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Assessment of operating room air distribution in a mobile hospital: field experiment based on VDI 2167

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SUMMARY

Air distribution in mobile operating room was assessed according to the recent acceptance test (VDI, 2004 [1]). This standard presents a simple and uniform validation procedure of operating room air distribution systems. Therefore it was applied as an objective method for evaluating performance of air distribution in the mobile operating room.

The original set-up and a modified set-up based on the VDI procedure were assessed. The latter attempts to represent arrangement of operating room in a more realistic way than the one defined in [1]. The experiment was conducted under direct summer outdoor conditions. The paper describes method and evaluation procedure of the acceptance test.

The results showed slightly moderate performance of the air distribution system. These results were further compared with the modified set-up and discussed. Recommendations based on the results and adjustments of VDI procedure are made towards improvement of both the evaluated system and the applied methodology.

INTRODUCTION

Operating rooms in hospitals are state-of-the-art applications of HVAC engineering. It should always protect the patient from acquiring infection during surgical operation, minimize spread of infectious agents, and create comfortable and healthy environment for the both patient and surgical staff. Unlike for the operating room in a fixed (normal) hospital little evidence was found on research in the operating rooms of mobile hospitals which are characterized by their unusual construction, low ceiling and deployment to almost any climate around the world.

Main objective of this paper was to classify the performance of the air distribution system in the mobile operating room. Currently no tailored procedure for classification of operating rooms exists in The Czech Republic. Cleanrooms classification is commonly applied for validation of air distribution in operating rooms. However operating rooms are not cleanrooms and require different approach for testing. One of the methods for evaluation performance of ventilation in operating rooms involves CFD modeling as successfully conducted by Memarzadeh and Manning [2]. The other approach is more medical than engineering. It involves microbacterial samples, which are very relevant to classification of air distribution efficiency i.e. its efficiency to reduce wound infection [e.g. 3, 4]. In 2004, draft of new procedure was issued by German Verein Deutsche Ingenieure (VDI). Their standard VDI 2167 [1] was proposed to present a simple, uniform validation and classification

procedure of air distribution systems in operating room surgical sites. Few tests were carried out in Europe recently following this procedure. However particular interpretation of the procedure usually slightly differed [5].

This paper compares two set-ups of field experiment based on the VDI [1]. The first set-up follows the original procedure while the second applies adjustments to reflect findings from reviewed literature. The standard [1] was further applied as an objective method for evaluating performance of air distribution in the mobile operating room for both of the set-ups. Additional data of the boundary conditions were taken to be used in future work for check of the numerical model.

The presented work is a part of a larger research focusing on numerical support to air distribution design strategy in mobile operating rooms. In future work experimental data will be used to check numerical model that will serve as a base case for performance prediction of different air distribution strategies in mobile operating rooms.

METHODS

Performance qualification of the operating room is a two-step procedure. First step should prove the aseptic area (surgical field) is sufficiently protected from its environment by means of the airflow distribution – *protection against load entry from outside* (set-up 1A, Figure 1 – left). The second step uses a modified arrangement of the pollution source that should detect any upward flow of contaminated room air from the floor into the protected area – *protection against load entry from inside* (set-up 1B, Figure 1 – left).

Additional measurement designated as set-up 2 (Figure 1, right) is based on the original procedure with two differences. This set-up reflects real arrangement of the operating room i.e. location of heat and pollution source. First, one cylinder representing a surgeon was placed on the operating table and served to mimic the patient i.e. generation of a protective flow above patient [6]. Literature review revealed the agents causing wound infection are the microbes attached to the skin squames liberated from uncovered body parts (face, ears, neck of surgeons and uncovered hands of nurses) [2, 7, 8, 9]. Moreover participation of the floor pollution to the wound infection remains uncertain [10]. Therefore the source of contaminants was replaced from the floor (set-up 1) to the neck of one standing and one sitting person (Figure 1 – right).

Experimental set-up

The experiment was conducted under direct summer outdoor conditions (July 2006) in central Moravia in the Czech Republic. Mobile operating room stood alone, i.e. not connected to other parts of the mobile hospital. Temperature of air at the intake of air-conditioning unit during measurement was between 26 °C a 34 °C. The outside conditions were sunny and the air was calm.

The operating room of ~ 6.2 x 5.3 x 2.1 m (width x length x height) had three double-hanged doors built in three side walls (in mission they connect operating room with other parts of mobile hospital). Operating table 210 x 90 cm with top edge at 90 cm above the floor was placed close to the wall without the door. Representative instrument table had size of 68 x 45 cm with top edge at 90 cm above the floor. Personnel working in this operating room agreed upon the layout of the room (depicted in Figure 1) prior to the experiments.

HVAC unit placed inside the room conditioned solely outside air. Two fabric diffusers 33 x 242 x 3 cm) located on the ceiling supplied $\sim 1000 \text{ m}^3/\text{h}$ of $12 \text{ }^\circ\text{C}$ cold air. This is usually supplied flow rate that corresponds to air change of $\sim 15 \text{ h}^{-1}$. The air is exhausted through pressure outlet with diameter of 20 cm located under the ceiling (Figure 1). Overpressure in the operating room against the exterior was 63 Pa. Room air temperature was set according to VDI 2167 [1] to $22 \text{ }^\circ\text{C}$.

Six cylinders – simplified dummies – simulated the heat flow produced by surgical staff. Arrangement of cylinders as well as their construction is in agreement with [1]. Total heat load of the cylinders was 800 W. Three types of light were turned on in the operating room. Six lights were integrated into the central part of the ceiling, four fluorescent tubes were attached on the side-walls and two surgical lamps were focused on the surgical table. Total internal heat load (i.e. incl. lights) was $\sim 1320 \text{ W}$. Heat load from other equipment e.g. monitors or machines of anesthesiologist were not considered in order to comply with the VDI [1]. The heat balance inside the room was affected by appreciable unsteady wall heat flux from outside environment that however was not directly measurable.

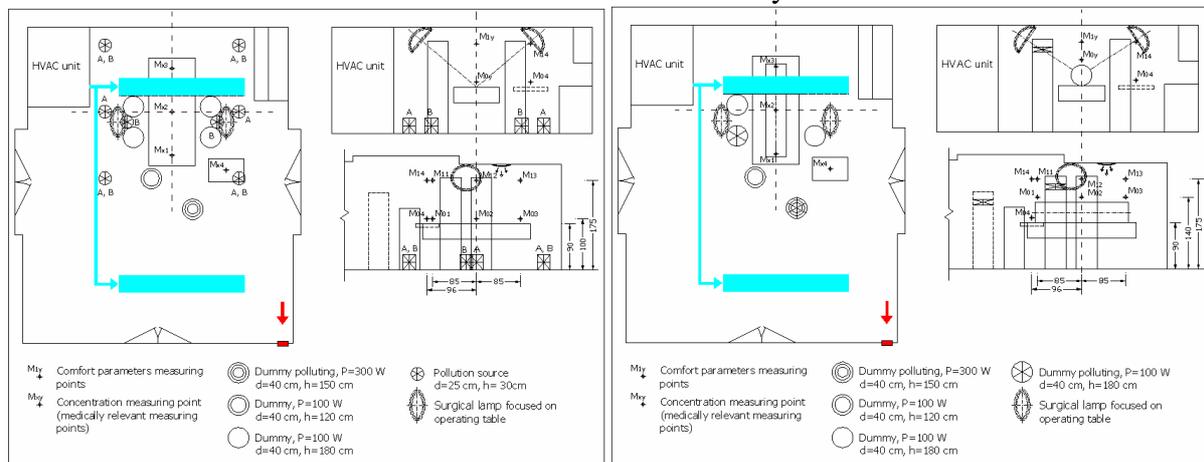


Figure 1. Experimental set-up 1: Protection against load entry from outside-A (in first step) and inside-B (in second step) (left) and set-up 2: protection against load entry from occupants (right); dimensions are in cm.

Experimental classification of the protective effect requires unspecified aerosol that should simulate source of contamination [1]. This unspecified aerosol was represented in our measurement by tracer gas SF_6 . Literature shows in rooms with high air exchange rates and sufficient turbulence the measurement results with fine aerosol are similar to those with trace gas [9, 11]. The tracer gas was evenly distributed into the six polluting cylinders (set-up 1 A/B) or into the evenly perforated tubes around the necks (set-up 2). Locations of the contamination source are depicted in Figure 1.

Measurement

The concentration measurements were performed under steady state conditions using a calibrated gas monitor based on photo-acoustic infrared detection method. The protection effect of the ventilation system was expressed in terms of SG index that represents local protection effect of air distribution system [1]. Index is defined as $SG_x = -\log(C_x/C_{ref})$, where C_x is the concentration at measuring point M_{xy} in mg/m^3 , C_{ref} – reference concentration in mg/m^3 that emulates the load of the operating room under test posed by a constant number of persons with constant emission of airborne contaminants including, e.g. germs. The supply air

was free of the used tracer gas. The least favorable of the local protection classes (the smallest numerical value) is used to characterize the actual protective effect of the operating room compared to the required protective effect against load entry from outside and inside.

Typical range of protective effect is from 5 (excellent) via 1 (very moderate) to 0 (no protective effect in sense of the dynamic screen). New operating rooms build in accordance with the guideline shall have a protective effect of 4 proven by measurements as it is convenient to make interdisciplinary use of these operating rooms. Carrying out both operations involving the implanting of extraneous material as well as operations on already contaminated areas in the same operating room is the current standard in many hospitals [1]. Older operating rooms where endoprosthetic operations of operations with a similar infection hazard are carried out require a protective effect of at least 2.

VDI 2167 requires to measure concentration of contamination at three points above the surgical table (M_{01} , M_{02} a M_{03} – Figure 1). In order to obtain more information on possible distribution of contamination three additional points were measured (M_{11} , M_{12} a M_{13}) and two points above the instrument table (M_{04} , M_{14}). This place often represents larger area (70 %) for bacterial sedimentation than the wound (30 %). Even though the instruments are exposed to a lower risk of contamination than the wound, they can result in significant contamination of the wound [2, 12, 13].

Comfort parameters (temperature, velocity and turbulence intensity – TU) were measured once during the particular set-ups using omnidirectional thermometers. Thermal comfort was evaluated above the surgical table at the height of heads of surgeons (M_{11} , M_{12} a M_{13} – Figure 1). Draft rate (DR) [14] was derived from the measured parameters automatically. In addition to mentioned measurements the surface temperatures of walls and equipment were taken by the contact thermometer to be in future work used to check the results of CFD experiments.

RESULTS

Classification of protection index SG

According VDI just the measurement points (M_{01} , M_{02} a M_{03} – Figure 1) are taken into consideration for classification of protection index. From the results presented in Figure 2 it is obvious that there were no substantial differences between set-up 1A and set-up 1B for these measured points. SG_x for set-up 1A was 2.2 and 2.1 for set-up 1B. Error bars drawn in the figure represent the min. and max. standard deviation of the calculated SG_x . This means the total protective effect of the air distribution system is 2.1.

If we look at the additional measured points above the surgical table (M_{11} , M_{12} a M_{13} – Figure 1) the values are somewhat lower (worse) but still within the class 2. The lowest values were measured at points M_{11} , M_{12} ($SG_x=2.0$). Generally, based on the measured data, the distribution of contamination above the surgical table was quite uniform. Since the results from above the instrument table were similar to the rest it could be claimed that the contamination (tracer gas) was evenly distributed over the critical areas and airflow had only moderate effect on protection of these sites.

When a dummy simulating the patient was placed on the surgical table and location of pollution source replaced to the necks (set-up 2) the local protective effect changed notably (Figure 2). The highest local protective effect was calculated for the location M_{13} ($SG_x=2.4$)

and M_{03} ($SG_x=2.3$). That was most likely because the place was screened out from the contamination released on the other side of the clean airflow from the diffuser (Figure 1). The lowest value was calculated at point M_{12} ($SG_x=1.8$). Polluted air from one of the surgeons is probably rising up towards the ceiling due to the temperature difference between the surgeon surface and room air. Supplied airflow causes the room air to entrain into it i.e. the contaminated flow from the polluting surgeon could reach the locations M_{11} and M_{12} . From the Figure 2 it is obvious the contamination distribution over the critical areas is much more uneven compared to the set-up 1. Nevertheless overall protection index for this air distribution system and set-up 2 (M_{01} , M_{02} a M_{03} - Figure 1) is equal to 2.

Results from the both the set-up 1 and set-up 2 showed the same overall results ($SG = 2$). Since the test was carried out on a new air distribution system its protection effect in regard to [1] was slightly moderate.

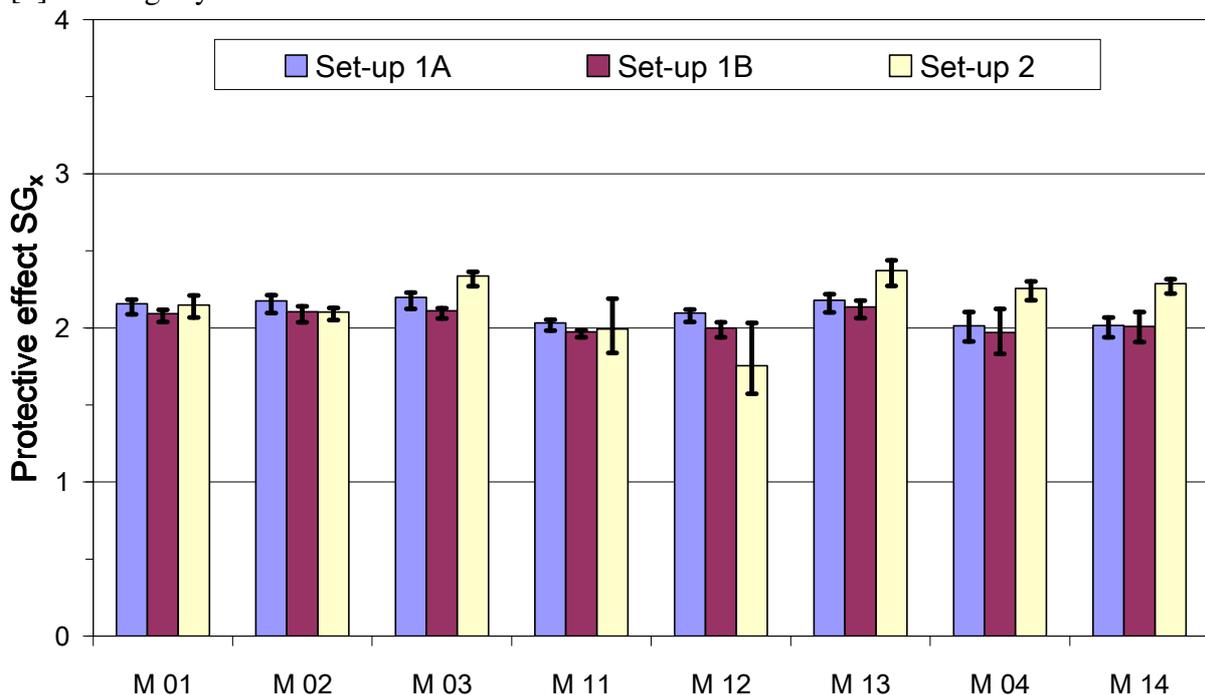


Figure 2. Local protective effect for set-up 1A and 1B and for set-up 2 at different measured points (see Figure 1). Error bars represent the min. and max. standard deviation of calculated SG_x index.

Thermal comfort

The supply and room air temperature changed due to the increased wall heat flux through the day. Therefore during the set-up 1 the supply air temperature was ~ 12.5 °C and 14.5 °C during the set-up 2. Thermal comfort measurements above the operating room at points (M_{11} , M_{12} a M_{13} – Figure 1) are summarized in the Table 1.

Even though the temperatures shifted by 6 K between the set-ups due to the lower cooling capacity of the air-conditioning unit, temperature differences between the particular measurement points were similar. There was 1 K difference between M_{11} and M_{13} . The temperature difference between the supply air temperature and the temperature at the points M_{12} and M_{13} was up to 8.5 to 13 K.

Table 1. Thermal comfort parameters above the surgical table for set-up 1 (left) and set-up 2 (right). t, v, TU, DR are temperature, velocity, turbulence intensity and draft rate of the air at particular point, and t_s is temperature of the supplied air.

	M ₁₁	M ₁₂	M ₁₃		M ₁₁	M ₁₂	M ₁₃
t [°C]	21.5	20.7	20.4	t [°C]	27.1	26.8	26.0
v [m/s]	0.07	0.06	0.19	v [m/s]	0.06	0.11	0.17
TU [%]	49	54	33	TU [%]	50	32	37
DR [%]	4	3	22	DR [%]	2	5	11
ts [°C]	12.0			ts [°C]	14.0		

Higher airflow rate or lower heat load would be necessary to achieve in this type of air distribution in order to achieve lower temperature difference. Moreover higher cooling capacity of air-conditioning would be necessary in order to control the room air temperature in required limits (i.e. ~ 22 °C). Air velocities were similar in both set-ups. The highest air velocity was measured at the point M₁₃ (up to 0.19 m/s). That was likely caused by declination of the supplied flow towards the side walls. Air in the rest of the points was rather stagnant i.e. ~ 0.06 m/s. The draft rate (depicted in Table 1) at all measured points was well within the standard requirements (20 %) with the slight exception of measurement point M₁₃ where the draft rate was ~ 22 %.

Temperature of the surfaces measured once between the set-ups were as follows: surgeon dummy 30.5 °C ± 1.4 K, nurse 41.1 °C ± 3.7 K, anesthesiologist 34.3 °C ± 2.0 K, top of the surgical lamp 39.4 °C and 50.7 °C at the bottom, ceiling temperature ~ 31 °C, floor temperature 27.5 °C, and sidewalls ~31 °C.

DISCUSSION

Protection effect of the air distribution system was analyzed according to the procedure of VDI 2167 [1]. Air supply was able to protect the critical areas against the load entry from outside a little bit better than against the load entry from inside. The difference is however rather insignificant across all the measured points. The flow from the supply diffuser was not efficient enough to flush the contaminants away from the measurement points representing critical areas above the table. Since the tested air-distribution system is rather new it should achieve higher value of SG than only 2.

Unlike the uniformity of measured concentrations in the set-up 1 the distribution of concentration was significantly affected by the changed location of the pollution source in set-up 2. However the overall protection effect remained the same i.e. 2. Thus even though the modification of the original VDI procedure [1] presented by the set-up 2 is more realistic it did not reveal (in assessed type of the air supply) different overall protection effect. However it more realistically describes the operating room environment and thus should represent more accurate results.

Thermal comfort measurements showed that in order to achieve preset room air temperature of 22 °C control of the air-conditioning unit had to decrease the supply air temperature down to 12 °C. This condition is particularly risky when anyone of the surgical team gets into the direct contact with this cold air at velocity ~ 0.2 m/s. Moreover if the cold air would reach the patient on the surgical table it could cause hypothermia of the patient and thus complications during and after the surgical operation [15, 16]. These results will be even more critical

particularly in case of deployment of mobile hospital (operating room) in much hotter climates than the assessed one.

Installed fabric diffusers have some advantages and disadvantages. Very positive is their height (~ 3 cm) that does not decrease the height of the ceiling and further if in any point occupants accidentally hit the diffuser it is soft and should not pose any injury. The disadvantage is often cleaning/changing of the diffuser and effective blinding at the end of the flat diffuser. Analysis on bacterial safety of these diffusers seems to be appropriate before they are used in practice.

Based on the presented results we recommend improving the air-conditioning system including the air distribution terminals in order to comply with higher standard as defined by protection effect [1]. The VDI procedure seems to be very useful however in regard to conducted measurement (set-up 2) change in terms of location of pollution sources are recommended. This could be particularly true when various (e.g. mixing, localized) air supply are used. Moreover internal heat load generated by always present equipment should be considered as well in the update of the VDI methodology.

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