of variations across different locations and times within operating rooms. This study, conducted in a local health unit in northern Portugal, aimed to (1) assess levels of desflurane and sevoflurane in various areas of the operating sector during surgeries and (2) identify the locations and periods with the highest exposure, along with the factors contributing to these levels. The study also quantified the aforementioned anesthetic gases and compared occupational exposure levels to the NIOSH-recommended limits.

2. Materials and Methods

2.1. Surgery Unit and Anesthetic Process

The study was conducted in the surgical suite of a local health unit located in the northeast of Portugal. The unit was inaugurated in 1973 and has undergone several renovations over the years, especially since 2004. Figure 1 presents an illustration of the surveyed surgical suite. In brief, the surgical block consists of two operating rooms—one for scheduled general surgeries and the other for emergency surgeries. Each one has an area and volume of approximately 30 m^2 and 78 m^3, respectively, as well as disinfection, recovery, and medical files rooms, and a patient transfer area. The ventilation in the operating room was manually controlled by the HVAC (heating, ventilation, and air conditioning) system, which includes both bag filters used for coarse particle filtration (replaced weekly) and high-efficiency filters (replaced annually). The system ran continuously and lacked an air recirculation mechanism. All the other compartments were designed to ensure the cleanliness and safety of health professionals and patients.

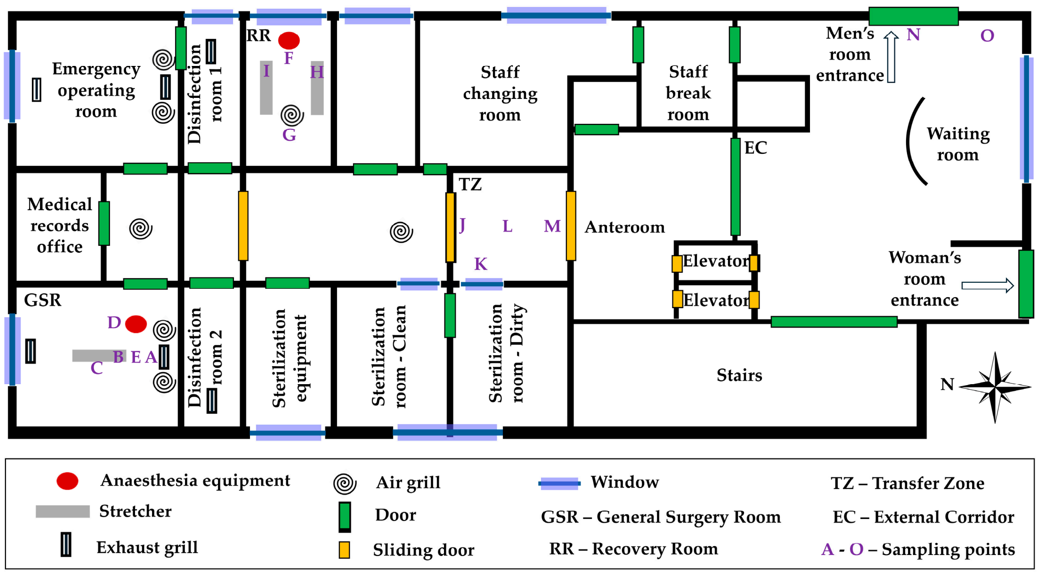


Figure 1. Illustration of the layout and key areas of the operating room, including the scheduled and emergency surgery rooms, disinfection and recovery rooms, and patient transfer area. The letters A to O in the figure represent the locations where measurements were taken.

The anesthesia system used in the hospital is the Leon Plus model from Löwenstein Medical SE & Co. KG, Bad Ems, Germany. It uses a precise electronic gas mixture in a wide flow range of 200 mL/min up to 18 L/min and is thus usable from the semi-open to quasi-closed range. In the semi-closed circular system, the adjustable pressure limiting (APL) valve is opened to allow excess gas to be removed from the system, reducing the risk of barotrauma. However, the relatively high flow of fresh gas enables the use of an external vaporizer, which can provide a higher and more accurate percentage of anesthetic gas for the mixture. In the closed circular system, the APL valve, which allows variable pressure within the anesthesia system using a spring-loaded unidirectional valve, is completely closed. Although this is the most efficient anesthetic ventilation system, it leaves little margin for error. The fresh gas flow must meet the patient's exact needs, and the soda lime must absorb all the exhaled carbon dioxide. The minimal flow in this system allows for the use of only one vaporizer within the circuit.

The anesthetic gases used by the anesthetists were desflurane ($C_3H_2F_6O$; CAS: 57041-67-5, 1 ppm = 6.87 mg/m^3 at 1 atm and 25 °C) and sevoflurane ($C_4H_3F_7O$; CAS: 28523-86-6, 1 ppm = 8.17 mg/m^3 at 1 atm and 25 °C), with the specific choice of gas varying according to the anesthesiologist's preference. During the surgeries, these gases were administered after intravenous anesthetic induction with propofol, followed by endotracheal intubation.

During the surgeries, there were always 5 people present (a surgeon, an anesthesiologist, 2 nurses, and a member of the study team), in addition to the patient. The medical, nursing, and auxiliary staff, along with medical and nursing interns, move through the operating unit during clinical activities.

2.2. Measurements of Physical–Chemical Parameters

The study monitored 20 surgeries from January to June 2019, of which 8 were performed with desflurane and 12 with sevoflurane, with all of them conducted in the general surgery room. Additionally, three similar trials were conducted on days when no surgeries were performed to establish a baseline situation and simultaneously allow for more rigorous comparison and validation of the results.

Measurements of desflurane, sevoflurane, carbon dioxide (CO_2), temperature (T), and relative humidity (RH) were taken in three areas of the operating unit, the general surgery room (GSR), the recovery room (RR), and the transfer zone (TZ), during surgeries and non-surgery periods. Measurements were also taken in the external corridor (EC) for comparison. Measurements in the GSR were taken at five points: the entrance of the room (A), the anesthesia tubing near the patient (B), the medical team area (C), near the anesthesia equipment (D), and where the anesthesiologist stands (E). In the RR, measurements were taken near the anesthesia equipment (F), at the room's exit (G), and near patients 1 (H) and 2 (I). In the TZ, measurements were taken near door 1 (J), near the window (K), in the central area of the transfer zone (L), and near door 2 (M). In the EC, two random points were chosen for measurement: near the entrance to the men's room (N) and near the window of the external corridor (O).

The GASERA ONE PULSE, a multigas analyzer from Gasera, Turku, Finland, was used to measure the levels of WAGs and CO_2. This device uses infrared photoacoustic spectroscopy and operates continuously, allowing for real-time, in situ air sample collection and analysis. The equipment was configured to measure the anesthetic gases of interest, as well as CO_2, ethanol, and water vapor, enabling sample collection and analysis every 3 min. Only a few milliliters of each sample needed to be injected into the photoacoustic gas cell of the device to achieve detection sensitivity. Ethanol and water vapor measurements were conducted to correct cross-interference in the readings of volatile anesthetics and CO_2, respectively. CO_2 concentrations were also measured to assess ventilation conditions, then compared with thresholds set in international and national standards e.g., [20,21] and Portuguese law [22]. Ventilation rates were estimated using the methodology described in the ASHRAE Standard 62.1 [23] and Persily and de Jonge [24].

Additionally, an IQ-610 probe from Graywolf Sense Solutions and a low-cost temperature and humidity sensor integrated with an Arduino platform were used to measure the T and RH, then compared with the Technical Specifications for HVAC Installations —ET 06/2008 [21,24]. Thermal comfort was assessed using the psychometric diagram adapted by Givoni [25]. The IQ-610 probe was used for the first ten surgeries, while the low-cost sensor connected to an Arduino platform was used for the next ten surgeries. Both the IQ-610 probe and the Arduino-based system ensured accurate real-time measurements. The Graywolf probe was mounted on a mini tripod, positioned centrally in the measurement spaces on a movable table approximately 1.50 m high. The Arduino-based sensor allowed for portability and quick setup. Measurements were taken for approximately 1 h in the RR, TZ, and EC, and between 2 and 4 h in the GSR, depending on the duration of the surgeries. The IQ-610 probe was also used to measure CO_2 levels outside the local health unit, at a height of approximately 1.5 m, as part of another study conducted in parallel on thermal comfort and indoor air quality in the operating theatre environment [26].

2.3. Data Analysis

The data were processed using Microsoft Excel and JMP 11 to calculate the weighted averages of anesthetic gases administered to patients (based on surgery time), perform statistical analyses, and to estimate the air change per hour (ACH), using the equilibrium carbon dioxide analysis approach—a specific application of the constant-injection technique outlined in ASTM E741 [23,24]. This methodological approach assumes a constant outdoor airflow rate, a nonzero and constant outdoor CO_2 concentration, an equilibrium of indoor CO_2 concentration, a steady CO_2 generation rate within the space, and no CO_2 loss mechanisms other than ventilation. The estimation of CO_2 production by the building occupants was based on the O_2 consumption and respiratory quotient (RQ) methodology, which is sometimes designed by the DuBois method with METs, e.g., in [24,27,28]. The ACH values were estimated under the following conditions: number of occupants = 5; the metabolic equivalent of task (MET), also designed frequently by a metabolic rate of 1.8 (higher than the value used for standing individuals performing light activities (1.4) and lower than the value of 2.0 usually for individuals walking at 0.9 m/s), body mass = 60 kg, height = 1.65 m, outdoor CO_2 concentration = 400 ppm, and an operating room volume = 78 m^3.

In addition to the descriptive statistics, comparisons were made between data collected at different locations and between sampling points within each location. After checking for normality and homogeneity of the data, ANOVA and Tukey's post-hoc test were applied, with a significance level set at $p < 0.05$. Whenever ANOVA assumptions were not met, the non-parametric Kruskal–Wallis test was applied, followed by multiple comparisons of the mean ranks.

Data visualization through boxplots was also performed with RStudio 2024.04.2 Build 764 software to represent the distribution of the analyzed parameters. In these plots, the central line inside the box indicates the median, the box itself spans the interquartile range (IQR) between the first (Q1) and third quartiles (Q3), and the "whiskers" extend to 1.5 times the IQR. Any data points outside this range were considered outliers and were plotted as individual points. Additionally, the mean is shown as a small square within the box.

OriginPro® 2024 software was used to obtain a multiple correlation matrix between the results of T, RH, CO_2, anesthetic gas residues (WAGs), surgery time (t), the number of people present in the room (N), and the weighted average of the concentration of gas delivered (WA). This allowed for the verification of correlations between these variables. The concentration of gas delivered (WA) was calculated as a weighted average based on the percentage of anesthetic gas administered over the duration of the surgery. The anesthesiologist adjusts the percentage of gas delivery multiple times throughout the surgery. For each adjustment, the percentage of gas and the corresponding time at that level were recorded. The weighted average was then calculated by multiplying each percentage of gas by the time it remained in use, summing these products, and dividing by the total surgery time. This approach reflects the varying levels of anesthetic gas administered at different stages of surgery.

3. Results

3.1. Environmental Conditions

3.1.1. Thermal Comfort Assessment

The boxplots in Figure 2 illustrate the interquartile range and the extreme values of T and RH in the four examined spaces.

During the study period, the air T values ranged from 19.4 °C to 30.2 °C, with the minimum T being recorded in the GSR and the maximum in the EC. Notably, the GSR and RR exhibited lower but similar T values, which can be attributed to the air conditioning provided by the HVAC system. Statistical analysis using the Kruskal–Wallis test revealed that the Ts in the GSR and RR were similar, with statistically significant differences observed when compared to the TZ and EC.

Regarding the RH of the air in the different evaluated spaces, the minimum values ranged from 11.4% to 22.3% (RR and EC, respectively) and the maximum values ranged from 53.1% to 57.9% (EC and GSR, respectively). The locations with the lowest average air humidity values were the TZ and RR (34.1% and 35.6%, respectively), while the GSR had the highest (42.7%). The average RH level obtained was 38.9%, with a minimum of 22.3%, a maximum of 53.1%, and a median of 40.6%. Using the psychometric diagram adapted by

Givoni, it was found that the operating suite falls within the thermal comfort zone with low humidity (classification D) [25].

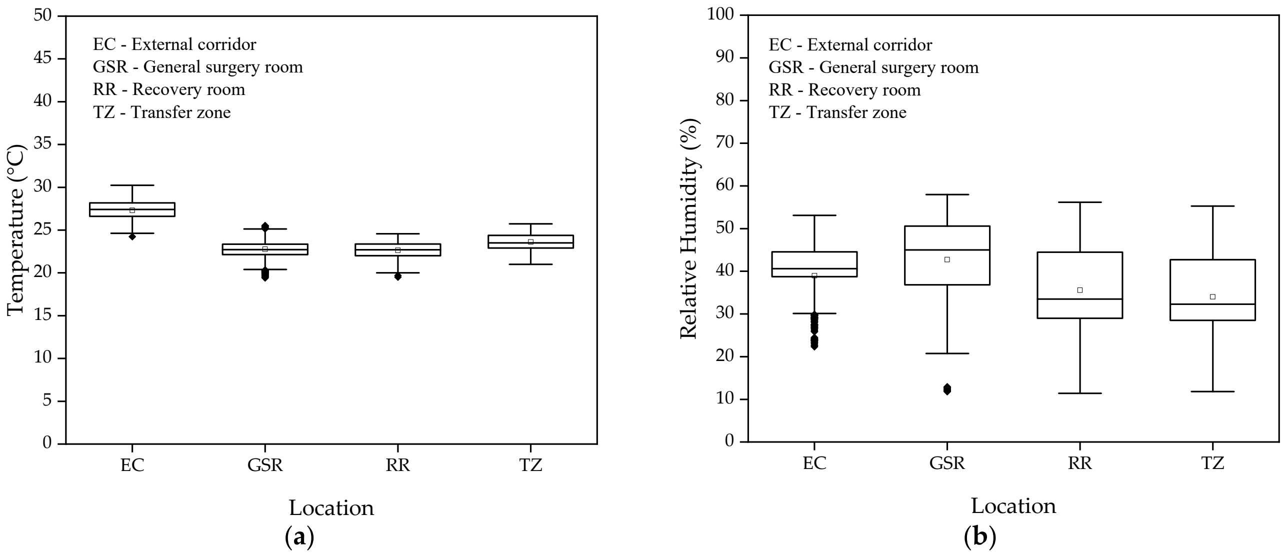


Figure 2. Boxplots representing the levels measured in the different hospital areas for: (**a**) T; and (**b**) RH. The boxes illustrate the data distribution: the central line represents the median (middle value), the edges of the box correspond to the quartiles (encompassing 50% of the central data), and the dots outside the boxes indicate extreme values (outliers). The "whiskers" extend to 1.5 times the interquartile range (between the first and third quartiles) and the outlined square markers (resembling tiny dots) denote the mean value.

3.1.2. General and Simplistic Evaluation of Air Exchange Rates

Table 1 summarizes CO_2 concentration measurements (ppm) across the various compartments of the studied area, including the minimum, maximum, median, mean, and standard deviation, for periods without surgeries and periods with surgeries. Figure 3 also presents boxplots of CO_2 concentrations (ppm) for the same studied spaces in both situations to complement the variations in CO_2 levels in each compartment, as well to more clearly highlight the differences found among the external corridor area and the different compartments of the surgical suite.

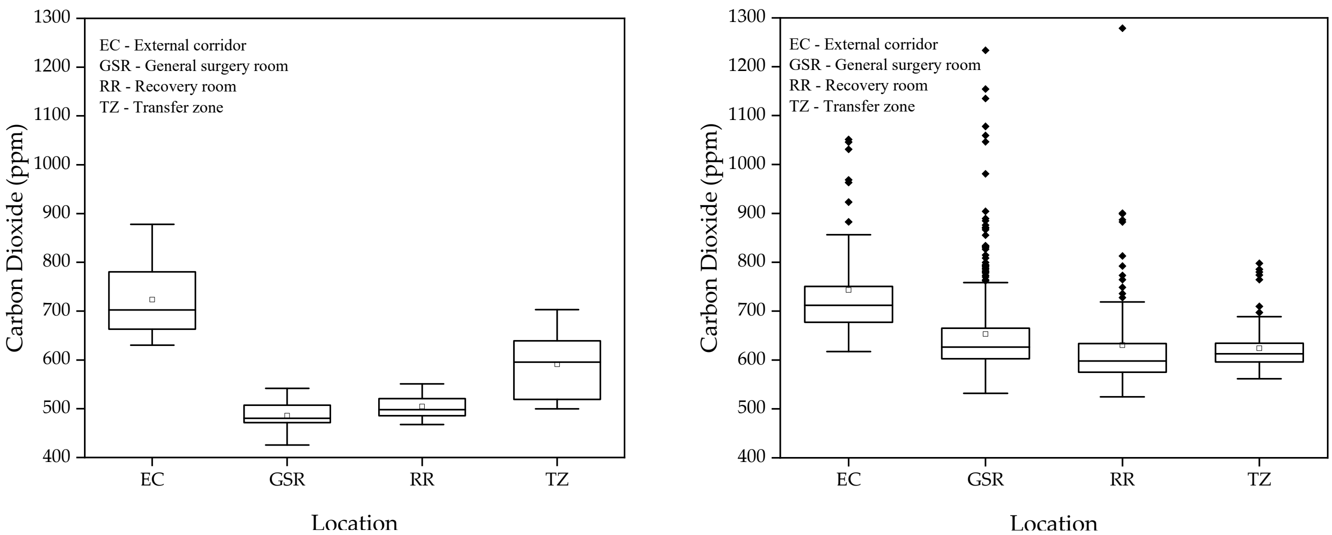
Table 1. Summary of descriptive statistics for CO_2 concentrations obtained in different hospital areas in periods without and with surgery.

		CO_2 (ppm)			
Location	**Parameter**	**Without Surgery**		**With Surgery**	
External corridor (EC)	Minimum	630.3		544.6	
	Mean ± standard deviation	727.4 ± 74.0		682.2 ± 112.9	
	Median	702.7	a	657.2	c
	Maximum	877.8		1051.23	
General surgery room (GSR)	Minimum	425.7		531.9	
	Mean ± standard deviation	485.9 ± 29.9		632.2 ± 76.9	
	Median	480.4	b	614.1	a
	Maximum	541.8		1233.5	
Recovery room (RR)	Minimum	467.7		524.9	
	Mean ± standard deviation	504.5 ± 26.0		625.3 ± 133.7	
	Median	498.1	c	595.2	b
	Maximum	550.7		1890.6	

Table 1. *Cont.*

		CO_2 (ppm)			
Location	**Parameter**	**Without Surgery**		**With Surgery**	
Transfer zone (TZ)	Minimum	499.8		529.0	
	Mean ± standard deviation	591.0 ± 71.8		618.3 ± 46.3	
	Median	595.4	c	609.7	a
	Maximum	703.0		797.9	

Note: Different lowercase letters within the same column indicate significant differences ($p < 0.05$) in CO_2 levels across the different operating room compartments, as determined by the Kruskal–Wallis test.



(**a**) (**b**)

Figure 3. Boxplots representing CO_2 concentrations assessed in the different hospital areas for periods (**a**) without surgeries and (**b**) with surgeries. The boxes illustrate the data distribution: the central line represents the median (middle value), the edges of the box correspond to the quartiles (encompassing 50% of the central data), and the dots outside the boxes indicate extreme values (outliers). The "whiskers" extend to 1.5 times the interquartile range (between the first and third quartiles) and the outlined square markers (resembling tiny dots) denote the mean value.

The CO_2 levels measured in various spaces during periods without surgeries ranged between 426 and 878 ppm. The lowest CO_2 values were observed in the GSR and RR, with average values of 486 ppm and 505 ppm, respectively. These values were lower than those measured in TZ (591 ppm) and much lower than those registered in the EC (727 ppm).

During surgical periods, the CO_2 levels ranged from 525 to 1890 ppm. The lowest concentrations were observed in the TZ and RR, with mean CO_2 levels of 618 ppm and 625 ppm, respectively. Similarly to the non-surgical periods, the external corridor area recorded the highest average concentration, while the maximum levels were found in the GSR and RR.

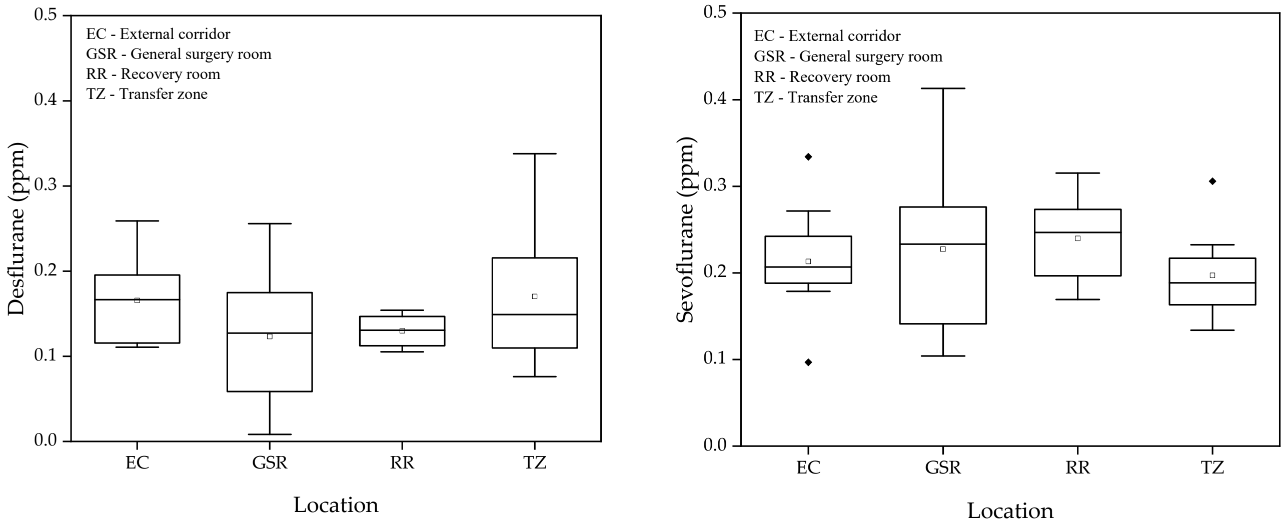
For both situations, without and with surgeries, the Kruskal–Wallis test confirmed significant differences in the CO_2 levels across all compartments. As expected, however, the operating suite exhibited substantially lower CO_2 levels compared to the external corridor.

As mentioned in Section 2.3, CO_2 concentrations were also used to estimate the ventilation rates, expressed in ACH, for the SGR. Using the average indoor CO_2 concentration, a rate of 7.0 ± 1.8 ACH was estimated, while a rate of 7.6 ACH was determined using the CO_2 concentration corresponding to the median. These ACH values closely align with the figures provided by the healthcare facility's technical team.

3.2. Concentrations of Anesthetic Gas Residues (WAGs)

3.2.1. Without Surgery

Figure 4 presents the concentrations of desflurane and sevoflurane measured during the periods when no surgeries were taking place in the operating suite.



(**a**) (**b**)

Figure 4. Boxplot of WAG concentrations for different non-surgical hospital areas for (**a**) desflurane and (**b**) sevoflurane. The boxes illustrate the data distribution: the central line represents the median (middle value), the edges of the box correspond to the quartiles (encompassing 50% of the central data), and the dots outside the boxes indicate extreme values (outliers). The "whiskers" extend to 1.5 times the interquartile range (between the first and third quartiles) and the outlined square markers (resembling tiny dots) denote the mean value.

It was observed that the variability of values between the different spaces was relatively low, with the highest recorded values not exceeding 0.34 ppm for desflurane and 0.41 ppm for sevoflurane. Tukey's test confirmed the absence of significant differences between the mean values from the different locations evaluated for both gases. These results indicate that even in the absence of the use of anesthetic gases, the measurements are not null but do have values below 0.45 ppm.

3.2.2. With Surgery

Table 2 presents the average residual concentrations of desflurane and sevoflurane in different spaces, evaluated during 20 surgeries, along with the respective minimum, mean, standard deviation, median, and maximum for each space. In general, measurements in the TZ and EC were consistently below 2 ppm for both gases, with a reduced range over the trials. These locations fully comply with NIOSH recommendations, with the lowest levels being observed in the EC due to its distance from the sources of anesthetic gas emissions, making this location a reference. The maximum value was 0.35 ppm for sevoflurane, while the minimum values were 0.07 ppm and 0.03 ppm for desflurane and sevoflurane, respectively.

In the GSR, the average values of sevoflurane were relatively low, although those for desflurane occasionally exceeded 2 ppm, indicating adverse situations. In the RR, the average concentrations of sevoflurane were 0.24 ppm in periods without surgeries and 2.06 ppm in periods with surgeries, while the desflurane concentrations were 0.13 ppm without surgeries and 3.13 ppm with surgeries. It was observed that the measurement results from the EC and TZ, with and without the occurrence of surgeries, were quite similar. In the GSR, desflurane concentrations were 1.58 ppm during surgeries when the gas exhaust system was off, compared to 0.12 ppm in periods without surgeries. In the

RR, the difference was greater, with averages of 0.24 ppm without surgeries and 2.06 ppm with surgeries for sevoflurane, and 0.13 ppm and 3.13 ppm for desflurane, respectively. The Kruskal–Wallis test demonstrated that all locations showed distinct patterns, with all of them being significantly different from each other for both gases. Figure 5 presents the boxplots of the spatial variations in the residual concentrations of desflurane and sevoflurane in the indoor air of each location assessed.

Table 2. Residual concentrations of desflurane and sevoflurane in different hospital areas during surgery.

Location	Parameter	Desflurane (ppm)		Sevoflurane (ppm)	
External corridor (EC)	Minimum	0.07		0.03	
	Mean ± standard deviation	0.18 ± 0.07		0.17 ± 0.06	
	Median	0.17	a	0.11	a
	Maximum	0.35		0.33	
General surgery room (GSR)	Minimum	0.08		0.04	
	Mean ± standard deviation	1.58 ± 18.33		0.41 ± 0.53	
	Median	0.62	b	0.31	b
	Maximum	37.8		8.78	
Recovery room (RR)	Minimum	0.35		0.25	
	Mean ± standard deviation	3.13 ± 5.58		2.06 ± 9.08	
	Median	1.32	c	0.78	c
	Maximum	31.1		76.68	
Transfer zone (TZ)	Minimum	0.16		0.16	
	Mean ± standard deviation	0.48 ± 0.43		0.30 ± 0.09	
	Median	0.31	d	0.27	d
	Maximum	1.73		0.53	

Note: Different lowercase letters within the same column indicate significant differences ($p < 0.05$) in anesthetic gas concentrations across the different operating room compartments, as determined by the Kruskal–Wallis test.

In the measurements conducted in the GSR, a significant variation was observed in the concentrations of desflurane and sevoflurane at different points in the room. The values of sevoflurane were consistently lower than those of desflurane, except for the measurement point near the patient's breathing circuit (Figure 5a,b, point B) where the concentrations of desflurane and sevoflurane reached 10 ppm after the removal of the breathing tube. The highest concentrations of desflurane were recorded near the anesthesia equipment (Figure 5a, point D), reaching up to 37.81 ppm, especially when the gas exhaust system was turned off. The average concentrations of sevoflurane ranged from 0.28 ppm near the room entrance (Figure 5b, point A) to 0.65 ppm near the anesthesia equipment (Figure 5b, point D).

In the RR (Figure 5c,d), both desflurane and sevoflurane exhibited similar variation patterns to those observed in the GSR, with less variability at points F, G, and I. Point H, near the patient's breathing area, showed high variability for desflurane, with concentrations ranging from 0.58 to 31.30 ppm (Figure 5c). This point was identified as the most critical, reflecting a higher level of exposure to desflurane after general anesthesia.

In the TZ (Figure 5e,f), the levels of desflurane and sevoflurane were low at all of the monitored locations, with some variability within the recorded intervals. Desflurane reached higher levels on the day the exhaust system was turned off, allowing gas to accumulate in distant locations. Analyses using the Kruskal–Wallis test indicated that the differences between sampling points were not statistically significant, grouping them all in the same classification.

In the EC (Figure 5g,h), the spatial variability in the desflurane and sevoflurane concentrations was minimal, with values below 0.29 ppm and 0.27 ppm, respectively. These results align with the corridor's distance from the surgery room, indicating the limited dispersion of anesthetic gases. Measurements in the corridor also served as a control, with values near zero confirming that they fall within the instrument's detection range.

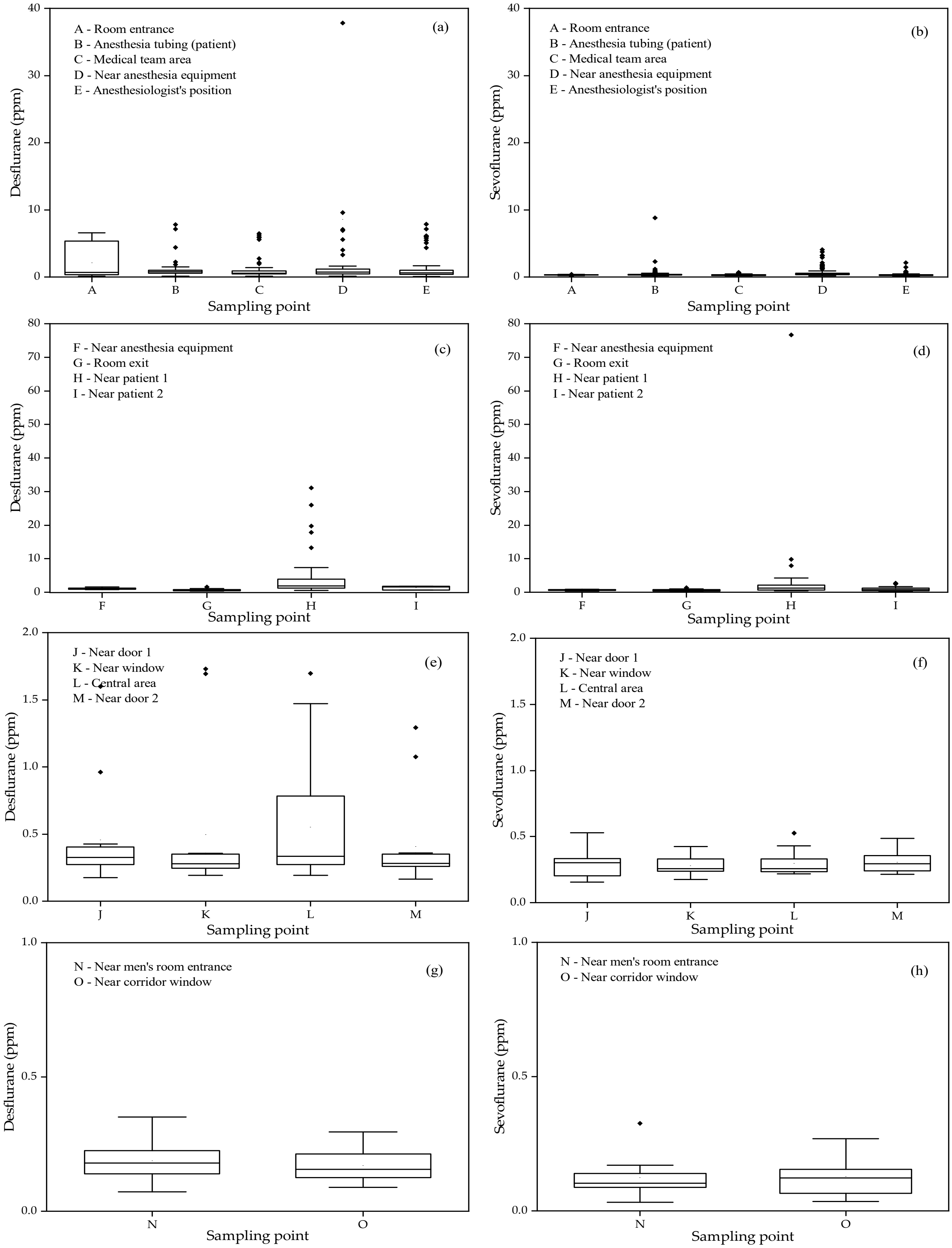


Figure 5. Spatial variations of WAGs for (**a**) desflurane in the GSR, (**b**) sevoflurane in the GSR, (**c**) desflurane in the RR, (**d**) sevoflurane in the RR, (**e**) desflurane in the TZ, (**f**) sevoflurane in the TZ,

(**g**) desflurane in the EC, and (**h**) sevoflurane in the EC. The boxes illustrate the data distribution: the central line represents the median (middle value), the edges of the box correspond to the quartiles (encompassing 50% of the central data), and the dots outside the boxes indicate extreme values (outliers). The "whiskers" extend to 1.5 times the interquartile range (between the first and third quartiles).

3.3. Anesthetic Gas Exposure over Time

3.3.1. Short Surgeries

This section evaluates the potential exposure of healthcare professionals in operating rooms during procedures lasting approximately one hour. Two distinct surgeries were analyzed, each supervised by different anesthetists and involving the use of desflurane as the anesthetic gas. Anesthetist 1 performed a laparoscopic cholecystectomy, while Anesthetist 2 conducted a quadrantectomy. Figure 6 compares the environmental levels of anesthetic gases during these surgeries.

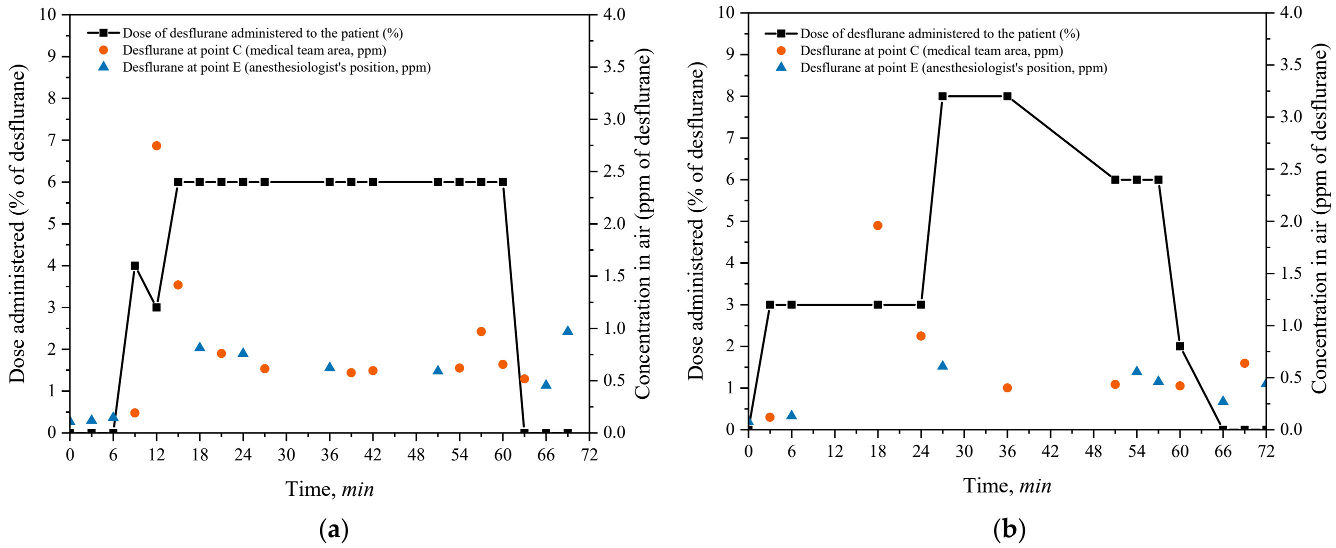


Figure 6. Desflurane concentrations measured during (**a**) laparoscopic cholecystectomy (Anesthetist 1) and (**b**) quadrantectomy (Anesthetist 2). The measurements were taken for desflurane administered (%), desflurane concentration at point C (medical team area, ppm), and desflurane concentration at point E (near the anesthetist, ppm).

Desflurane concentrations were sequentially measured at two specific points within the room: point C, in the medical team area, and point E, near the anesthetist. The black line in both graphs indicates the variations in the percentages of anesthetic gas administered by the anesthesia machine, which were manually adjusted by the anesthetists during the procedures. The weighted average concentration of gas administered was 4.29% for Anesthetist 1 and 4.32% for Anesthetist 2. The analysis of desflurane concentrations during the surgeries revealed important differences in exposure levels depending on the measurement location and the percentages administered by the anesthetists.

In Figure 6a, related to the laparoscopic cholecystectomy conducted by Anesthetist 1, a rapid increase in the concentration of desflurane administered by the machine can be observed, reaching 6% at the beginning of the procedure and remaining at this level for approximately 60 min before being abruptly reduced to zero. Measurements at point C show high initial desflurane concentrations, exceeding 2.5 ppm in the first 12 min of the surgery then decreasing and stabilizing below 2 ppm for the remainder of the procedure. In contrast, at point E, the desflurane concentration consistently remained below 1 ppm throughout the intervention.

In Figure 6b, related to the quadrantectomy supervised by Anesthetist 2, a gradual increase in the concentration of the desflurane administered can be observed, reaching 8% after 30 min. At 50 min, the concentration decreased to 6% and remained at that level until approximately 65 min, when the administration was discontinued. The measurements at point C indicate maximum concentrations of up to 1.5 ppm, consistently staying below 2 ppm during the entire procedure. At point E, the desflurane concentration also remained below 1 ppm.

3.3.2. Long Surgeries

The long-duration surgeries monitored exceeded 3 h. Anesthetist 1 conducted a conventional cholecystectomy lasting 3.25 h, while Anesthetist 2 performed a partial gastrectomy lasting 3.65 h, with both utilizing sevoflurane for anesthesia. Sevoflurane concentrations measured at point D, near the anesthesia equipment; point E, near the anesthetist for the cholecystectomy, and points C and E for the gastrectomy are depicted in Figure 7, together with the weighted average concentration of sevoflurane administered in both surgeries.

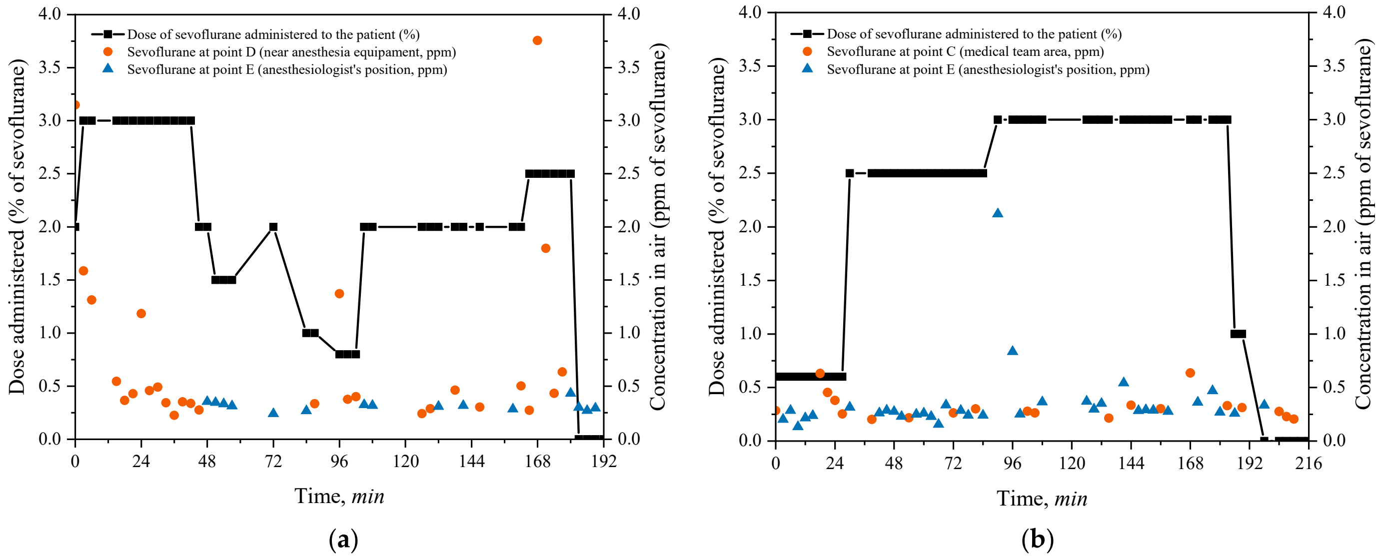


Figure 7. Sevoflurane concentrations measured during (**a**) conventional cholecystectomy (Anesthetist 1) and (**b**) partial gastrectomy (Anesthetist 2). The measurements were taken for sevoflurane administered (%), sevoflurane concentration at point C (medical team area, ppm), sevoflurane concentration at point D (near the anesthesia equipment, ppm), and sevoflurane concentration at point E (near the anesthetist, ppm).

The concentrations of sevoflurane administered by both anesthetists varied over time between minimums of 0% and maximums of 3%. The weighted average concentration of sevoflurane administered was 1.98% for the procedure by Anesthetist 1 and 2.16% for Anesthetist 2.

The evaluation of sevoflurane concentrations during the two long surgeries highlighted differences in the exposure levels based on the location of the measurement and the amount of anesthetic administered. In Figure 7a, which corresponds to the conventional cholecystectomy performed by Anesthetist 1, the sevoflurane administration starts at around 2.5% and decreases in stages throughout the 3.25 h procedure, eventually reaching 1%. At point D, near the anesthesia equipment, there were two peaks above 2 ppm, one at the beginning and another at the end of the surgery, while for the rest of the time the concentrations fluctuated but always remained below 2 ppm. At point E, near the anesthetist, the sevoflurane levels remained lower and were consistently below 0.5 ppm throughout the operation.

For the partial gastrectomy supervised by Anesthetist 2, shown in Figure 7b, the concentration of sevoflurane started at about 0.6% and increased to around 2.5% after the first hour. Around 96 min, it rose to 3% and remained at that level until approximately 192 min into the 3.65 h surgery. In the medical team area, the measurements at point C showed relatively stable concentrations, generally below 0.75 ppm. At point E, near the anesthetist, sevoflurane levels were generally lower than 0.5 ppm throughout the surgery, but there was a peak above 2 ppm at around 96 min.

3.4. Correlations Between Anesthetic Gas Levels and Environmental Factors

The correlation matrices presented in Figure 8 illustrate the relationships between the concentrations of the anesthetic gases desflurane and sevoflurane and environmental factors influencing the indoor air quality in the GSR and RR. The correlation matrix in Figure 8a,b evaluates the relationship between the concentrations of desflurane and sevoflurane, respectively, and environmental factors in the GSR and RR. These factors include the T, RH, CO_2 levels, WAGs, t, N, and WA.

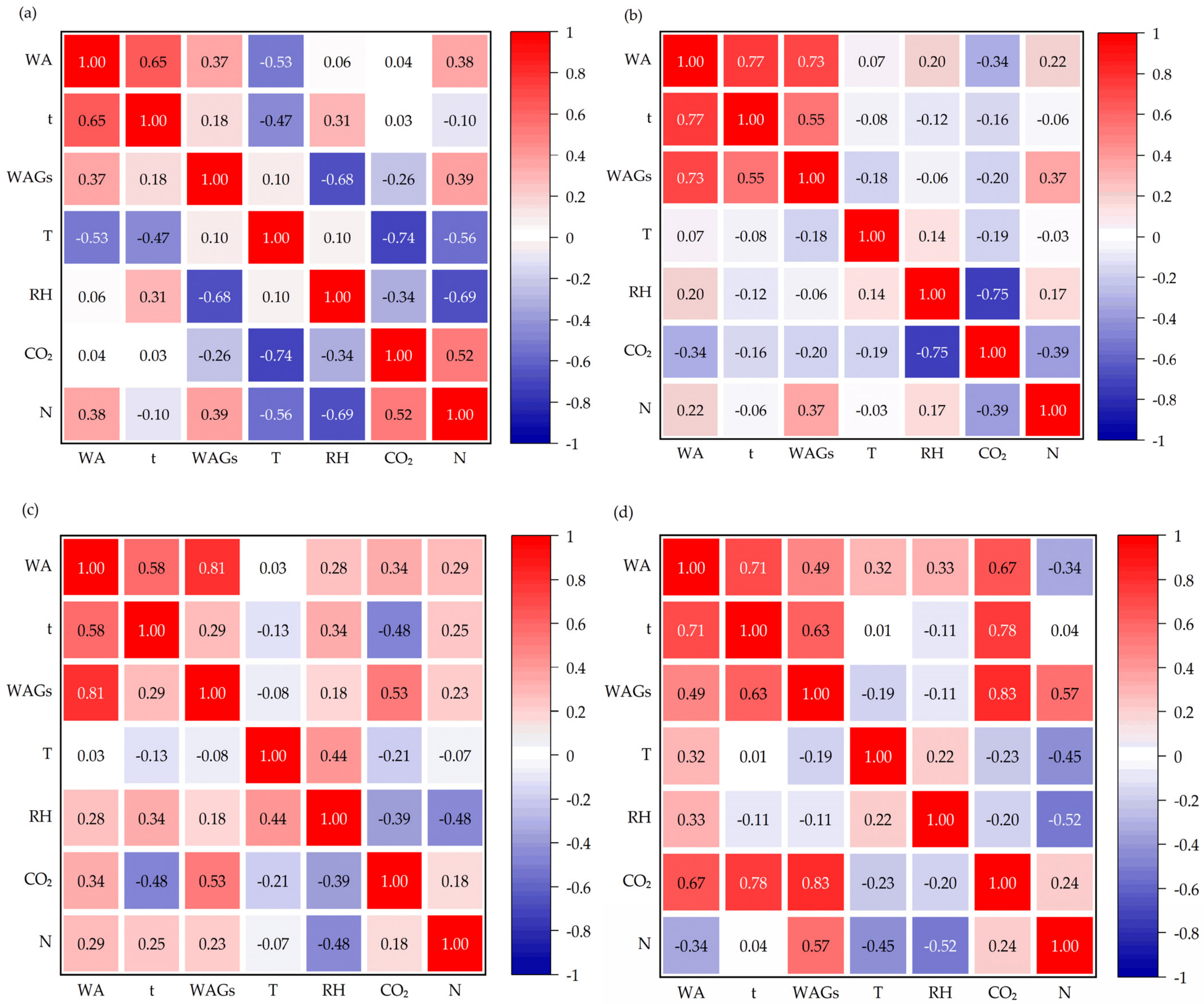


Figure 8. Correlation matrices for anesthetic gases across different scenarios: (**a**) desflurane in the GSR, (**b**) sevoflurane in the GSR, (**c**) desflurane in the RR, and (**d**) sevoflurane in the RR. The matrices illustrate the correlation between various factors related to gas levels and concentrations in each environment.

It can be observed that, for both matrices, the longer the t, the higher the WA of gas provided in the patient's anesthesia circuit. This correlation had a coefficient of 0.65 for desflurane and 0.77 for sevoflurane in the GSR. There was also a strong positive correlation between the WAG sevoflurane in the GSR and the WA provided to the patient, with a correlation coefficient of 0.73. Regarding the desflurane in the GSR, the correlation coefficient between the WA provided to the patient and the WAG desflurane was relatively low (0.37). In fact, it was found that regardless of the concentration provided to the patient, the levels of desflurane in the indoor air of the GSR were above 2 ppm, whereas with sevoflurane, higher concentrations were associated with more concentrated gas flows being inhaled by the patient.

Another evident aspect is the strong correlation between the WA and both WAGs in the RR (Figure 8c,d). The coefficient of this correlation was 0.81 for desflurane and 0.49 for sevoflurane. In other words, a higher concentration of gas provided to the patient was significantly linked to increased average airborne concentrations of desflurane and sevoflurane in the RR.

CO_2 levels were directly related to n in the GSR measurements of desflurane and in the RR measurements of sevoflurane. These correlations were 0.52 and 0.60, respectively. In fact, as expected, in these two analyses, it was found that a greater n was associated to higher average concentrations of CO_2. In the case of CO_2 measurements in the RR with sevoflurane residue, it was also observed that the higher WA, the higher the level of WAGs found in the RR, consequently leading to higher amounts of CO_2 being exhaled in this environment.

4. Discussion

This study assessed the levels of desflurane and sevoflurane in different areas of an operating sector in northern Portugal, identifying the key locations and periods with the highest exposure. The results revealed significant variations in the anesthetic gas concentrations across spaces and time during surgeries. Factors contributing to these variations were identified and occupational exposure levels were compared to NIOSH-recommended limits. These findings contribute to a better understanding of exposure risks within operating rooms, providing insights into ventilation and safety protocols.

Findings from the T assessments in the operating unit indicate that areas served by the HVAC system exhibit more effective control over thermal comfort conditions compared to other spaces. These findings are consistent with those obtained in a study conducted by Khankari [29], which demonstrated that HVAC systems have a significant impact on airflow patterns, T distribution, and the path of airborne contaminants in operating rooms. According to the technical standards for HVAC installations in hospital environments, some of which are mentioned in Section 2.2, the T in these areas remained within the recommended range of 17 °C to 27 °C for operating rooms and 24 °C for the recovery areas. However, in the EC, the recorded median T of 27.4 °C exceeded the optimal range, likely due to factors such as the lack of thermal control by the HVAC system, the southern location of the area (which exposed it to higher solar radiation), and the timing of measurements, which was typically in the afternoon. This underscores the need for continuous monitoring and management of the T in surgical environments to ensure both patient safety and healthcare professionals' comfort. Elevated Ts outside the recommended range can reduce operational efficiency, as noted by Palejwala et al. [30].

The RH values in all operating room areas fell below the recommended 30% to 60% range outlined in technical specifications. This is particularly concerning in the GSR, where RH conditions below 40% can facilitate infection transmission and worsen respiratory diseases, as discussed by Guarnieri et al. [31]. The manual control of humidity, as observed in this study, makes it difficult to maintain optimal levels. In the EC, the average RH of 38.9% did not meet the Decree-Law No. 246/1989 range of 50% to 70%. Additionally, the analysis of thermal comfort in the operating room, classified as D according to the classifications by Givoni, indicates that these conditions may interfere with professional performance and potentially lead to the contraction or worsening of respiratory diseases in exposed individuals [32]. Also, in line with other authors, including Thongkhome et al. [33], the findings of this work reinforce the importance of efficiently automated RH control to maintain a safe, comfortable, and productive environment.

The results from the study indicate that there was sufficient ventilation across the operating suite, as evidenced by the low CO_2 levels which serve as a good proxy for the effectiveness of ventilation. In general, the CO_2 levels were below the protection threshold of 1250 ppm for an 8 h exposure period, established by the Portuguese law [34]. This law is applied to commercial and service buildings for operations such as daycare centers, preschool education establishments, primary schools, and residential facilities for the elderly, and remains a highly relevant indicator for other types of spaces in the absence of specific information. The ASHRAE Standard 62.1 [23], which recommends a CO_2 differential of 700 ppm above outdoor levels (typically around 400–450 ppm) as an indicator of adequate ventilation, was met for the majority of the evaluation period. These findings align with previous studies by Ha et al. [35] and Wilson et al. [36], which also reported CO_2 concentrations below regulatory limits in well-ventilated hospital environments. The consistently low CO_2 levels, combined with reduced variability in anesthetic gas concentrations during non-surgical periods, suggest that the ventilation system effectively dilutes indoor pollutants. However, in environments where chemical products are used, even low CO_2 concentrations may not fully ensure adequate pollutant removal, making improved ventilation and extraction critical. This highlights the importance of maintaining optimal ventilation during surgeries to prevent excessive exposure to anesthetic gases, as emphasized in studies from Fogagnolo et al. [37].

In environments requiring exceptionally high air cleanliness, such as hospital operating rooms, the air change rate (ACH) is one of the most widely used metrics to assess hygiene and safety. This study estimates an approximate ACH of 7, slightly exceeding the values derived from the VRP method outlined in ASHRAE Standard 62.1 [38]. The standard specifies a minimum fresh air requirement of approximately 3.5 ACH, while emphasizing the need to account for special requirements such as pressure relationships, specific codes, and filter efficiency, as these factors can influence minimum ventilation rates. Additionally, the standard notes that procedures generating indoor contaminants may require even higher air exchange rates to ensure safety and maintain optimal air quality. In coherence with the aforementioned, there are several standards recommending ACH values for operating rooms that vary according to national and international standards, but most of them have established recommendations ranging from 15 to 25 ACH, expressed in total air (fresh plus recirculated air). The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) established a minimum recommendation of 20 ACH for operating rooms, of which at least 4 ACH must be fresh air (outdoor air). The Administração Central do Sistema de Saúde, IP [21] set a minimum of at least 5 ACH of fresh air and 20 ACH of recirculated air for hospital environments such as operating rooms. Adequate fresh air exchange is crucial to achieving contaminant dilution standards, such as reducing CO_2 levels, as recirculated air can aid thermal comfort but does not replace the need for fresh air to remove pollutants, especially if there is no specific system(s) for treating recirculated air. The surgical block is fully mechanically ventilated without air recirculation, i.e., all incoming air is 100% from outside, continuously operating and manually controlled based on thermal comfort conditions, with the aim to always maintain the minimum air exchange rate specified in national/international regulations, which at the time of the study was set to a minimum of 5 ACH.

The results of the WAG measurements showed that the concentrations of desflurane and sevoflurane in different areas of the operating room varied significantly during surgeries. In the CE and TZ, the concentrations were consistently below 2 ppm for both gases, with average values within NIOSH-recommended limits. However, in the GSR, the average values of desflurane occasionally exceeded 2 ppm, indicating a putative risk for adverse situations. In the RR, the levels of the WAGs desflurane and sevoflurane were 3.13 ppm and 2.06 ppm, respectively, suggesting that the ventilation in this room may be insufficient to mitigate emissions from the exhalation of anesthetic gases during anesthesia.

Additionally, it was observed that the most critical situations tend to occur more frequently in areas close to the anesthesiologist and near the patient's exhalation area, likely due to possible leaks in the anesthesia system and after removal of the patient's tubing. In fact, Norton et al. [39] corroborated that improper procedures or leaks can result in spikes in anesthetic gas concentrations, increasing the risk of exposure in healthcare professionals. The analysis of measurements in the GSR revealed significant variation in desflurane concentrations, especially when the exhaust system was turned off. This can happen, especially if there are failures in the anesthetic gas absorption or recirculation system. In closed or quasi-closed anesthetic systems, gas recirculation relies on a careful balance between oxygen administration and CO_2 absorption, with little or no ventilation to the outside. If the system is not perfectly adjusted or if there are leaks, anesthetic gases exhaled by the patient can accumulate in the environment. Additionally, as the patient continues to exhale small amounts of a WAG, even in a closed system, there is always some risk of these gases being released into the environment, particularly during interventions such as adjusting the mask or tubes. If room ventilation or waste control systems are inadequate or deficient, this can result in exposure to higher concentrations of anesthetic gases in the indoor atmosphere. These results underscore the critical importance of keeping exhaust systems operational during surgeries.

During the short-duration laparoscopic surgical procedure (Figure 7a), point C, located in the medical team area, showed initial concentrations exceeding 2.5 ppm, surpassing the NIOSH safety limit of 2 ppm. This increase may be attributed to the proximity to the patient, where exhaled gas or gas not captured by the ventilation system can temporarily accumulate. At point E, near the anesthetist, the levels remained below 1 ppm, possibly due to the efficient use of exhaust systems to better control gas dispersion in that area. During the quadrantectomy (Figure 7b), measurements at both point C and point E consistently remained below the limit, suggesting that the control of desflurane administration was more efficient, possibly due to improvements in air circulation or adjustments to the ventilation system.

During the long procedures (conventional cholecystectomy and partial gastrectomy), peaks in the sevoflurane levels at point D (near the anesthesia equipment) may have been caused by momentary gas emissions, particularly during the initiation and termination of administration, when the exhaust system may be less efficient. Although these peaks above 2 ppm were short-lived, they indicate a potential need to improve ventilation around the equipment. At point E, near the anesthetist, the concentrations remained well below 0.5 ppm, except for a peak of 2 ppm during the gastrectomy (Figure 8b) which may have occurred during adjustments to the anesthesia machine or room ventilation changes. This suggests that exposure is generally controlled, but momentary variations related to anesthesia handling or airflow dynamics can occur.

Finally, the multiple correlation matrix corroborated the following findings: (i) longer surgery durations are consistently associated with higher concentrations of both anesthetic gases, possibly due to the increased period during which the "pollution source" is actively emitting, as well as to a time-dependent accumulation effect; (ii) a higher number of occupants in the surgical environment naturally increases the concentrations of anesthetic gases and CO_2, and (iii) CO_2 levels may serve as an indirect indicator of ventilation effectiveness and accumulation of anesthetic gases, particularly in ventilation systems without air recirculation.

Although the presented results are valuable, it is important to highlight some limitations that may have influenced the interpretation of the data. The sample of surgeries observed was relatively small, with only two duration categories (short and long). Additionally, the performance of one of the surgeries with the exhaust system turned off directly influenced the concentrations of anesthetic gases and CO_2 found, but we must not forget that ensuring better indoor air quality can lead to greater deterioration in outdoor air quality.

5. Conclusions

The study allowed the conclusion that the breathing areas of patients and healthcare professionals are significantly exposed to WAGS, particularly after removal of the endotracheal tube. Higher concentrations were observed at specific points, suggesting the need to improve ventilation systems and operational practices. The implementation of effective control measures is essential to minimize occupational risks and protect workers' health. The findings also highlight the need to pay particular attention to long-term surgeries, during which adequate comfort and ventilation/extraction conditions are pivotal for promoting health, well-being, and optimal performance in surgical settings. Overall, this study provides valuable data for developing more stringent safety policies in the hospital environment.

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