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Formaldehyde Concentration in an Anatomic Dissection Room with Three Different Ventilation Configurations Using Computational Fluid Dynamics

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Abstract

Formaldehyde is used to preserve cadavers in medical educational institutions for its long durability and non-degradability. Continuous exposure to the toxic vapors of formaldehyde by students, faculty, and histopathology laboratory workers is suspected to cause various symptoms like neurasthenia, upper and lower airway irritation, coughing, wheezing, heartburn, and several other symptoms. World Health Organization (WHO) and the American Conference of Governmental Industrial Hygienists (ACGIH) have introduced regulatory requirements to limit the levels of formaldehyde exposure to students and faculty during dissection. The use of human cadavers is a part of medical education and exposure to formaldehyde needs to be investigated. The main objective of this work is to determine the formaldehyde concentration under various ventilations system such as natural, air-conditioned, and fan-induced ventilation. Computational fluid dynamics (CFD) is used to investigate and compare the spread of formaldehyde from a cadaver in an anatomic dissection hall. The average formaldehyde concentration at the breathing zone in the anatomic dissection hall for 3 different types of ventilation systems is air-conditioned (AC) (1.69 ppm), followed by naturally ventilated (5.4 ppm) and fan-induced system (5.59 ppm). AC-based systems are effective in reducing the formaldehyde concentration and should be preferred.

Keywords: Formalin; Deposition; Formaldehyde; Anatomy dissection hall; Computational fluid dynamics; Ventilation.
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1. Introduction

Medical education institutes are required to safely and appropriately preserve cadavers for educational purposes. Preserved cadavers should be kept away from harm, destruction, and decomposition. This is accomplished by the embalming process where the cadaver is treated with specialized chemicals, especially formaldehyde.[1] Formaldehyde which has a molecular formula of H_2–C=O is saturated (30–50% by weight). It is flammable, colorless, and highly reactive at room temperature. Formalin is an aqueous solution of formaldehyde that is commercially available.[2]

The major concern with the exposure of formaldehyde to living beings is that it irritates the skin, eyes, and also respiratory system which includes the nasal cavity and the lungs. Studies on the effects of exposure to formaldehyde on students in anatomic dissection halls show eye burning and irritation, running nose, skin itching, nausea, fatigue, breathlessness, and suffocation as major symptoms.[3–6] Laboratory experiments on mice and monkeys demonstrate degenerative non-neoplastic effects and nasal tumors on rats, for an inhaled formaldehyde greater than 6 ppm. It is also seen that inhaled formaldehyde greater than 0.08 ppm can cause eye and respiratory tract irritation in humans.[7] Another study on formaldehyde exposure in mice and rats has reported an increased level of toxic chemical impact on minute volume.[8] Several studies have demonstrated the usefulness of computational fluid dynamics (CFD) in analyzing the flow patterns in the human nasal cavity.[9–11] Recently, CFD has also been used to identify the COVID-19 virus deposition regions inside the human nasal cavity.[12] A study by J. S Kimbell *et al*.[13] utilized CFD to investigate the formaldehyde deposition in the human nasal cavity. Formaldehyde deposition was found to occur in the mid-nasal septum in humans and 5-μm

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particle simulations showed 25% nasal deposition efficiency.[14]

It has been established that a proper ventilation facility is required in the dissection room to minimize formaldehyde exposure in the students.[15,16] The World Health Organization (WHO) regulates the air quality with formaldehyde of less than 0.08 ppm[2] whereas the American Conference of Governmental Industrial Hygienists (ACGIH) sets an upper limit of 0.3 ppm.[17] Bhat *et al*.[5] reported a significant rise in the concentration of formaldehyde in dissection halls of Indian medical schools where the formaldehyde concentrations of 2.02 ppm and 5 ppm were found in a government school and a private medical institute, respectively. Similarly, Ahmed *et al*.[18] reported higher levels of formaldehyde concentration in anatomy labs when compared to other laboratories at Sharjah University. To reduce the formaldehyde levels, several researchers have suggested the use of a localized ventilation system in the dissection table.[18–20] Spraying of urea solution has also been suggested by a few researchers to reduce the formalin levels in the anatomic dissection lab.[21]

Formaldehyde deposition studies in an anatomic dissection room are performed with the use of measuring devices. To the best of our knowledge, there are no studies that utilize computer-based simulations to accurately predict the formalin concentration levels and therefore necessitates this study. In this study, the circulation of formaldehyde vapor is visualized using CFD in an anatomic dissection hall with three different types of ventilation setups. The study compares the effect of natural, air-conditioned, and fan-induced ventilation systems on the formaldehyde concentration in the room.

2. Methods and materials

2.1 Air Flow theory

Flow simulations in CFD essentially involve the conservation of laws of physics, which include mathematical forms for one continuity, three momenta, and an energy equation which are indicated in equations (1), (2), and (3).

$$\nabla . \mathrm{u} = 0 \quad (1)$$

$$\rho \frac{\partial \mathrm{u}}{\partial \mathrm{t}} + \rho \mathrm{u}.\nabla(\mathrm{u}) = -\nabla \mathrm{p} + \nabla.\left(\mu(\nabla \mathrm{u} + \nabla \mathrm{u}^{\mathrm{T}})\right) + \mathrm{F} \quad (2)$$

$$\rho \mathrm{C_P} \frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \rho \mathrm{C_P}\, \mathrm{u}.\nabla \mathrm{T} = \nabla.(\mathrm{k}\nabla \mathrm{T}) + \mathrm{Q} \quad (3)$$

where 'u' indicates the air velocity, 'ρ' is the fluid density and 'μ' is the dynamic viscosity, 'p' is the pressure of the fluid, 'T' is the temperature, 'k' is the conductivity, 'Q' is the heat transfer and C_P is the specific heat. Since steady-state assumptions are considered in this work, the time derivatives are neglected during analysis. Also, no body force is used in solving the above governing equations, the body force term 'F' will not be considered by the software.

2.2 Modelling and meshing

The present study visualizes the distribution of formaldehyde vapors in an anatomy laboratory using the three different types of ventilation setups. The airflow analysis in an anatomic dissection hall is simulated using the commercial CFD solver ANSYS FLUENT 2020 R2. The dimensions of a typical anatomic dissection hall considered in this study are 32 × 12.19 × 3.66 m which is of a private Indian medical college.[5] The dissection hall is assumed to consist of 10 tables having cadavers. It is assumed that all the cadavers are the source of formaldehyde at any given point in time indicating the dissection activity being carried out for students in the laboratory. The three different types of ventilation setups are natural air circulation, air-conditioned, and fan-induced. The natural ventilation consists of open doors and windows to facilitate the adequate flow of air into and out of the dissection hall as indicated in Fig. 1. The air-conditioned room consists

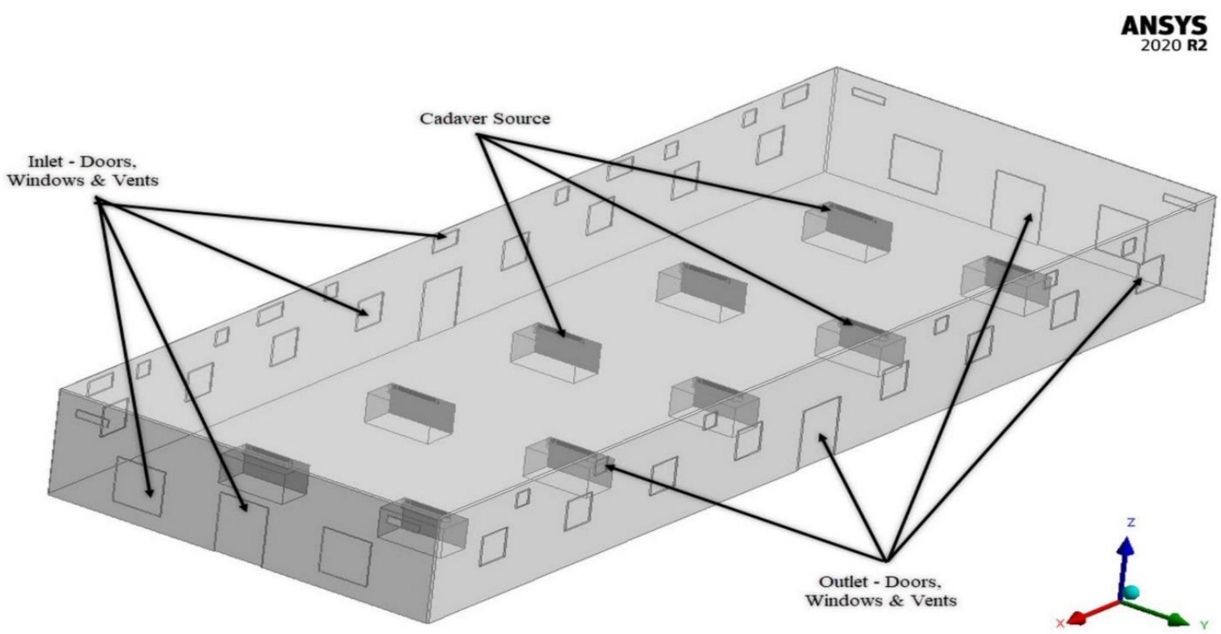

Fig. 1 Naturally ventilated anatomic dissection room.

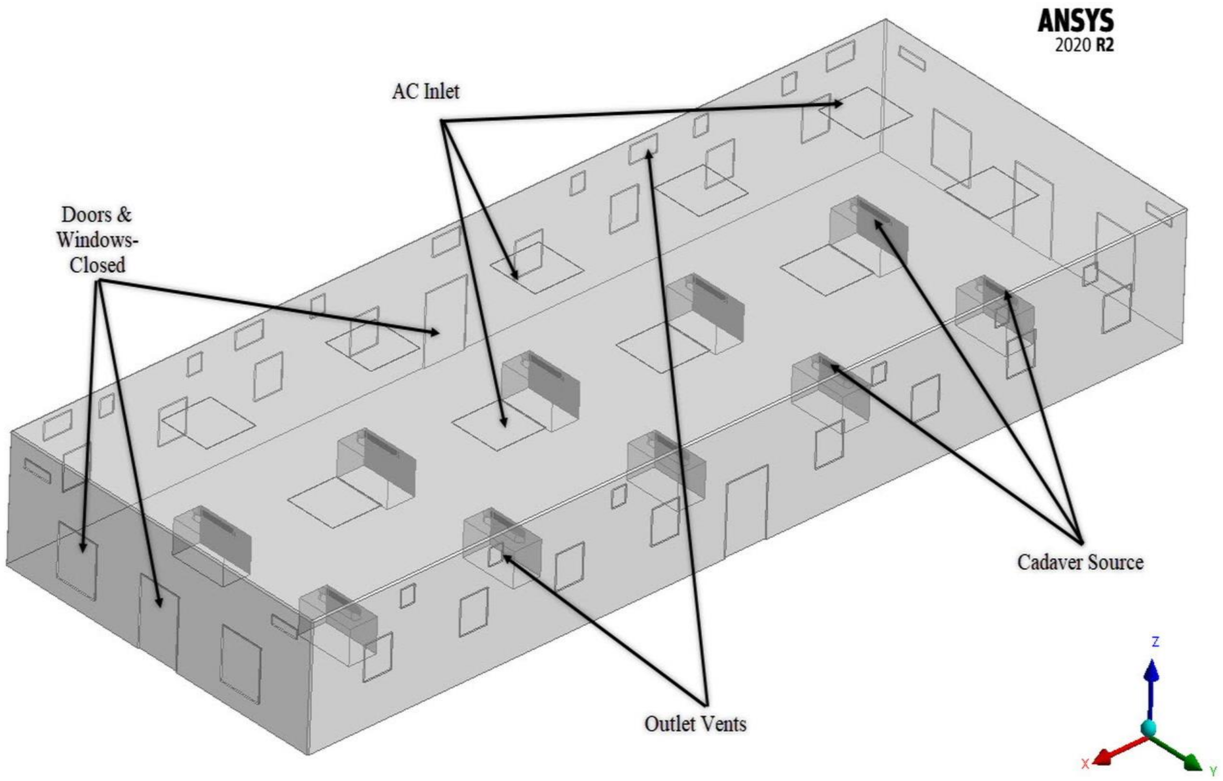

Fig. 2 Air-conditioned anatomic dissection room.

of an air-conditioned (AC) inlet along with exhaust as indicated in Fig. 2. The fan-induced ventilation setup has fans to circulate air inside the dissection hall, with windows and open doors as shown in Fig. 3. The dimensions of the doors, windows, AC inlet and fans are given in Table 1. To simplify the analysis, furniture such as chairs, and desks and heat-generating sources like bulbs, heaters, and lights are not considered in the study.

Table 1. General dissection room dimensions.

Room	32 × 12.19 × 3.66 m
Windows	1.5 × 1.5 m
AC Inlet	1.5 × 1.5 m
Door	1.5 × 2 m
Exhaust	0.5 × 0.5 m and 1.0 × 0.25 m
Cadaver Dimensions	1.2 × 0.3 m
Fan	1.2 m diameter with a central hub of 0.3 m diameter

The ceiling fan is modeled as a cylindrical disc with an outer and inner diameter of 1200 mm and 300 mm, respectively. This disc is assumed to be located 300 mm from the ceiling depicting an actual ceiling fan. This is similar to the ceiling fan study previously carried out by earlier researchers.[22,23] Fig. 4 shows the sample polyhedral mesh that was developed using ANSYS FLUENT 2020 R2 to simulate the airflow in the naturally ventilated dissection hall. Polyhedral mesh has advantages over the traditional tetrahedral mesh in terms of faster convergence, lesser computational time, and lesser number of cells during meshing. The grid independence test is performed by refining the computational domain in terms of coarse, medium, and fine mesh. The velocity at a location very close to one of the cadavers is considered to check for mesh independence. For the naturally ventilated system, the mesh counts were 346770, 404182, and 562212 for coarse, medium, and fine mesh, respectively. It is noted that the difference in velocity at the selected location of the dissection hall is negligible when the mesh is refined from medium to fine as shown in Fig. 5. Thus, the medium mesh is considered for further calculations without significant changes in the final results and optimized computational cost and time. The same procedure is applied for other cases and the mesh counts finalized after the mesh independence check was 404182 cells for naturally ventilated, 538438 cells for air-conditioned, and 1127460 cells for fan-induced mathematical models.

2.3 Boundary conditions and solution methodology

The 3D steady-state simulation was carried out in ANSYS FLUENT 2020 R2 CFD solver. The simulation was run on a system with the Intel (R)Xenon(R) E-2124G CPU@3.40 GHz, which took approximately 2 days to complete the simulation. A Shear Stress Transport (SST) k-ω turbulence model was employed to capture the turbulent nature of the flow and the suitability of the same for the indoor environment was confirmed by the results of experimental findings.[24] The energy equation was also invoked to account for the temperature adopted in the analysis.

The dissection hall walls are considered to be rigid, with

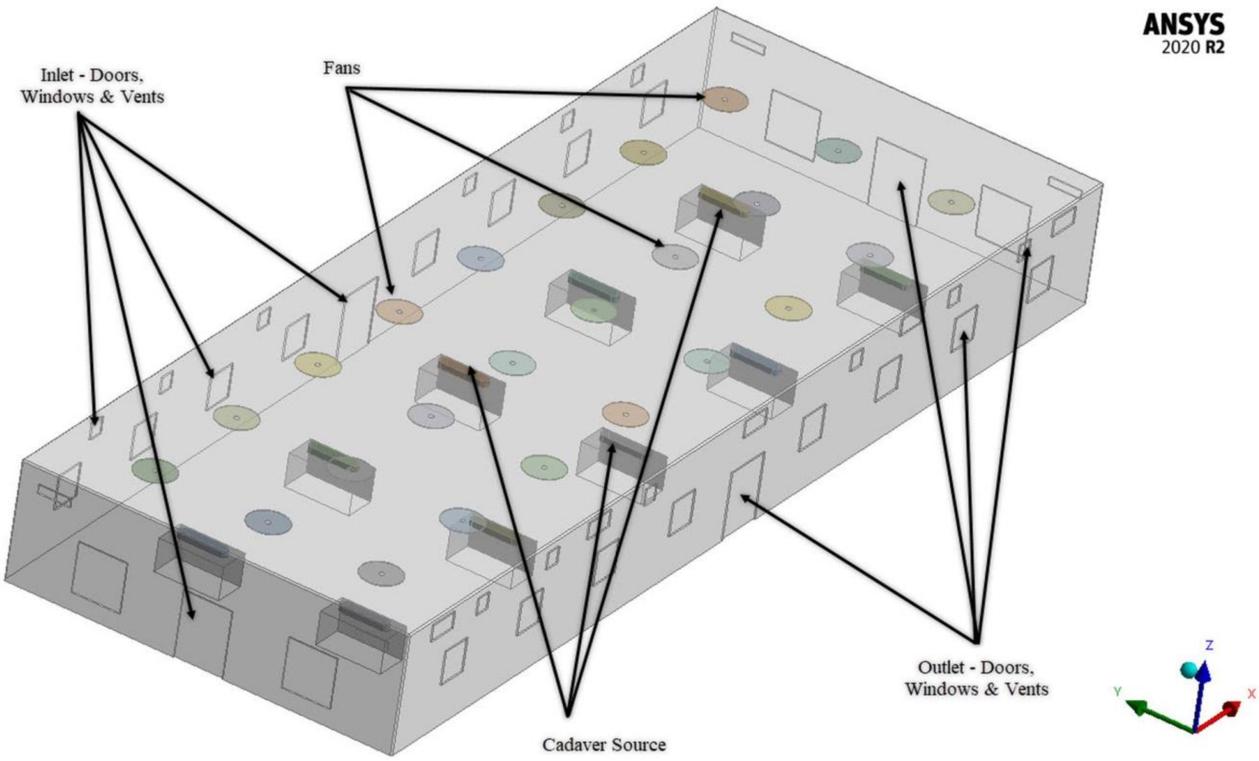

Fig. 3 Fan-induced anatomic dissection room.

the no-slip condition and assumed at a temperature of 27 °C for all the wall surfaces. The air in the dissection hall along with the cadaver is assumed to be at 27°C. For the fan-induced dissection hall, the fan is modeled as a cylindrical disc with momentum sources in the radial, axial, and theta components as 0, 55, and 8 kg/m^2s^2, respectively.[22] For naturally ventilated and fan-induced ventilation systems, the doors and windows are assumed to be open. Inlet air through the doors and windows is assumed to be 2 m/s and the "pressure outlet" conditions are maintained at the outlet doors and windows. The mass fraction of 0.0088 is considered to depict a relative humidity of 40%. In an air-conditioned dissection hall set up, the doors and windows are closed, whereas the exhausts are kept open for the flow of air out of the system. Air from the AC is maintained at a temperature of 18°C and with a speed of 3 m/s. The cadavers are the only source of formaldehyde with a constant emission rate and diffusion coefficient. A study on the formaldehyde emission rates from the cadaver source in an anatomy laboratory has an average emission of 3.15 mg/min per table which is equal to 5.25×10^{-8} kg/s.[25] The boundary conditions used are summarized in Table 2.

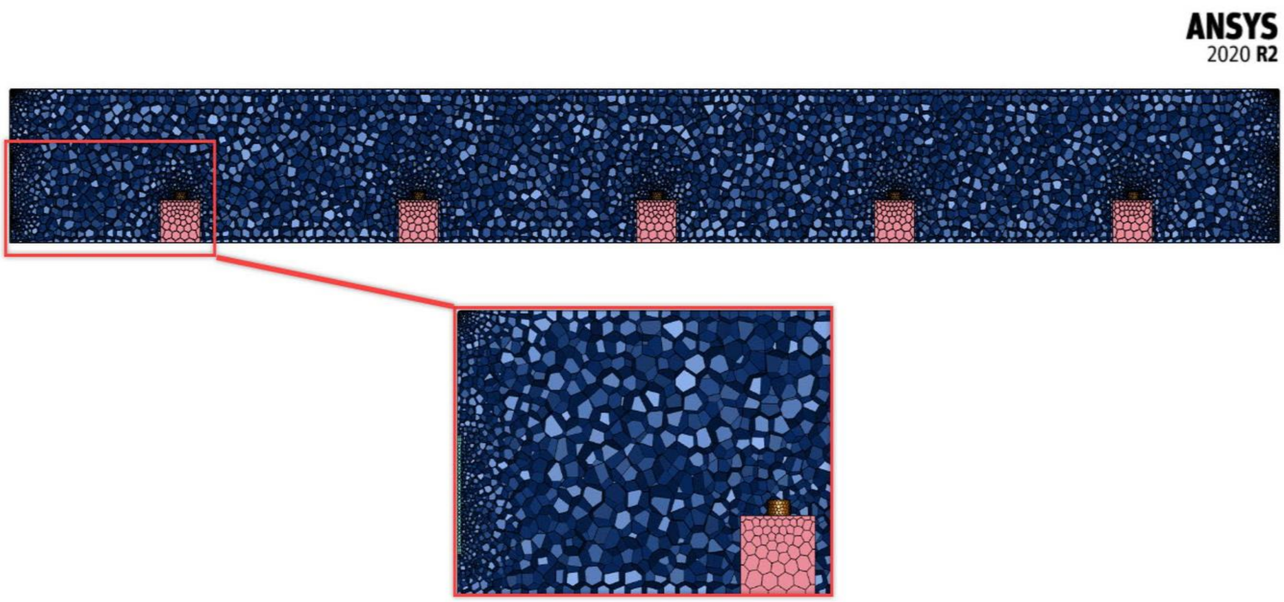

Fig. 4 Sample meshing is shown for natural ventilation with polyhedral mesh.

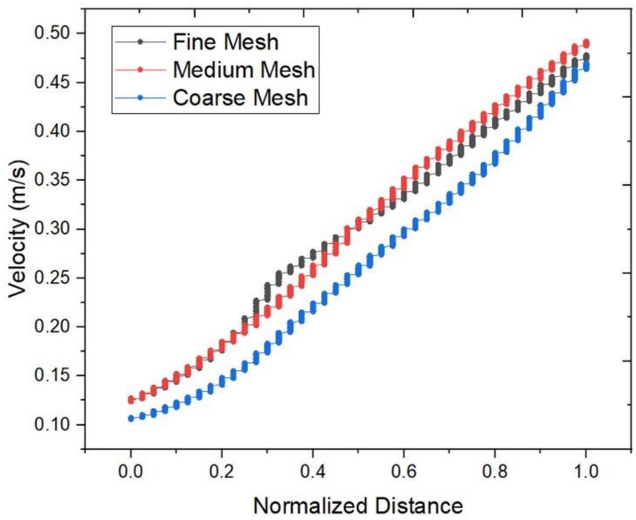

Fig. 5 Mesh independence study for naturally ventilated dissection hall.

Table 2. Boundary conditions for numerical simulation.

Boundary type	Boundary Condition
Walls	Temperature: 27°C
Air Inlet from Doors & Windows	2 m/s at 27°C
AC Inlet Velocity	3 m/s at 18°C
Formaldehyde Emission Source (Cadaver)	Mass flow inlet; HCHO emission rate: 5.25×10^{-8} kg/s

The algebraic equations that are obtained by integrating the partial differential equations (PDE) over the cells are solved iteratively and continued until convergence is achieved. The relationship between velocity and pressure corrections is obtained using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm where a steady-state solver is used to enforce mass conservation and obtain pressure. The finite volume method (FVM) with a second-order upwind scheme is used to discretize PDE to algebraic equations. The species transport model is utilized in this study to model the formaldehyde emission from the cadaver source. The formaldehyde diffusion coefficient is maintained at a fusion coefficient: of 2.88×10^{-5}.[26]

Figure 6 shows the sampling locations inside the cadaver dissection hall for an air-conditioned room. These locations are identical to experimental locations used in the literature to determine formaldehyde concentration in the air-conditioned room.[5]

3. Results and discussion

This study investigates the airflow patterns in addition to the spread of formaldehyde inside an anatomic dissection hall using CFD. The influence of three different ventilation systems on the spread of a formaldehyde concentration inside an anatomic lab is visualized. The formaldehyde distribution is affected by the airflow distribution inside the room. Fig. 7 shows the airflow patterns in the breathing zone of the dissection hall. It can be observed that a near-uniform flow pattern is achieved with the air-conditioned set-up with a higher velocity air circulation surrounding the cadaver. On the contrary, the fan-based ventilation of the room has several fans to provide air circulation. This results in a flow regime having several localized re-circulatory patterns. This pattern and flow

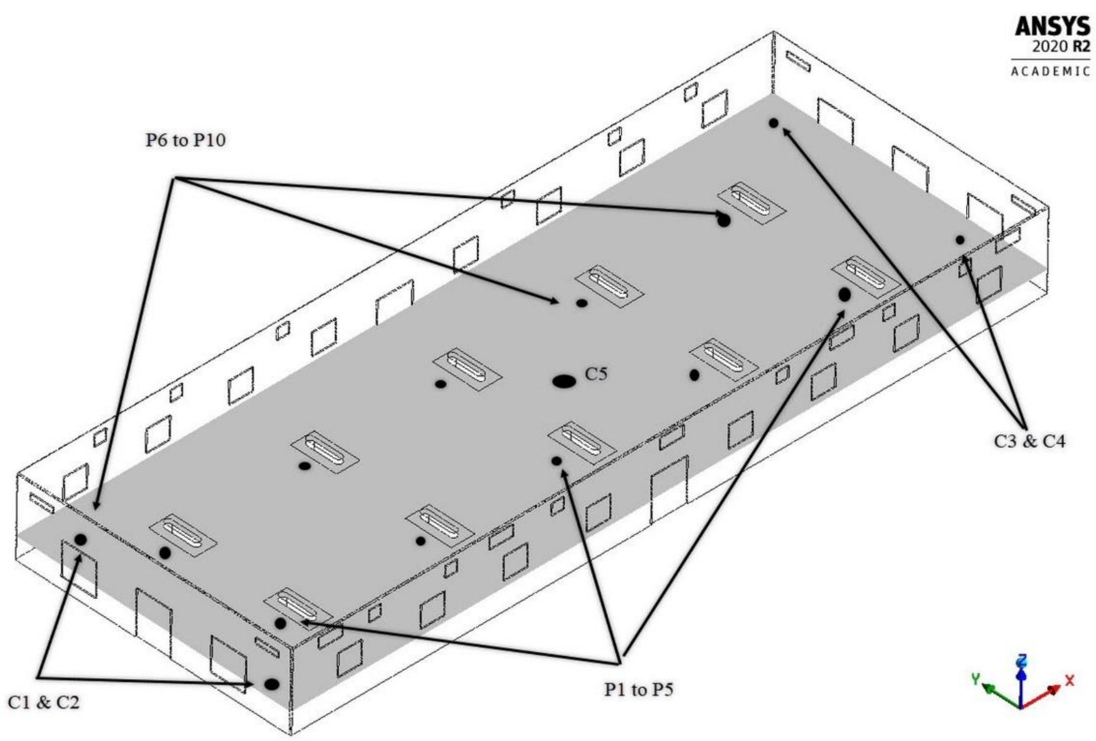

Fig. 6 Locations for formaldehyde concentrations.

the magnitude was similar to the fan-based ventilation system carried out by previous researchers.[22] The natural ventilation resulted in a very low-velocity flow, providing an inadequate supply of air into the room. Thus, the airflow patterns are different for the 3 types of ventilation systems investigated in this work.

The average concentration of formaldehyde in the room is extrapolated from the sampling locations shown in Fig. 6. These sampling locations are identical to the experimental studies carried out in the literature.[5] It can be observed from Table 3 that the formaldehyde concentration for an air-conditioning system is nearly identical to those reported in the literature. The study by Keil *et al*.[25] showed the concentration ranging from 0.51 to 1.48 ppm whereas the present study shows an average formaldehyde concentration of 1.69 ppm. Table 3 presents the concentration of formaldehyde at the sampling locations for a fan-based ventilation system. The present study shows a concentration of 5.59 ppm which is in close agreement with the findings of Bhat *et al*.[5] for the fan-ventilated room. The formaldehyde concentrations of 2.02 ppm and 5.00 ppm were found in the government school and private medical institute, respectively.[5] It is also established in this study that the formaldehyde concentration is higher in the case of the fan-based system when compared to the air-conditioned set-up. Thus, the air-conditioned cadaver room results in a lower concentration of formaldehyde among the 3 ventilation systems studied.

The majority of the formaldehyde exposure studies carried out by researchers use instruments that measure the air samples for the concentration levels.[5,27] These instruments measure instantaneous values of concentration obtained at one particular point in time, which cannot be considered a reliable metric for formaldehyde exposure. The primary advantage of CFD-based numerical study is its ability to determine the formaldehyde concentration at any location inside the room. From Table 3 it is confirmed that the average formaldehyde concentration values obtained in the present study closely replicate the experimentally reported values in the literature for identical sampling stations.

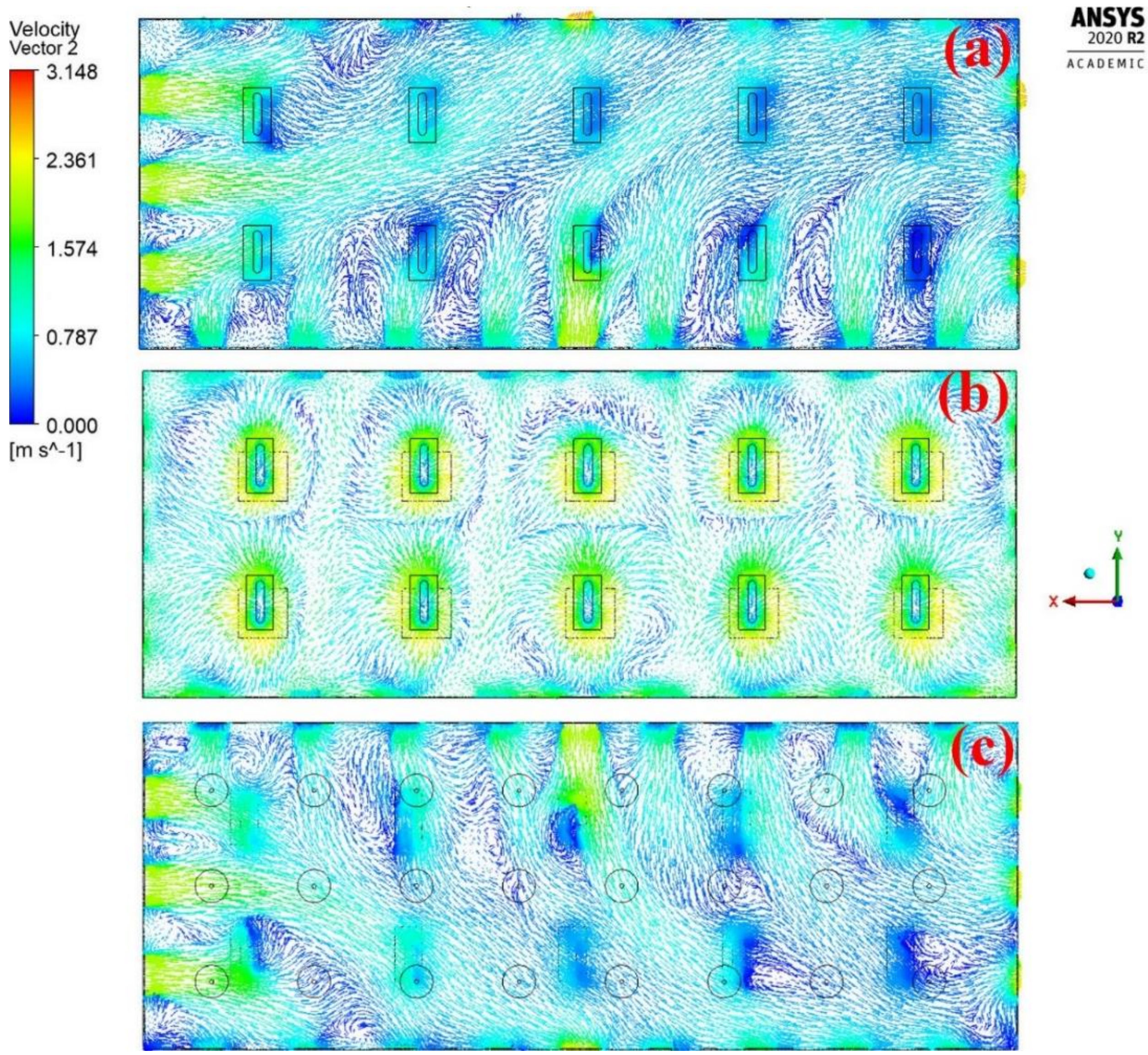

Fig. 7 Airflow patterns at the breathing zone for (a) naturally ventilated, (b) air-conditioned, and (c) fan-induced dissection halls.

Table 3. Formaldehyde concentration in air-conditioned and fan-induced dissection hall for sampling points.

Ventilation Type	Reference	Formaldehyde Concentrations mg/m^3 (ppm)
Air-conditioned	Keil *et al.*[25]	0.635–1.82/(0.51 – 1.48)
	Takigawa *et al.*[28]	2.108-3.010/(1.71–2.45)
	Ohmichi *et al.*[29]	0.35 -1.26/(0.29 – 1.03)
	Present Study	2.074/(1.69)
Fan Induced	Bhat *et al.*[5]	6.14/(5.0)
	Present Study	6.86/(5.59)

Figure 8 provides the distribution of formaldehyde at 4 different rake positions at the center of the room in the naturally ventilated, air-conditioned, and fan-induced rooms. The formaldehyde concentration is obtained at 4 different elevations (indicated as Rake 1, 2, 3, and 4) at the centreline of the dissection hall with heights of 0.5 m,1.2 m, 2 m, and 3.3 m from the floor. Formaldehyde concentrations at 250 equispaced locations are captured along the length of the dissection hall which are known as rake points. The concentration values of formaldehyde are expressed in ppm and the dimensions along the length of the dissection hall are normalized and dimensionless. There is a very significant variation in the formaldehyde concentration than those reported in the sampling locations in Table 3. The formaldehyde concentration has spiked to more than 160 ppm at certain locations in the fan-based ventilation system. Also, the naturally ventilated room has a higher concentration of up to 50 ppm in some locations within the rake line. The WHO regulates the air quality with formaldehyde of less than 0.08 ppm[2] whereas the ACGIH sets an upper limit of 0.3 ppm.[17] The air-conditioned set-up produced a concentration to a maximum of 1.6 ppm which is much lower than that reported for the fan-based or the natural ventilation system. These localized spikes can be attributed to the air recirculation patterns associated with fan-based rooms. Consequently, fan-based ventilation is not desirable for dissection rooms associated with formaldehyde exposure to students and faculty. Furthermore, the experimentally determined formaldehyde concentration at a few sampling locations does not provide accurate distribution in the dissection room. This has consequences on the health of the students and the faculty manning the room.

Continuous exposure to the toxic vapors of formaldehyde by students, faculty, and lab technicians can lead to upper and

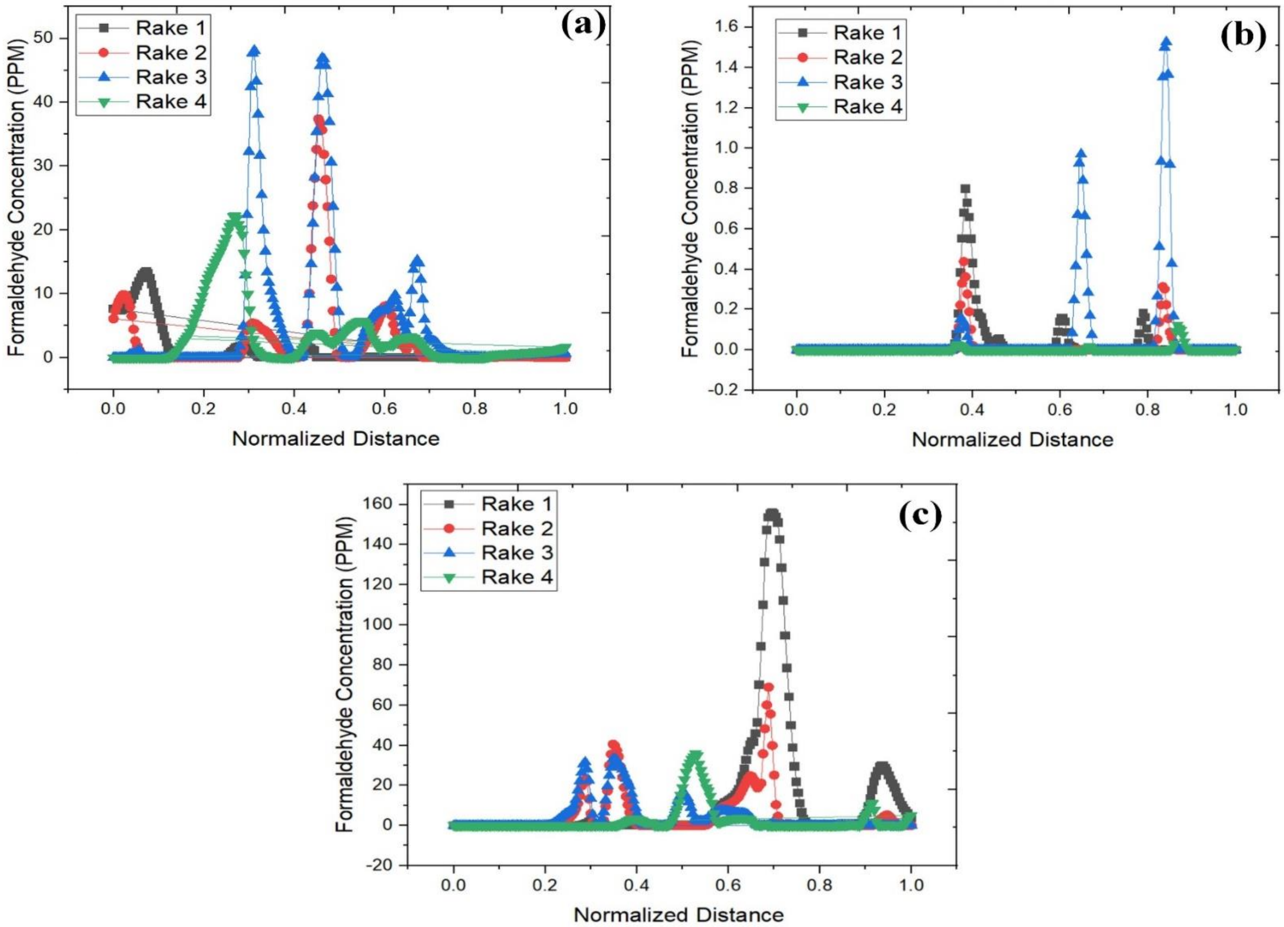

Fig. 8 Formaldehyde concentration distribution for Rake 1 to 4 in (a) naturally ventilated dissection hall, (b) AC dissection hall, and (c) Fan induced dissection hall.

lower airway irritation, coughing, wheezing, and heartburn.[3,5] The periodic exposure to formaldehyde is classified as a carcinogen that is detrimental to the well-being of the persons involved. Fig. 9 indicates the formaldehyde concentrations in the breathing zone at the left, right, and center of the room. The naturally ventilated room shows the highest concentration followed by a fan-based ventilation system. Only the AC set-up consistently provides lower formaldehyde vapor distribution in the room. The heavy formaldehyde gas tends to settle down which is reflected in very high concentrations in the natural ventilation system. This is the reason why the natural airflow is not able to remove the heavier formaldehyde from the dissection hall. Based on the findings it is advisable to place more fans at the rake 1 location.

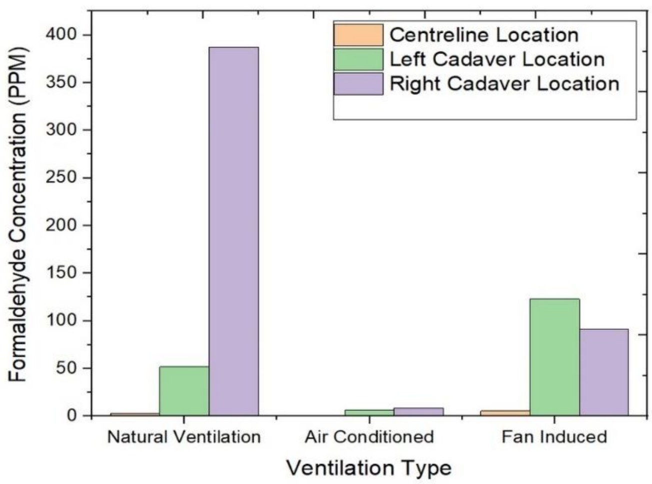

Fig. 9 Concentrations of formaldehyde at the breathing height of 1.2 m.

The concentration of formaldehyde in three ventilation setups at the cadaver location is shown in Fig. 10. The contour plots show the lowest formaldehyde distribution in the air-conditioning setup. In the case of the fan-based and the natural ventilation system, there is a prominent distribution that is not desirable. Another observation is that the formaldehyde concentration is localized around the cadaver dissection table. This has implications for the teaching/learning process wherein the students and instructors may be exposed to a higher concentration of formaldehyde. As a consequence, it is recommended to adopt an air-conditioning-based setup for all the anatomy dissection halls.

The present study gives the formaldehyde deposition patterns in an anatomy dissection room with three different types of ventilation setups. The results show that an air-conditioned dissection hall has the lowest concentrations of formaldehyde when compared to the naturally ventilated and fan-induced rooms. Further measures can be adopted to optimize the exhaust system in the AC ventilation system to decrease the formaldehyde levels by providing a higher exhaust mass flow rate and localized hood exhaust at each cadaver table which is considered in the future study.

The study does not employ the furniture set and the heat-generating items in the dissection hall which may influence the airflow and temperature. The study is limited to only one relative humidity, velocity, and temperature condition. The simulations are carried out only in steady-state conditions that are consistent with the condition of the anatomy dissection hall in the presence of cadavers. Time-dependent transient conditions can be studied for a more precise concentration distribution of formaldehyde.

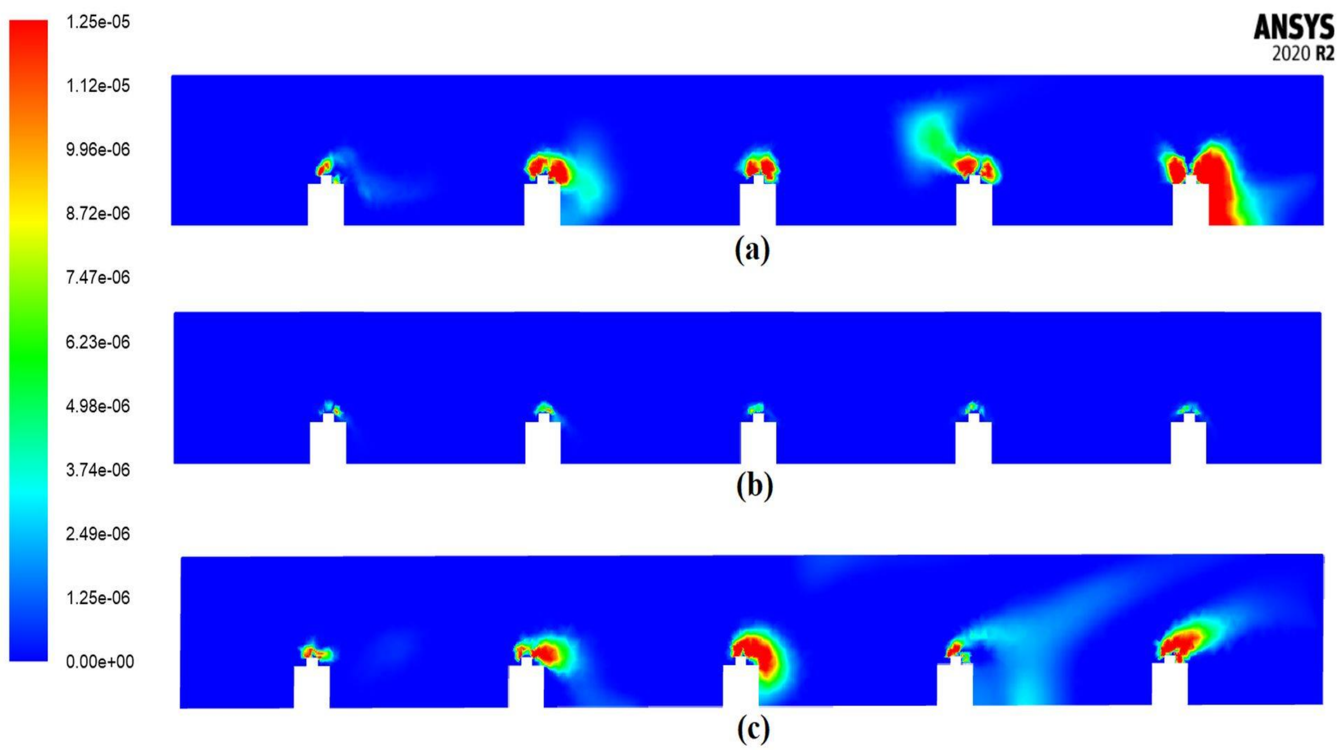

Fig. 10 Formaldehyde concentration plots for (a) natural (b) air-conditioned and (c) fan-based ventilation.

4. Conclusion

This study evaluates the formaldehyde concentration in a typical anatomic dissection hall with 10 cadavers and with three different types of ventilation. The results indicate that the air-conditioned dissection hall has the lowest formaldehyde concentration when compared to the naturally ventilated and fan-induced ventilation. The fan-based system and the natural ventilation account for ppm as high as 160 and 400 ppm which are well beyond the acceptable limits. Furthermore, the sampling locations adopted in the experiments do not provide an accurate description of the distribution of formaldehyde inside the room which necessitates the importance of this study.

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Conflict of interest

The authors declare no conflict of interest.

Supporting information

Not applicable.

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