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A MATHEMATICAL MODEL TO PREDICT AIR QUALITY IN OPERATING THEATRES.

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Acceptable exposure to indoor air contaminants is often achieved by ventilation stategies. A mathematical model, incorporating ventilation, recirculation and (sources of) immission was developed to describe exposure to volatile anaesthetics in operating rooms. Several workplace surveys were used to design the model, feed it with reliable immission data and to validate its predictions. Our results show that this model might be a powerful tool for the design and modification of ventilation systems in operating rooms and other workplaces.

INTRODUCTION

Ventilation strategies are often designed to maintain acceptable carbon dioxide levels (offices, public buildings), to achieve certain climate conditions (computer rooms), or to prevent dissolution of locally emitted compounds.
In a hospitals' operating room, a high air change rate (> 15 hr^{-1}) is applied to maintain the patients' sterile environment (laminar flow principle). Normally, under these conditions chemical air contaminants (e.g nitrous oxide) are rapidly cleared. However, to reduce energy costs (heating/cooling, humidification) ventilated air is often partially recirculated. This causes a rebound of gaseous aircontaminants and therefore higher concentrations. Insight in this immission-ventilation-recirculation process is crucial to efficiently achieve or maintain acceptable levels of gaseous aircontaminants [1,2,3,4].

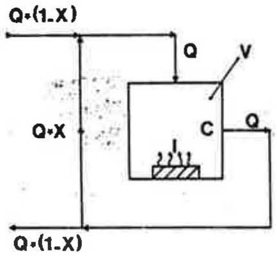
Recently we performed a workplace study in our university hospital [5]. Nitrous oxide levels were measured in several operating rooms (OR) as a function of work activities, (local) ventilation, equipment specifications and percentage of recirculation. The data were used to construct a mathematical model to describe and predict nitrous oxide levels under various conditions.

METHODS

Measurements were carried out in the University hospital of Maastricht, the Netherlands. The operating room complex consists of 10 operating rooms and one recovery room. In all operating rooms a scavenging system was available.
All OR's and recovery are connected to the same aircondioning unit which acts seperately from the rest of the hospital. The OR's are ventilated by the laminar flow principle; air is supplied through a plenum above the operating table and removed through grates in one of the side walls (air change rate 17 hr^{-1}). The percentage of recirculated air varies from 0-70 %.

Mathematically, the amount of nitrous oxide (A) that enters the OR per unit of time (dA/dt) can be described as the difference between total immission (I) plus recirculated amount and the amount which is eliminated by ventilation:

$$\frac{dA}{dt} = (I + X * Q \times C) - Q * C \qquad (1)$$



in which:
A = the amount of N_2O (mg)
Q = air flow in and out the OR (m^3/hr)
I = immission (mg/hr)
X = fraction of the ventilated air, which is recirculated
C = concentration of N_2O in the air, assuming a well-stirred model

If we substitute A = V·C (V = the distribution volume= volume OR) then,

$$\frac{V \cdot dc}{dt} = I - QC\ (1 - X) \qquad (2)$$

Equation (2) is the basis of the simulation model that was incorporated into a PC using the TUTSIM-program (Technical University Twente, The Netherlands).
The model, however, is based on several assumptions:
- constant immission and constant recirculation;
- distribution of immitted N_2O is instantaneous and complete over the entire OR (well-stirred model [6]).

Nitrous oxide (N_2O) levels were measured continuously and detailed workplace observations were done during 18 days in 3 different operating rooms. Pilot experiments showed that N_2O-levels were highly place dependent. Therefore a specific environmental monitoring strategy was used:
- The OR was subdivided into 3 different areas (zones),
  1:Area outside the plenum near the exhaust grids.
  2:Area outside the plenum, close to the ventilator.
  3:Area underneath the plenum.
  Additional measurements were carried in the supplied air to detemine the N_2O concentration at the air inlet (zone 4). The concentration measured in zone 1 was regarded to be similar to that leaving the OR (well-mixed)
- Zone-concentrations of N_2O were determined during a number of complete operating programmes, during which the anaesthetic handling was carefully recorded.
- Ventilation and recirculation were measured during the whole study period.

RESULTS

In Table 1 the nitrous oxide concentrations measured in the different zones are listed. Average recirculation during measurements was 20 %. Data are corrected for the time distribution of an average surgical program.

Table 1:Mean time weighed concentrations of nitrous oxide in the zones of the operating rooms during use.

Zone	N_2O-conc. (ppm)	Days of measurement	N_2O-conc (ppm)
1 (well mixed air)	41.2	8	43.9
2	99.6	6	81.3
3	32.6	4	36.5
4 rebound a)	8.2		

a) Background concentration caused by the partial recirculation of the exhausted air.

The simulation model was used to calculate the total immision of nitrous oxide for the conditions met with in the workplace study (volume OR=120 m^3, airchange rate = 17 hr^{-1} and 20 % recirculated air). To obtain total immission an N_2O-concentration of 43.9 ppm (zone 1, well mixed air) was substituted; total immission under these workplace conditions is then 132 gr/hr (73.2 liter/hr), which is about 24 % of the total N_2O supply (310 liter/hr) during surgical programs. The simulated N_2O concentration at the air inlet (plenum) under these conditions is then 8.8 ppm. This is the same as the concentration measured in zone 4.

Using the observations during our workplace survey we calculated the contribution of each source to total N_2O immission (Table 2). Based on our findings and calculations, we proposed several measures to reduce N_2O immission to the hospital management. It was calculated that a reduction of 58 % of the immission could be achieved by technical improvements of the anaesthetic equipment and consistent use of caps with suction.

Table 2: Duration, concentration and contribution to N_2O-immission of the different anaesthetic activities for zone 1 during an "average" surgical program (derived from measurements and observations of 18 surgical programs).

Activity/source	Time (%)	N_2O conc. (TWA in ppm)	Contribution to total N_2O-immission (%)
- Artificial respiration (Tube with scavenging)	48.9	56.4	66.2
- Spontaneous respiration (Tube with scavenging)	17.0	27.3	11.1
- Spontaneous respiration (Mask with scavenging)	6.0	29.3	4.2
- Spontaneous respiration (Mask without scavenging)	1.9	219.9	9.5
- Patients during in- and extubation and transport	16.9	22.2	9.0
- Rebound plenum*	9.3	8.2	---*

*Rebound immission is already incorporated in the listed values.

Using our model, the effect of the proposed N_2O reducing measures (58 % of immission) on mean environmental N_2O concentration (volume OR=120 M^3, Air-change rate 17 hr^{-1} and 20 % recirculation) was simulated. Under these conditions nitrous oxide concentration for zone 1 (well mixed air) was predicted to be 25.9 ppm and the inlet concentration would be 5.0 ppm.

One year after the first study and 6 months after these (proposed) measures became common practice measurements were repeated. Nitrous oxide levels were assessed in zone 1 and 2 and in the air-inlet. During the latter period the average percentage recirculation was about 10 %.
After intervention the mean N_2O concentration in zone 1 was 20.4 ppm (Cout) and 12.3 ppm was detected at the air inlet (Cin). To compare these data with the predicted data we adjusted these values for differences in anaesthetic activities and corrected the simulated data for the difference in recirculation. Simulated N_2O concentration for zone 1 is about the same as the actual concentration (22.5 ppm resp. 21.4 ppm)

EXTENDED RESULTS

One of the benefits of modelling is that it can be used to predict and study (exposure) effects of altered conditions, e.g. recirculation, ventilation, immission ect. Two examples are described in this section:

a. The effect of recirculation on mean environmental exposure was simulated at two different immissions of N_2O. The results are illustratedin figure 2a. At the highest immission (132 gr/hr, original situation in the OR) mean exposure exceeds the TLV (25 ppm), even when 100 % fresh air is supplied (no recirculation). At lower immission (76 gr/hr, situation after intervention) the TLV will be exceeded only when more than 20 % of exhausted air is recirculated.
Moreover the effect of different airchange rates on environmental exposure to N_2O were simulated for the lower immission. The results are illustrated in figure 2b.

b. The simulation model can be used to calculate nitrous oxide levels for other (hospital) workplaces. However this requires detailed knowledge about N_2O sources of that particular workplace. We choose an OR of an outpatient clinic. Since we had no data, the presented data of the OR's in this study were used to get a rough estimation of nitrous oxide levels for an operating room in the outpatient clinic of our hospital. In these operating rooms predominantly small operations (e.g. tonsilectomy) are carried out. During most of these operations patients are breathing spontaneously and no scavening is applied. Nearly always masks (without scavenging) are used.
Total immission was simulated for a surgical program in wich :
   - 35 % of the program is spent to surgery; patients breathing spontaneously using masks
   - 35 % of the program is spent to in/ex tubation and patients transport.
   - 30 % of the program no anaesthetic activities take place.

During such program total N_2O immission would be 61.5 gr/hr (with scavenging) and 261.2 gr/hr (without scavenging). When this surgical program would be carried out in the OR of an outpatient clinic (Volume=56 m^3, airchange-rate=17 hr^{-1}, no recirculation) the mean N_2O concentration would be 35 ppm (with scavenging) and 149 ppm without scavenging.

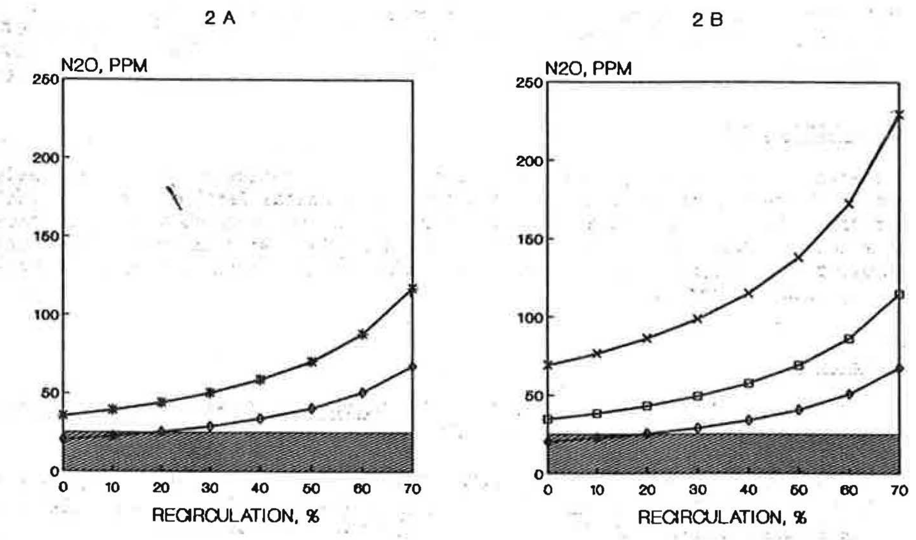


Figure 2

a) Effect of recirculation of ventilated air on the mean concentration of N_2O in zone 1 at different immissions. The symbol ◊ depicts an N_2O-immission of 76 gr/hr, ✱ depicts an immission of 132 gr/hr.

b) Effect of recirculation of ventilated air on the mean concentration of N_2O (zone 1) in an OR after intervention at different airchange rates. The symbols depict airchange rates of 17 hr^{-1} (◊), 10 hr^{-1} (□) and 5 hr^{-1} (×).

The shaded area indicates when compliance with the TLV (25 ppm) is attained.

DISCUSSION

The model described in this paper is based on several assumptions. One of these assumptions is that the distribution of immitted N_2O is instantaneous and complete over the entire OR (well-stirred model). Because of the laminar flow this assumption is certainly not valid; we therefore used the concentration of air leaving the OR (which is similar to that in zone 1) as the model 'well mixed air' concentration.

One of the great benefits of this model is that the efficiency of certain N_2O reducing measures can be predicted (calculated). For example, simulation revealed that under the original conditions met with in our workplace study, exposure to N_2O would still exceed the TLV even when 100 % fresh air (no recirculation) is supplied. Therefore we recommended measures to reduce total immission.

Moreover, the exposure measured after intervention was similar to the predicted level.

We showed how the model can be applied to other (hospital-based) workplaces. Total immission for a particular workplace can be calculated when N_2O concentrations and percentage recirculation are known. When this information is lacking the data presented in this paper can be used to get a rough estimation of the total immission. As most indoor air problems are related to CO_2 levels, and the latter immission is easily estimated, this approach will not meet serious impedements to apply our model to other workplaces.

With respect to the hospital setting our model is a powerful tool to:
- design of ventilation systems in operating rooms and recovery's.
- Check the effects of N_2O reducing measures.

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