Different HVAC airside system designs of the surgical operating theatres—their impact on the surgery staff and patient health

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ABSTRACT
There are several factors that affect the hygiene in the surgical operating theatres. The HVAC airside system plays an important role to maintain the adequate hygiene level in the operating theatres. The present paper displays comparisons between different HVAC airside designs to assess their impact on the surgery staff and patient health and comfort. The present work utilizes a numerical modelling technique to predict local flow field characteristics, heat transfer and air distribution profiles. To reduce the infection possibilities of the surgery staff and patients, it should reduce the backward flow from the polluted zones towards the clean zones and the recirculated zones; also, the air infection by direct and indirect ways should be avoided. The present paper introduces suitable design of the HVAC airside system that is based on application of 'the centralized partially ceiling supply flow' with the two extract levels to ensure the hygiene of the occupancy of the operating theatres.

INDEX TERMS
Surgery staff; Operating theatre; Health effects; IAQ assessment; HVAC design

INTRODUCTION
Hospital operating theatres are classified as clean rooms. The HVAC airside system that services the operating theatres has a primary task, to limit the particulate concentration in the room and to provide the optimum conditions for hygiene and comfort. To build a HVAC airside system, which is capable of fulfilling these requirements, is a great challenge for designers. The teams that work in the operating theatre (surgeons, anaesthetists, nurses, and orderlies) do interact with room environment. Most of infection possibilities are ascribed to the respiratory diseases. The exposure to the anaesthetic gases is most common problem that faces the surgery staff and even the patients. The critical factor for the air quality is the efficacy of the air conditioning and filtration system (Moscato *et al.*, 2000), and their efficacy depends on many design aspects and not only on the airflow characteristics. The airflow distribution pattern plays an important role to reduce the surgery staff and patients' exposure to the hazards. The good design of the HVAC airside systems creates this optimum flow pattern and consequently the required protective area.

EARLY PRACTICE OF AIRFLOW DESIGN
There are several recommendations about the optimum airflow design in the critical areas such as the surgical operating theatres; however, there are few publications on this topic. These recommendations succeeded the laminar/linear airflow concept, which was introduced to provide a restricted air movement (Scott, 1970). The directional and free turbulence airflow provide a clean environment (Gurry, 2001). Most of the guidelines advise the use of vertically downward flow and do not recommend any horizontal supply air configurations. The supply airflow from ceiling or high wall mounted and extracting air from several ports located near the floor is proposed to maintain the downward flow (Pfost, 1981; Streifel, 2000). There are

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some considerations to avoid direct airflow towards the patients and to provide a sufficient air stream to the surgery staff in the operating theatres (Bhattacharyya, 2000). Indeed, these guidelines are sufficient in the present status, but the problem that faces the HVAC airside system designers is, how to build the system that is capable to follow efficiently these guidelines.

PRESENT OBSERVATIONS AND PROBLEM ANALYSIS

Most of the surgical operating theatres designs suffer from the improper airflow distributions that would increase the infection possibilities among the surgery staff and the patients. Such a situation leads us to identify the recommended and un-recommended airflow patterns in the operating theatres. The first rule that should be followed is creating a protective area around the patients and surgery team or at least at the respiration level, as shown in Figure 1. The intensity of pollution is relative to the location in the operating theatres. This intensity increases nearer to and in the vicinity of the operating area or the extract ports, and decreases near to the clean air supply outlets. It therefore proposed to divide the theatre space hypothetically into several zones and analyze the nature of the flow in each zone and the interaction between the different zones. Therefore, the whole domain can be divided to three main zones, namely supply zone, activity zone, and dirty or exhaust zone, as shown in Figure 1. The activity zone lies between 1 m height and 2 m height (based on 3 m finished height) to contain the patient and the surgical staff. From the practical viewpoint the interaction among the three zones in the forward and reverse direction is existed. Only the complete 'piston effect' flow can prevent the backward or the reverse interaction from the pollutant zones to less pollutant or clean zones (Kameel, 2002).

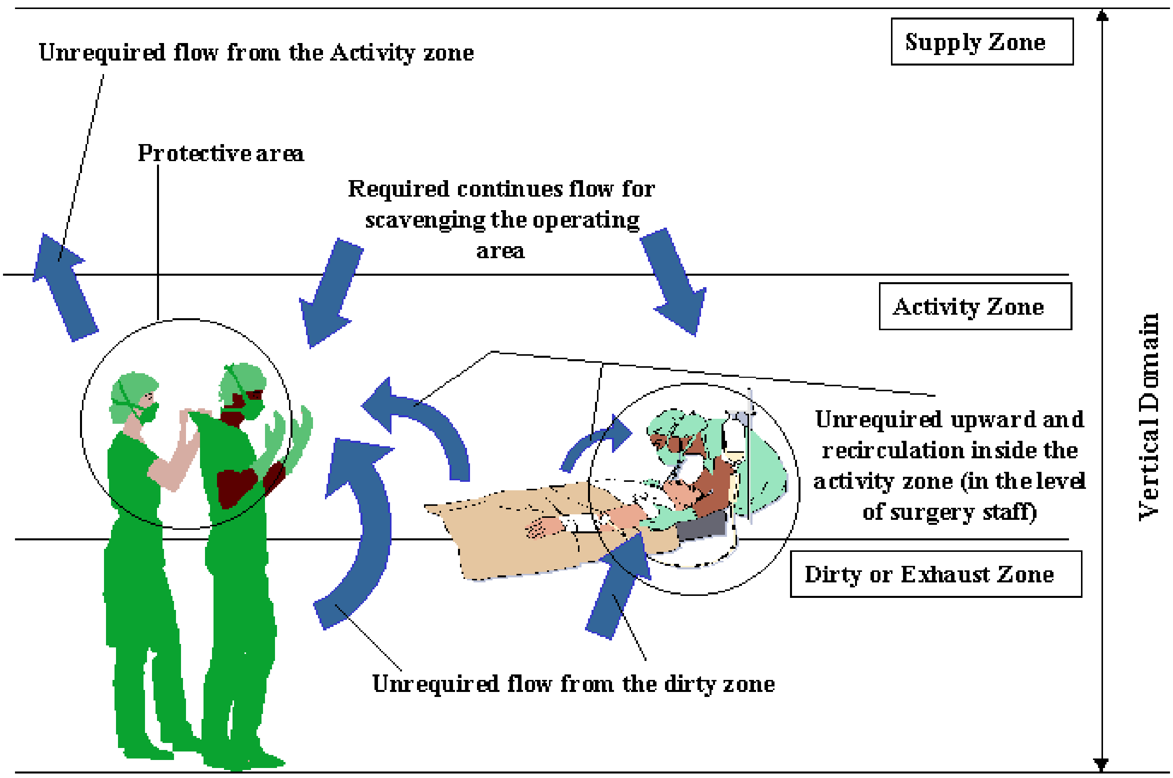


Figure 1 Airflow nature in the surgical operating theatres.

Hypothetically, the protective areas in the theatre are the areas that receive clean air only and scavenge all the pollutant air. Receiving any polluted air from any other zone or area decreases the air quality level of the protective area. Receiving any polluted air can be entrained directly or indirectly. The direct way stems from the upward flow from the dirty zone to the activity zone, or from the recirculation of polluted air in the activity zone itself. On the other hand the indirect way arises from receiving polluted air from the clean zones, which should supply the protective areas by the clean air. The clean supply area can be infected by the recirculated flow from the activity and dirty zones, Figure 2.

NEW APPROACH

The required protection for the surgery staff and the patients depends mainly on the airflow distribution pattern. Proper Design of the HVAC airside would reduce the risks of infection with energy and comfortable conditions gain. Several attempts were carried out to simulate the airflow distribution pattern, experimentally and numerically, to get the proper HVAC airside design (Kameel, 2002; Kameel and Khalil, 2003; Liu and Moser, 2002). All previous attempts found that air outlets and extracts are critical parameters responsible for obtaining a 'contaminant free' environment.

From the present observations, one can conclude that the complete laminar vertically downward flow can prevent any upward or recirculated flow from the dirty or the activity zones. Following the 'complete piston displacement effect' design can attain this. This design can be realized using a complete perforated ceiling as the supply of the operating theatre in the present study. Moreover it is supposed that to reach the complete laminar downward flow and the sterile environment, that the extract air will be extracted from the floor to prevent any air flow recirculation (Kameel, 2002). In the practice, this solution can be classified as unpractical solution. So, most of previous researches introduced several solutions to be as near as possible to the ultimate solution.

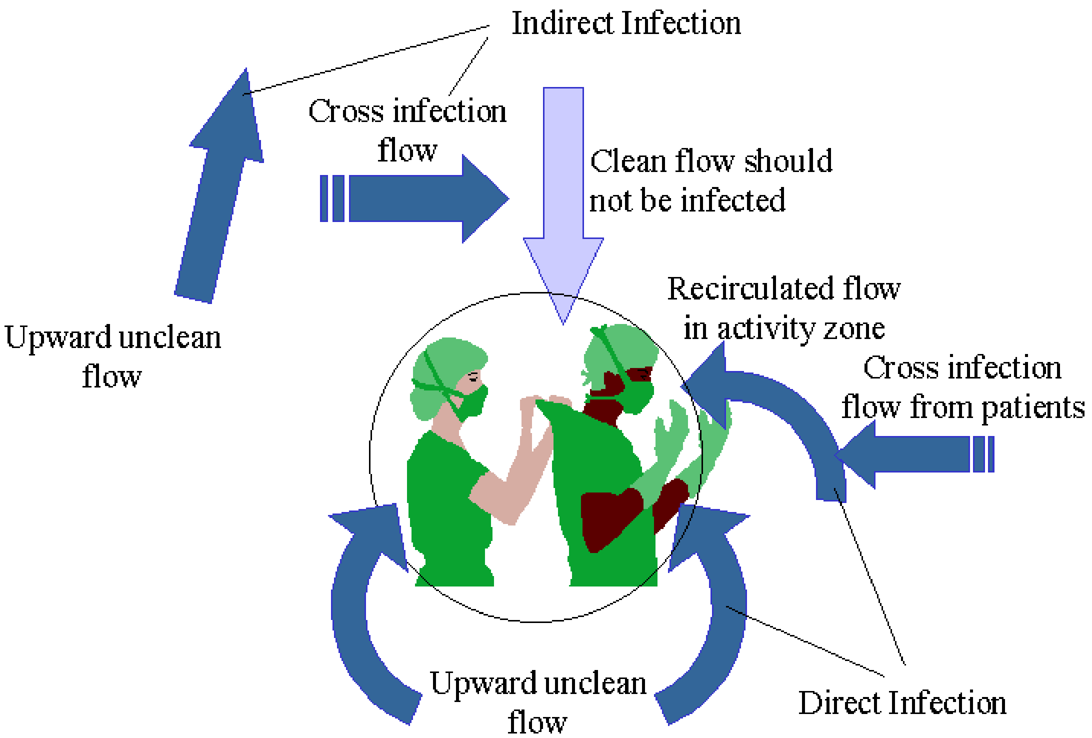


Figure 2 Infection sources of the protective area in the activity zone.

METHOD OF ANALYSIS

The present work utilizes a numerical modelling technique to predict local flow field characteristics, heat transfer and air distribution profiles. A numerical procedure, using a Computational Fluid Dynamics (CFD) model capable to solve all scalar transports, was utilized to determine the airflow characteristics in the surgical operating theatres.

Time averaged velocities were obtained by solving the governing equations using a 'SIMPLE Numerical Algorithm' (Semi Implicit Method for Pressure Linked Equation). The turbulence characteristics were represented by a modified and appropriately extended two-equation k–ε model to account for normal and shear stresses and near-wall functions. Fluid properties such as densities, viscosity and thermal conductivity were obtained from references.

The present work made use of the computer program 3DHVAC (Kameel, 2002; Kameel and Khalil, 2003). The program solves the differential equations governing the transport of mass, three momentum components, energy, relative humidity, and air contaminant local-mean-age in three-dimensional configurations. In the present study, the HVAC airside analysis is based on the analysis of the streamline pattern of the flow and the ratio of the circulation zones' volume to the space volume with the aid of integrated Neural Network program (Kameel, 2002). A sample of the results of such analysis is shown here in Figures 3 and 4.

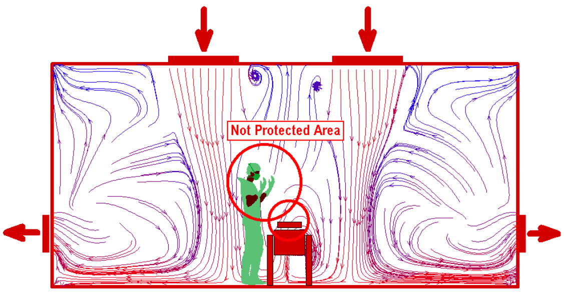


Figure 3 Distributed partially ceiling flow (with lower extraction level only).

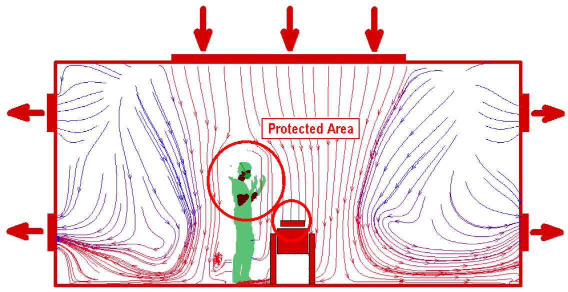


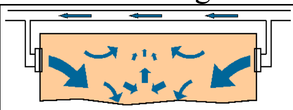
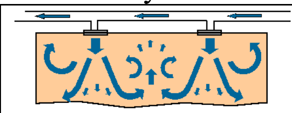
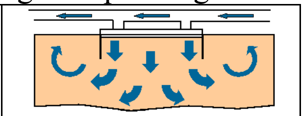
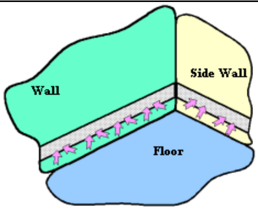
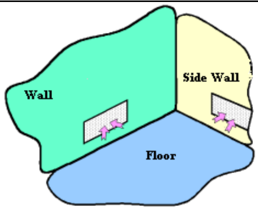
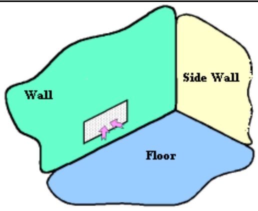
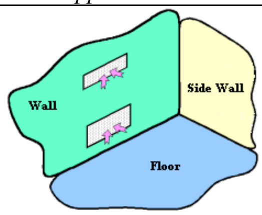
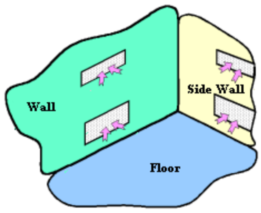
Figure 4 Centralized partially ceiling flow (with two extraction level).

RESULTS

Table 1 represents different types of these trails. Some of these solutions are already existed in the real practice and the others are virtual and are proposed for future implementation. Table 1 introduces an analysis for each design. This analysis of airside designs, energy efficiency, and Indoor Air Quality (IAQ) performance indicated the necessity of careful selection of the optimum locations of the supply outlets and extraction ports. The cross horizontal flow was found to result in what is termed as inefficient sick design, and should be excluded as an airside design in future. On the other hand, the downward flow that is developed by separate individual ceiling supply diffusers does not adequately furnish the functionality of the downward flow for providing sterile environment in the operating area. Indeed, the relocation of separate diffusers over the operating area could be developing sufficient downward flow without any upward flow over the operating area.

Actually, the central ceiling supply plenum and perforated diffuser over the operating area provides a solution for the complex situation of healthcare application by providing acceptable IAQ level in the operating zone with proper comfort and flow pattern. The partial walls are recommended as a good design parameter to provide directed flow and to protect the supplied clean airflow from the cross horizontal infection. The upper level of extraction participates in the flow guiding and prevents any upward flow from the mixing with the clean air and reduces the recirculation zones.

Table 1 Different types of airside designs of the HVAC systems in surgical operating theatres

Supply Designs Extract Ports Designs	 Horizontal Cross Flow	 Distributed Partially Ceiling Flow	 Centralized Partially Ceiling Flow
	Airflow can be supplied from two opposite walls or from the four walls, also can be supplied from corners.	*Airflow is supplied from multi perforated ceiling diffusers distributed in the ceiling, especially around the surgery zone.*	*Airflow is supplied from multi perforated ceiling diffusers distributed in the ceiling center.*
 *One level and near floor extract is around the room perimeter.*	The horizontal cross flow is not recommended even with all types of extracts, due to the strong horizontal jet flow interactions and consequent effects on the airflow pattern and turbulence in the operating area and the activity zone, which enhances the infection. The infection possibility is increased with this type of supply air arrangements. This type also is not energy efficient due to the presence of air short circuits between the supply and the extraction due the nearing of the outlets and inlets.	The presence of the upward airflow in the operating area does not provide the optimum protection to the patients or the surgery team. The strength of the side recirculation zones near to the walls and ceiling are increased due to the exclusion of the upper extract ports.	This design results in increasing the strength of the recirculation zones near to the walls and ceiling. But provides a complete protection of the operating area. Using the partial wall is highly recommended.
 *One level and near floor extract from the four walls or four corners.*			
 *One level and near floor extract from the two opposite walls.*			This design is not recommended due to the presence of large areas of the recirculation zones.
 *Two levels extract from two opposite walls.*	Not Applicable	The upper extraction level participated to decrease the upward airflow and the recirculation zones.	This design is recommended. The extract ports can be located on the wider opposite walls to enhance the design efficacy.
 *Two levels extract from four walls or four corners.*	Not Applicable		This design is highly recommended to provide a complete clean environment with fewer areas of the recirculation.

CONCLUSIONS

- The IAQ in the surgical operating theatres was shown here to depend mainly on the airflow distribution pattern. The optimum design of the airflow pattern can protect the surgery staff and the patients against infection possibilities.
- It was shown that the operating zone is most important domain in the surgical operating theatre; extract locations were also shown to be influential.
- The vertical airflow displacement design was found to be the most effective design. Unfortunately, the vertical displacement (plug flow) design based on several individual perforated ceiling diffusers is not highly recommended.
- The extract system design should be developed on the basis of two extract levels, one near the floor and the other at about 2 m from the finished floor. Very few practical designs around the world use upper level of extract.

RECOMMENDATIONS

The air is not just a medium, but it can be considered as an effective tool in the hands of the HVAC airside system designers of the medical care facilities to provide clean environment, and to provide the required protections for the surgery staff and the patients. The fully vertical downward flow 'complete piston effect' configuration can be considered as the ideal design of the airflow distribution pattern to provide clean operating theatre.

To reduce the infection possibilities of the surgery staff and patients, it should reduce the backward flow from the polluted zones towards the clean zones and the recirculated zones, also, the air infection by direct and indirect ways should be avoided. The suitable design of the HVAC airside system is based on incorporating 'the centralized partially ceiling supply flow' with two extract levels to ensure the hygiene of the operating theatres.

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