Indoor air quality and airflow distribution as a new factor in surgical operating theatres: a new hypothesis

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ABSTRACT
This paper reviews the previous attempts to evaluate the Indoor Air Quality (IAQ), investigates previously proposed IAQ factors and analyses the evaluation methods of these factors. The present work also introduces a new hypothesis of the optimum HVAC airside system design of the surgical operating theatres to achieve the comfort and hygiene levels. The present work is devoted to propose and formulate a new scale capable of adequately evaluating the airflow pattern in the surgical operating theatres. The proposed new scale is proposed to cover the local and overall air quality evaluations. The present new hypothesis is developed to overcome the difficulties experienced using other IAQ evaluations for typical surgical operating theatres. This paper recommends some designs of the supply air outlets to provide the vertically downward airflow as a practical solution. The near ceiling and near floor extract ports are to be used instead of the hypothetical complete floor extracting as a practical solution.

INDEX TERMS
Ventilation effectiveness; Operating theatre; Neural network; IAQ assessment; HVAC design

INTRODUCTION
Indoor Air Quality (IAQ) use and application are more critical in healthcare facilities due to the dangerous microbial and chemical agents present and the increased susceptibility of the patients. Hospitals and other healthcare facilities are complex environments that require ventilation for comfort and to control hazardous emissions. Surgical operating theatre is the most important and complex zone in the hospital, and requires more careful control of the aseptic conditions of the environment. Most of the previous researches aiming at evaluating the IAQ were based on the evaluation of the air distribution depending on the residence and leaving age of the air supplied to the enclosure. Other attempts were also reported to indicate the effectiveness of contaminant removal by the entire airflow pattern as an indication to the IAQ, as reviewed by Kameel (2002).

PRESENT PRACTICE
Building a ventilation system that is capable of efficiently fulfilling all comfort and hygienic requirements is a great challenge and an arduous task that consequently requires accurate definition and characterization of current designs and air quality evaluating methods. Different guidelines were established to provide comprehensive information about the HVAC designs in the healthcare facilities, especially the critical applications, such as the surgical operating theatres. These guidelines succeeded the laminar/linear airflow concept, which was introduced to provide a restricted air movement in the special facilities (Michaelson *et al.*, 1966; Scott, 1970). The airborne bacteria in an operating room might not be eliminated even by providing 'bacteria free' air from the air handling units, when using directional and free turbulence airflow (Gurry, 2001). Most of previous guidelines advise the use of vertically

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downward flow and did not recommend the use of 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 advocated to maintain the downward flow (Pfost, 1981; Streifel, 2000). Various definitions of ventilation effectiveness have been used for the assessment of the air distribution influence on the IAQ. Those definitions were limited to few configurations without any general design criterion; but they can be used as scale of the air distribution effectiveness to assess the different airside HVAC designs for the same configuration (Sandberg and Sjoberg, 1983; Skaret and Mathisen, 1983; Nielsen, 1998). Most of the previous researches, reported in the open literature, were based on simple ideas to evaluate the IAQ based only on the air distribution, limited by the prevailing air velocity patterns. Those attempts can be grouped into three efficiency scales groups that have been widely used as a measure of ventilation system, namely; mean age of air, air exchange efficiency, and contaminant removal efficiency (Ross, 1999).

Indeed, the scientific approaches to achieve a quantitative evaluation scale of the IAQ faced different obstructions related to the factors that were used and included in the evaluation procedure. The optimum selection of these factors, until now still, needs more investigations to promote our comprehension of the relationship between the IAQ and the airflow characteristics. Previous attempts concluded that the relationship between IAQ and the airflow characteristics could not depend on the mathematical or experimental techniques only. The IAQ should be studied on a fuzzy synthetic discrimination basis (Han and Chen, 2001). The IAQ is affected by several factors and the level of it is a fuzzy idea (Zhu *et al.*, 2001). These attempts succeeded the analysis of grey incidence as a base to evaluate the IAQ in different domains. It was found according to their analysis and comparison with other methods that the grey assessment is an ideal method of assessing concerned with several parameters because the procedure is simple and the outcome is credible.

PROPOSED HYPOTHESIS

To achieve and maintain good IAQ conditions, it is necessary to remove or dilute airborne contamination in the enclosed space. Ventilation air distribution pattern has a great effect on the IAQ in enclosed spaces especially healthcare applications. The primary tasks of ventilation system are to remove the contaminated air from the room and to supply the occupied region of the room with clean air. So the present newly proposed hypotheses would fulfil those tasks to correlate the IAQ and airflow characteristics. Consequently, to consider air distribution characteristics as individual factors on the evaluation of IAQ, a new criterion or standard scale to act as a reference to our evaluation should be proposed. To create the new index, the optimum air distribution in the operating theatres hypothesis should be established. The present methodology will be divided into two ways, assuming the a hypothetically perfect ventilated surgical operating theatre, and establishing the technique that will evaluate any designed room relative to the perfect operating theatre. To formulate the new index, the concept of using a complete perforated ceiling as the supply of the operating theatre is followed 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. The present hypothesis that depends on establishing an air curtain in the room is shown in the Figure 1 and is considered as the perfect hypothetical situation. That curtain will also ensure no recirculatory flows, and will provide a complete sterile environment with no cross contamination. Such an assumption was based on rightly neglecting any horizontal air movement, because of the persistent vertical air supply penetration into the room space.

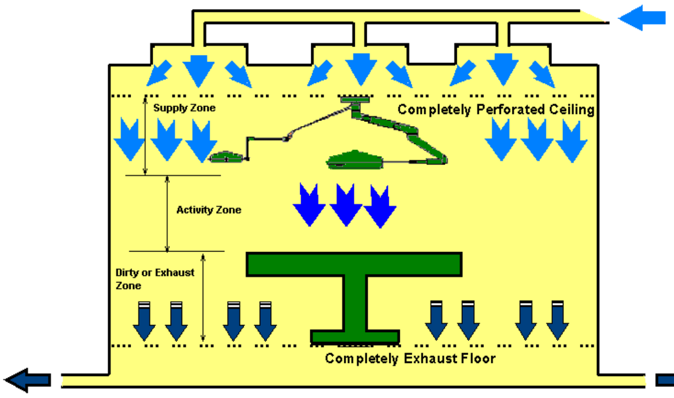


Figure 1 Proposed perfect operating theatre.

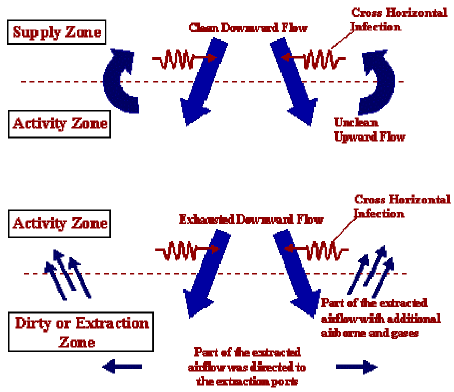


Figure 2 Interaction in the actual design.

Many of the surgical operating theatres designs suffer from the improper airflow distributions, which increase the infection possibility in the operating theatres. This promotes the interest to re-evaluate the actual designs and the nature of the operating theatres. It was therefore proposed to divide the theatre volume into several zones and analyse the nature of the flow in each zone and the interaction between the different zones. Therefore, the whole domain of the proposed perfect operating theatre can be hypothetically divided to three characterized zones, namely; supply zone, activity zone, and dirty or exhaust zone, as shown in Figure 1. The activity zone usually lies between 1 m height and 2 m height (based on 3 m finished height) to enclose the patient and the surgical staff active domain. According to this, the activity zone is the most important area in the room and should be protected by the airflow to attain optimum comfort and hygiene conditions. The activity zone and especially the operating zone is the main source of pollution in the operating room (excluding any infection from any neighbourhood spaces). The downward vertical flow will prevent the pollution particle transformation to the air upstream (based on free turbulent flow and passive action of the pollution particles). So, in the proposed perfect operating theatre, the supply zone will be protected from cross air infection. Naturally, the dirty zone will be more polluted than the activity zone due to the prevailing airflow mechanism.

PRACTICAL DESIGN

There are many observed interactions between the supply and activity zones, in the practical designs, which are served by individual perorated ceiling diffusers. This method of air supply resulted in establishing recirculating flows in the two zones, with consequent interaction from the activity zone toward the supply zone. Figure 2 represents this criterion. The unclean flow came from the infection sources in the activity zone or from the sources in the dirty zone passing through the activity zone. That unclean airflow can create a serious problem as it passes to the supply zone. The supply zone is then infected and the clean airflow may also be influenced. Moreover the clean downward flow will not be capable of following the airborne removal in the same manner as of the ideal airflow presented in Figure 1. Also, there are many interactions observed between the dirty and activity zones. The flow should be extracted from the activity zone to enter the dirty zone, which houses the exhaust ports (this is a common design practice). Those ports will extract the exhausted airflow, but due to air pressurization in the operating rooms, some portions of the air will also recirculate and back to the activity zone, Figure 2.

As mentioned earlier, the airflow has a great influence on the aseptic environment of the activity zone. Need for a criterion capable of yielding the air distribution effectiveness in the activity zone for different design, is urgently required to assist the designers to construct the optimum HVAC design for the given architecture design. This index should take into account the influence of the presence of the horizontal and vertical flow in the activity zone, and the influence of the flow that comes from the neighbouring zones especially the exhaust zone. So the index will depend on the weighting of the flow direction to the ideal case that was presented in the present investigation.

PROPOSED EVALUATION TECHNIQUE

The airflow distribution pattern can be evaluated using a mental evaluation. This is the most proper technique close to the real practice. Any professional ventilation designer can evaluate the ventilation efficiency by a looking on the airflow pattern. This was the base of the proposed technique. So it was found the fuzziness technique is the suitable one to assess the effect of the airflow pattern and ventilation design efficiency on the IAQ (Kameel, 2002).

Neuro-Fuzzy (NF) systems are intelligent systems that combine knowledge, techniques, and methodologies from various sources. Quintessence of designing intelligent systems of this kind that recognizes the hypothetical patterns (airflow characteristics of the proposed perfect theatre, here) and adapt themselves to cope with actual patterns (airflow characteristics of the practical theatre, here) are based on the Artificial Neural Networks (ANN). It will be assumed that the flow at the perforated ceiling is fully clean air (given grade 1 as a datum) and the flow at the extract ports in the floor as the fully polluted air (given grade 0 as a datum). The first step to develop an evaluation scale of the ventilation efficiency and its influence on the IAQ, is to define the characteristics that can better describe the airflow pattern and to formulate the parameters that recognize the airflow pattern to the ANN program.

The ANN program produces an evaluation index for each point in the practical design based on the status of the corresponding point in the hypothetical ideal theatre design, which is served by the perfect airside design. This evaluation index should categorically lie between 0 and 1. This evaluation scale is proposed as Local Ventilation Index (LVI). Ventilation assessment of the whole theatre will be based on the Global Ventilation Index (GVI), which is based the volume average of the LVI. The evaluation of IAQ in the present work is based airflow distributions only without the presence of the thermal factors. Many factors affect the IAQ evaluation LVI. In the present work, the factors considered are of the geometrical and fluid flow types. LVI is a function of (Geometry, Air Particle Path, Scavenging Flow, and Turbulence) for each point (p). The proposed IAQ parameters are as follows:

$$\phi_g = Z_p/H, \quad \phi_f = \tau_p/\tau_n, \quad \phi_t = \Delta\tau_p/[(\Delta\tau_p, k/\varepsilon 0] \quad \text{(at each point p)}$$

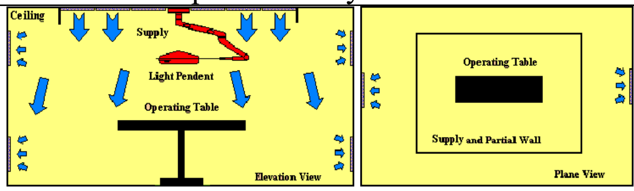
The present analysis is based on two approaches. The first approach depends only on the geometrical parameter ϕ_g and fluid parameter ϕ_f to introduce an index of the air effectiveness. The second approach depends on the geometrical, fluid parameters, and turbulence characteristic ϕ_t to introduce another index of the air effectiveness. In order to validate the present applied Computational Fluid Dynamics CFD model, and the ANN program which incorporates the IAQ parameters for evaluation, those parameters are compared with the numerical results of previous researches. The comparisons show a qualitative agreement with a maximum discrepancy of around 15%. Also, the comparison of the ANN model gives a good indication about the training results of the present ANN model (around 7% for training), with respect to the massive number of data used for training (Kameel, 2002).

PROPOSED PARAMETRIC CASES FOR SIMULATION

The present cases follow Health Technical Memorandum (HTM) 2025, developed by the National Health Service (NHS) Estates of UK. In the present cases, the effect of velocity change and the effect of change of Air Change per Hour (ACH) were considered. Table 1 shows the parametric cases in the present study. The IAQ parameters obtained from the solving of governing partial differential equations with the aid of CFD model. These IAQ parameters were delivered to the ANN program to obtain the results of two approaches.

Table 1 The parametric cases in the present study

Case	SL/L x SW/WD	H_{LL} /H	H_{UL} /H
1	0.3 x 0.36	0.266	0.73
2	0.5 x 0.36	0.266	0.73
3	0.667 x 0.36	0.266	0.73
4	0.3 x 0.6	0.266	0.73
5	0.5 x 0.6	0.266	0.73
6	0.667 x 0.6	0.266	0.73
7	0.3 x 0.8	0.266	0.73
8	0.5 x 0.8	0.266	0.73
9	0.667 x 0.8	0.266	0.73
10	0.5 x 0.8 *	0.266	0.73
11	0.5 x 0.8 †	0.266	0.73



Room Dimension L x WD x H = 6 x 5 x 3 m
Partial Walls falls 0.5 m from ceiling.
Supply Dimension Length (SL) x Width (SW), m
*ACH = 40 except * ACH = 20, † ACH = 60*
Any Exhaust Port Dimension is 0.4 x 2.0 m
Operating Table: 2 x 0.5 m, with 1.0 m Height
H_{LL}: Lower Level Grille Center Height from floor
H_{UL}: Upper Level Grille Center Height from floor

RESULTS AND DISCUSSIONS

The Global Ventilation Index (GVI) is calculated according to the first and second approaches, GVI_1 and GVI_2 based on the first and second approaches respectively. Also, the room air change efficiency ε_{ac} was calculated according to Kameel (2002). Figures 3 and 4 represent the curves of the values of GVI_1, GVI_2, and ε_{ac} with the dimensionless groups (SL/L) and (SW/WD). These figures represent contrasted trends of the global ventilation index proposed in the present work and the air change efficiency. Increased trend of the global ventilation index indicates more distributed air, acceptable distribution of the air according to its age, and effective turbulent air distribution is capable to remove or dilute the airborne contamination. On the other hand, the increase of the air change efficiency does not mean a good distributed air, but in contrast, it indicates bad air distribution in some applications. One can conclude that the IAQ can not depend only on analytical or empirical based models.

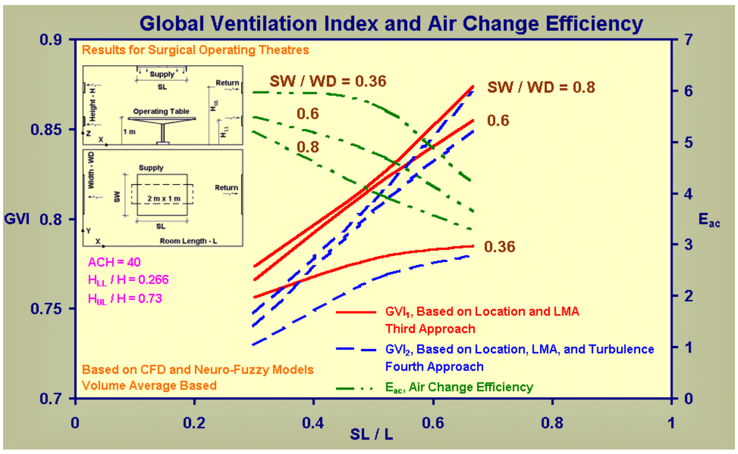


Figure 3 Numerical and fuzziness results of the parametric cases.

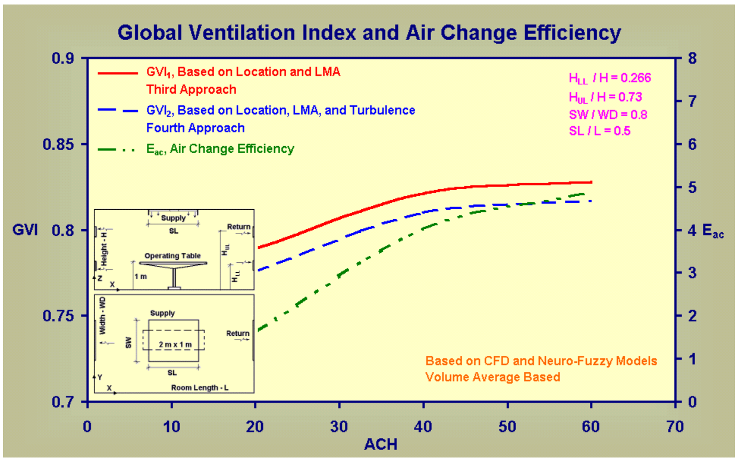


Figure 4 Numerical and fuzziness results of the parametric cases.

CONCLUDING REMARKS

Indeed, the IAQ is a fuzziness quantity based on a specific definition of the ideal flow pattern for the application under consideration. The proposed Neuro-Fuzzy models with the aid of air change efficiency are found useful tools to evaluate the ventilation performance. The proposed new scale is capable of covering the local and overall indoor air quality evaluations. The present new hypothesis is developed to yield more pronounced measures of the IAQ evaluations in surgical operating theatre, than commonly known scales. This method is recommended for the evaluation of present designs of the ventilation systems to provide a complete vertically downward flow.

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