A surgical site infection (SSI) occurred in 2.9% of all surgical operations in conventionally ventilated operating theatres (OT) in The Netherlands (PREZIES, 2012). A SSI is associated with a serious health risk of the patient and increased healthcare costs. Lidwell et al. (1982) found a significant positive correlation between the contamination of the air and the number of SSIs in OT. As a result, the effectiveness of unidirectional flow (UDF) ventilation systems have been studied increasingly and such a system was prescribed in Dutch guidelines. Although the system performs properly in an at rest situation, several studies showed concerns related to the position of the surgical light, limited space available for the operating team and instrument tables. Furthermore, clean air first passes the surgeon before reaching the wound, while research has shown that persons are the main source of bacteria in the OT.

Clean air in operating theatres is of major importance to reduce infection risk. This article describes the performance of a new solution for ventilation in operating theatres based on full-scale measurements. The main advantages are an optimized airflow pattern, from urgent to less urgent areas, higher comfort for the surgeons and lower energy consumption.

Keywords: Surgical site infection, air quality, relative particle concentration, operating theatre, hospital environment, personal ventilation, experiment, CFD.

Introduction

A surgical site infection (SSI) occurred in 2.9% of all surgical operations in conventionally ventilated operating theatres (OT) in The Netherlands (PREZIES, 2012). A SSI is associated with a serious health risk of the patient and increased healthcare costs. Lidwell et al. (1982) found a significant positive correlation between the contamination of the air and the number of SSIs in OT. As a result, the effectiveness of unidirectional flow (UDF) ventilation systems have been studied increasingly and such a system was prescribed in Dutch guidelines. Although the system performs properly in an at rest situation, several studies showed concerns related to the position of the surgical light, limited space available for the operating team and instrument tables. Furthermore, clean air first passes the surgeon before reaching the wound, while research has shown that persons are the main source of bacteria in the OT.
Contrary to the previous Dutch guideline, in 2014 a performance based guideline was introduced which offered the opportunity to develop alternative ventilation systems for the OT (WIP, 2014). Therefore, a new ventilation system is researched in this study which makes use of a reversed airflow direction, from critical to less critical areas. The clean air supply is released around the wound area from a blanket which is spread out over the patient’s body during the operation. Two configurations were designed: configuration 1 concerns a blanket where HEPA-filtered air is supplied around and parallel to the wound area (Figure 1a); configuration 2 makes use of HEPA-filtered air which is supplied from the top surface of the blanket, perpendicular to the wound area (Figure 1c). Similar approaches were applied to the instrument tables as well (Figure 1b and d). The performance of the local ventilation systems was studied in a full-scale experimental set-up. However, first a parameter study was applied in order to evaluate a wide range of situations.

Parameter study
A parameter study was performed on a simplified model, which represents the wound area of the patient and its immediate surrounding (Figure 2). Both particle measurements and computational fluid dynamics (CFD) simulations were performed to investigate the performance. Particles of size 0.5-0.7µm were measured in the center of the wound at 0.12m height (Figure 3). Next to this, Steady-state
RANS CFD simulations using a RSM model were performed on a replica of the experimental model. Contamination was modeled as a scalar.

The supply velocity and supply temperature of the clean airflow were the two most critical parameters. For the non-isothermal situation the supply temperature of the clean airflow was 22°C higher than the contaminated air in order to prevent hypothermia of the patient. For configuration 2 a supply temperature of 5°C lower than the contaminated airflow was considered to increase comfort for the surgeons.

Measurement results of configuration 1 showed that a higher supply velocity of the filtered airflow significantly reduced the particle concentrations, while a higher supply temperature significantly increased the particle concentration. No significant differences were observed for different velocities and temperatures of the filtered airflow regarding configuration 2. Furthermore, under isothermal conditions, comparison of configuration 1 and 2 showed no significant difference in the measured relative particle concentration at a supply velocity of 0.40m/s and 0.30m/s respectively. The smoke visualization and CFD simulations demonstrated that for both configurations a layer of clean air is created around the wound area.

Figure 4. Smoke visualization of the contaminated airflow in the measurement model under isothermal condition of configuration 1 (left) and configuration 2 (right). In both situations it is clear that the contaminated air is lifted over the wound area.

Figure 5. Concentration field of the relative particle concentration at section z = 0.4m for (a) configuration 1 and (b) configuration 2. Contaminated air velocity was 0.30m/s, HEPA-filtered air velocity was 0.10m/s.
the wound (Figure 4 and 5). In general, simulated particle concentrations showed similar trends as the measurement results although results were more positive compared to the measurements.

In conclusion, based on the results of the parameter study a supply velocity of 0.40m/s and 0.30m/s was used in the full-scale setup for configuration 1 and configuration 2 respectively. Furthermore, for configuration 1 the non-isothermal situation could not be neglected in the full-scale setup and was therefore taken into account as well.

**Full-scale study – method**

Next, the performance of a prototype of the local ventilation systems was explored in a full-scale mock-up OT at Interflow, illustrated by Figure 6. Particle measurements (≥0.5µm) were performed in

![Figure 6. Full-scale test setup of the ventilating blanket and instrument table of configuration 1 (left) and configuration 2 (right) in the mock-up of the OT, the blue arrows indicate the clean airflows.](image)

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<td>Configuration 2</td>
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*Table 1. Median (range) of the relative particle concentration [%] for particles ≥0.5µm (N=60). The topview at the right side shows location of the measurement positions.*
an at rest situation, without people, according to the Dutch guideline (VCCN RL7, 2014). There was no additional ventilation in the OT and the fans for the local ventilation devices were placed outside the OT. A relative particle concentration was derived by comparing the particle concentration in the middle of the wound area and at the table with a reference point in the contaminated periphery. Measurements were divided over two series to improve the reliability of the data. Furthermore, smoke tests were conducted to visualize the airflows.

**Full-scale study – results and discussion**

The results of the full-scale measurements are demonstrated by Table 1. Regarding the ventilated blanket, a significant difference was observed between the two measurement series of the same configuration. The differences were probably caused by imperfections of the hand-made prototypes. Smoke tests showed that for configuration 1 turbulent air was supplied from the long side of the blanket, while a more constant airflow was supplied from the short side (Figure 7, left and middle). Regarding configuration 2, entrapment of contaminants in a local eddy above the wound area caused a high range of relative particle concentrations (Figure 7, right). Summarizing, configuration 1 yielded significant lower relative particle concentrations in the wound area than configuration 2. However, a relative particle concentration of 0.1%, as required by the WIP (2014), was not met for both configurations.

The instrument tables of both configurations demonstrated more uniform results compared to the ventilated blankets. The instrument table of configuration 2 satisfied the Dutch standard, while the instrument table of configuration 1 demonstrated significantly higher relative particle concentrations.

**Future applications**

According to the Dutch guideline the full-scale measurements showed that only the ventilated instrument table of configuration 2 was sufficient. For this reason, this could be a promising solution for application in OTs, for instance as an addition to the vertical UDF system to enlarge the clean area. Although results of the other ventilation devices did not satisfy the guideline, they might be used as an addition to OTs with a mixed ventilation system to improve the air quality at wound level and around the instruments. Furthermore, the local ventilation devices might be applied outside the OT where in that case operations can occur more safely (i.e. during field operations, operations in treatment rooms).

**References**


WIP (2014) Luchtbehandeling in operatiekamer en opdekruimte in operatieafdeling klasse 1. Werkgroep Infectie Preventie (WIP)