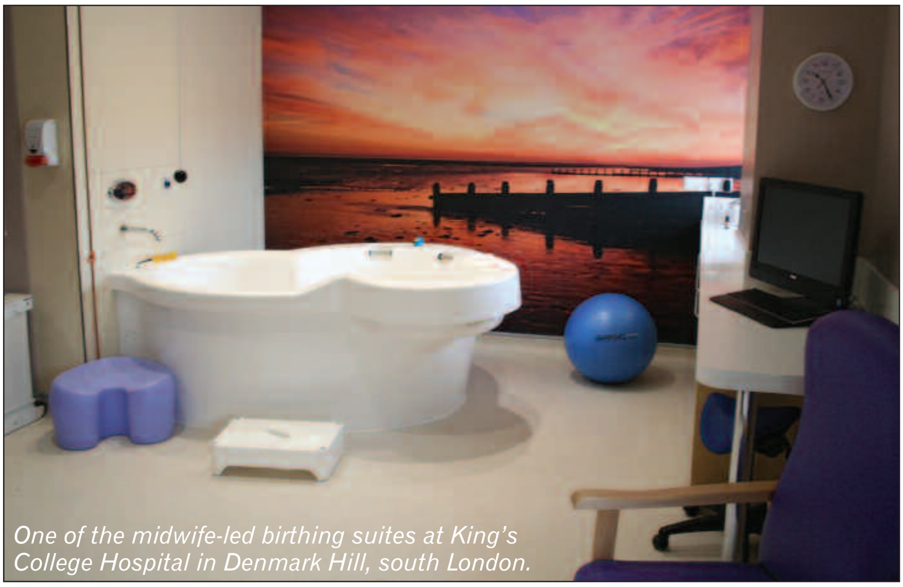
Priorities for birthing rooms set out

Phil Nedin, a Chartered Engineer, Fellow of IHEEM, and Past President of the Institute, who, recently left Arup – having worked for the company for 25 years – to set up his own consultancy, and Anna Coppel, a Chartered Engineer based in Arup's Advanced Technology and Research team in London, describe a design analysis that used computational fluid dynamics (CFD) to investigate and validate the effectiveness of a number of mechanical ventilation options often associated with birthing rooms, thereby ensuring a system that is fit for purpose. In such settings, they point out, the need to reduce the levels of nitrous oxide to a COSHH threshold is a legal requirement.

Engineers experienced in the design of hospital systems will express the view that there is a level of technical design complexity that surpasses that found in many other industry sectors. One such complexity is the design of mechanical ventilation systems. Specialist areas such as operating theatres, intensive therapy, and high dependency units, as well as isolation rooms, all have their specific ventilation needs, shaped by the clinical activity. The supporting parameters, such as filtration standards, air pressure regimes, flow characteristics, temperature, humidity, and volume flow rates, associated with specific numbers of air changes, are usually well defined through relevant Health Technical Memorandum (HTM) and Health Building Note (HBN) guidance.

One such space where a mechanical ventilation system is essential is in the birthing room of a maternity department. Design guidance related to this area has been updated over the years. However, this particular room is one of only a few in hospitals outlined below where there is a legal requirement to contain gas levels to within specific limits. This design analysis introduces the use of computational fluid dynamics (CFD) analysis to investigate and validate the effectiveness of a number of mechanical ventilation options often associated with a birthing room.



One of the midwife-led birthing suites at King's College Hospital in Denmark Hill, south London.

Courtesy of the King's College Hospital NHS Foundation Trust

Legal requirement

The critical ventilation requirement in a birthing room is the removal of the nitrous oxide gas, which is used as part of a 50:50 mixture with oxygen, on demand by the mother, to reduce the pain associated with child birth. The nitrous oxide (N_2O) has a specific threshold level within the COSHH Regulations (currently 100 ppm over an eight-hour period).[1] The COSHH Regulations are, of course, a legislative requirement, where the responsibility to satisfy the regulations is with the hospita'sl operational management. How this is monitored is not well documented in the design guidance. However, the impact of the COSHH Regulations on designers' responsibilities in this particular scenario is clearly defined – Schedule 2A of the COSHH Regulations 2002 Approved Code of Practice and Guidance at Regulation 7(7) specifies that the designer should 'design and operate processes and activities to minimise emissions, release and spread of substances hazardous to health'. Hence the designer has a responsibility to design a system that allows the facility to be safely operated.

Design guidance – past and present

There are five major guidance notes that usefully support the birthing room ventilation design process. We have considered these references in this design analysis. Although some have been superseded, many birthing rooms currently in operation will have been designed using the earlier guidance. It must be stressed that, when the original guidance was produced, there was little or no use of CFD in the industry, and this analysis is in no way a critical appraisal of the current or past guidance, but rather a review of the design options that are possible. It also sought to identify whether

Table 1: CFD-modelled mechanical ventilation options.

Extract location	Supply type	Air change rate	Extract face velocity (m/s)	Patient location
Gas terminal level	Passive supply through door	7.5	3.0	Head of bed
		7.5	0.5	Head of bed
		7.5	5.0	Head of bed
		10.0	3.0	Head of bed
		10.0	3.0	Middle of bed
		15.0	3.0	Head of bed
		15.0	0.5	Head of bed
	4-way ceiling diffuser	7.5	3.0	Head of bed
		10.0	3.0	Head of bed
		15.0	3.0	Head of bed
High level in ceiling	Passive supply through door	7.5	3.0	Head of bed
		7.5	3.0	Middle of bed
		10.0	3.0	Head of bed
		10.0	3.0	Middle of bed
		15.0	3.0	Head of bed
	4-way ceiling diffuser	7.5	3.0	Head of bed
		10.0	3.0	Head of bed
		10.0	0.5	Head of bed
		15.0	3.0	Head of bed
Skirting level	Passive supply through door	7.5	3.0	Head of bed
	4-way ceiling diffuser	7.5	3.0	Head of bed
50% high level in ceiling, 50% gas terminal level	Passive supply through door	7.5	3.0	Head of bed
		10.0	3.0	Head of bed
		15.0	3.0	Head of bed
		7.5	3.0	Middle of bed
		10.0	3.0	Middle of bed
		15.0	3.0	Middle of bed

the original air changes rate quoted in earlier guidance can still satisfy the requirements of the COSHH Regulations. The guidance notes are:

- Health Technical Memorandum 2025 (Crown Copyright 1994) – Ventilation in Healthcare Premises.[2]
- Health Technical Memorandum 03-01 (Crown Copyright 2007) – Specialised Ventilation for Healthcare Premises.[3] This HTM superseded HTM 2025.
- Health Building Note 21 – Maternity Department (Crown Copyright 1996).[4]
- Health Building Note 09-02 (Crown Copyright 2008) – Maternity Care Facilities.[5] This HBN superseded HBN 21.
- Health Technical Memorandum 02-01 (Crown Copyright May 2006) Medical Gas Pipeline Systems.[6]

Common design logic within superseded and current design guidance

There is a consistency in the past and present design guidance as follows:

1. There is a recognition that COSHH Regulations apply, and there is a defined threshold,
2. The air change rates quoted are between 10 and 15/hour. The increase was made in 2007 with the issue of HTM 03-01.
3. There is a recognition that 'local exhaust ventilation' (LEV) should be considered as part of the ventilation design strategy.

There are a few areas where clarification may be required:

1. The nitrous oxide is used as part of a 50:50 nitrous oxide/oxygen mix with the trade name of Entonox, which is used as an analgesic. This gas mix has an approximate density of 1.6 kg/m^3 at 15°C, which, for the sake of a ventilation system, can be considered close to air (1.2 kg/m^3 at 15°C). There is a significant difference in density of Entonox when compared with the anaesthetic gases found in operating theatres and recovery rooms, where the density of these gases can be greater than 8 kg/m^3. The density of the gas is important, as it will have an effect on the direction the exhaled gas could take when it enters the space, and this, in turn, will inform the effective position of the extract grille.
2. The terms 'LEV' and 'dilution' ventilation are used throughout the guidance, and could be confused, since they suggest a different approach to ventilation system design. Where the LEV approach looks to remove the contamination at source through appropriate extraction, the dilution approach mixes the contaminant within the bulk air, and removes it over time.
3. In HTM 03-01, under the heading of 'Removal and dilution of waste anaesthetic gases', Clause 7.20 states the need for the extract grille position to 'extract at low level, adjacent to anaesthetic-gas terminal units'. Clause 7.21 states specifically for birthing rooms the need for the extract grille position to 'extract at low level'. This may suggest to some that there are two positions for an extract grille – one at low level adjacent to the gas terminal outlets, and the other at low level (could assume at skirting level).

Purpose of the study

The purpose of this design study is to try to consider the optimum birthing room ventilation system arrangement, which, as a minimum, supports the operational aims of the facility to comply with the COSHH Regulations, by ensuring that the nitrous oxide levels within the birthing room space are within the threshold levels of 100 ppm.[7] In attempting to do this we have used our design, site testing, and our computer modelling experience, to create a series of computational fluid dynamics (CFD) models. Three basic questions of the ventilation system are considered:

1. What is the impact of the positions of the supply diffuser and extract grille?
2. What is the most effective ventilation strategy, dilution or LEV, or an alternative?

3 What is the optimum air change rate?

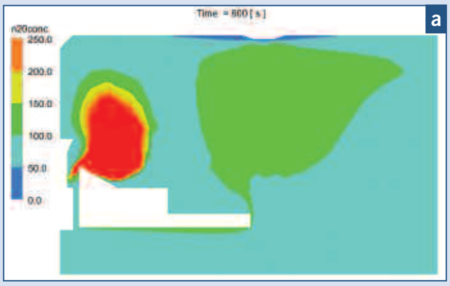
The CFD models were constructed to simulate three extract grille positions (Layout 1: skirting level; Layout 2: Gas terminal level; Layout 3: High level in the ceiling). There are two supply air inlet conditions – an active four-way diffuser in the room, and more passive transfer of air into the room. This passive air supply can be provided in a number of ways providing that the air is introduced at low velocity with no disruption to the extract system authority. We have applied three rates of air change to each condition – 7.5, 10, and 15 air changes/hour, and have considered three extract grille face velocities – 0.5 m/s, 3 m/s, and 5 m/s. The supply and extract air quantities are balanced for all conditions. Table 1 sets out the specific options that were modelled. A number of the options are presented in this analysis, and for consistency the heat loads included within the calculations involved the patient, the electrical medical equipment at the bedside, and the lighting.

Perhaps the biggest challenge to finding an optimum design solution to the ventilation in a birthing room is the quantity of analgesic gas that a patient uses during her personal delivery experience. This is undefined, and is accepted as being 'on-demand'. We have, however, assumed, for the benefit of the model, that 10 litres of Entonox will be inhaled and exhaled over a 10 minute period (1 L/min). This equates to 0.5 L /min of nitrous oxide.

Figure 1: System comparisons with two different supply air characteristics.

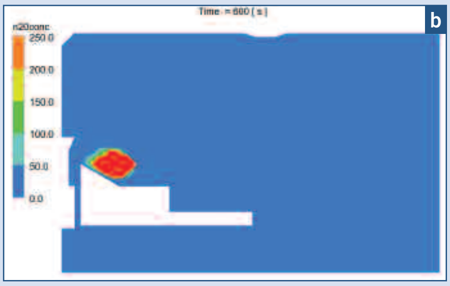
Air change rate	15.0
Supply type	Ceiling supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

Currently a solution showing general contamination within the room due to the vigorous mixing effect due to the supply air input.



Air change rate	15.0
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

Excellent result, with the only change being the introduction of a passive supply air input into the room to enable the extract system to operate with authority.



It should be noted that the COSHH Regulations stipulate a time-weighted average exposure over eight hours. However, it is not uncommon for staff in this department to move from one room to another, and hence be subjected to the gas for a large proportion of the working day.[1] In the absence of staff personal monitoring data, we need to design the most effective ventilation system for this room.

Ventilation system characteristics and results of CFD models

The graphical representations shown in this section represent a snapshot of the concentration of nitrous oxide within the room after a 10-minute period. The cooler colours (blue) indicate a lower concentration, and the warmer colours (green to red) a higher concentration.

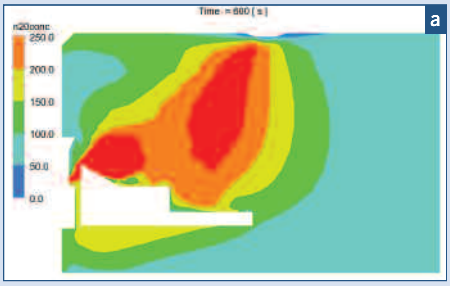
Figure 1 illustrates the output from two models, each with a supply and extract air change rate of 15 per hour, and extract grille positioned at the gas terminal level behind the bed and an extract grille face velocity of 3 m/s. The examples shown however have different supply air characteristics. Figure 1a has an 'active' supply air input from a four-way ceiling-mounted diffuser, providing a higher supply velocity, which encourages dilution through mixing, and Figure 1b a 'passive' supply air input with a lower velocity input, encouraging an LEV-based approach. We can see that the general level of gas after 10 minutes (modelled average Nitrous Oxide level in the room) is significantly higher in the dilution design than the LEV design. The velocity of the supply air appears to be a key factor on the disturbance of the air within the space. This disturbance appears to reduce the operational effectiveness of the extract grille to impose itself on the overall system, and to reduce the gas concentration at source, thus limiting the role of the LEV.

We can see from the graphics in Figure 1 that a 'passive' supply air input is a preferred solution to reduce the mixing of the gas within the room, and that an extract grille face velocity of 3 m/s has a

Figure 2: System comparisons with a reduced air change rate (10/hr).

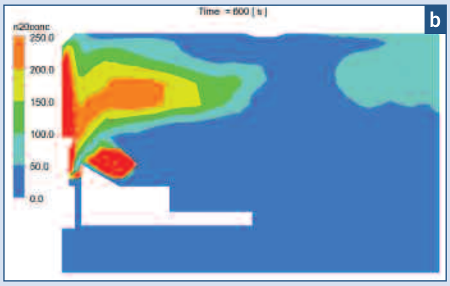
Air change rate	10.0
Supply type	Ceiling supply
Extract face velocity	3.0 m / s
Extract location	Gas terminal level

The ceiling supply vigorously mixes the air and creates levels of contamination.
The lower air change rate allows higher levels of contamination to build up.



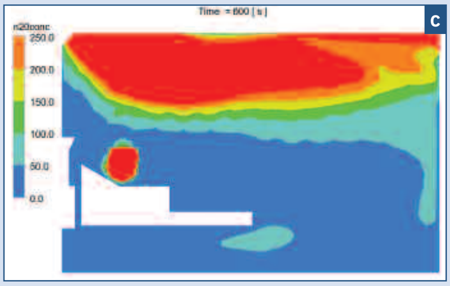
Air change rate	10.0
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

The introduction of a passive air supply into the room and a lower air change rate (10) allow a displacement system to begin to operate. The heavier contamination appears to be outside the working zone.



Air change rate	10.0
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Ceiling level

Introducing a ceiling extract removes the LEV effect, and the number of air changes (10) appears to disrupt the displacement effect.



greater operational authority, supporting an LEV-type solution which removes an amount of the exhaled gas at source.

We also modelled the cases with a reduced supply and extract air change rate of 10 per hour (Figs. 2a & 2b). There are a number of reasons for considering a reduced air change rate, including:

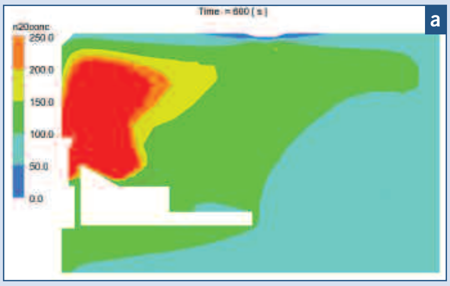
- Many birthing rooms currently in operation would have been designed to this level of ventilation due to the previous generation of guidance (HTM 2025 and HBN 21);
- Creating a passive supply air path that provides 15 air changes per hour into a standard birthing room may be practically challenging;
- The COSHH threshold for nitrous oxide is 100 ppm, whereas the threshold level for commonly used anaesthetic gases is around 50 ppm. However HTM 03-01 quotes the same number of air changes for birthing rooms and recovery rooms.

We can see that the 10 air changes per hour works well with a 'passive' supply characteristic (Fig. 2b), but again the contamination level increases when the supply air input provides a greater level of mixing due to the action of the ceiling supply (Fig. 2a). Figure 2c shows that introducing a ceiling extract removes the LEV effect, and the number of air changes (10) appears to disrupt the displacement effect. However, it does appear to be an improvement on the model illustrated in Figure 2a.

Figure 3: System comparisons with a reduced air change rate (7.5/hr) and an alternative extract grille position.

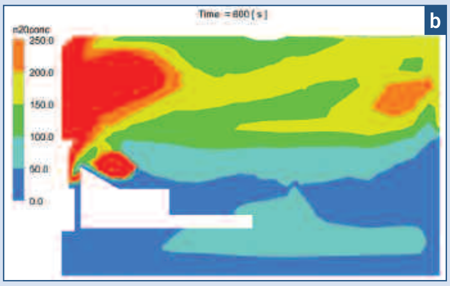
Air change rate	7.5
Supply type	Ceiling supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

In reducing the air change rate (7.5), the supply air mixing creates a high contamination level, and the displacement effect is lost.



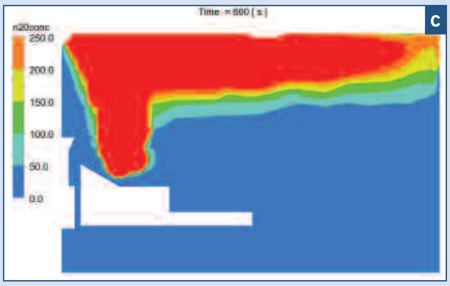
Air change rate	7.5
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

The introduction of a passive supply slightly reduces the contamination level as the displacement process begins. The higher contamination level is, however, within the working area.



Air change rate	7.5
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	High level in the ceiling

An extract grille position at ceiling level allows a thermal plume to function, and the passive supply unit creates displacement, moving contamination out of the working area.



Continuing the logic

Continuing the logic of reducing the air changes, Figure 3 shows how the system operates with 7.5 air changes per hour. This would reduce the current preferred air change rate by 50%, and make a significant energy saving. Here we can clearly see the mechanisms of the dilution approach (Figure 3a), and an LEV/displacement approach emerging from the analysis shown in Figure 3b.

Continuing to explore the displacement approach, where we use the thermal plume created by the patient to create positive air movement to high level, we analysed the impact of placing an extract grille at high level in the ceiling (Figure 3c). The stratification created by the displacement approach allows the contaminants to move to high level in the room.

The ceiling-mounted extract grille at high level in the ceiling reduces the challenges of co-ordinating an extract grille with the bedhead trunking system, moving any air noise generated by the extract grille face velocity from an area adjacent to the patient's head. It also acknowledges that the analgesic gas being used has a density close to that of the bulk air, and may rise on the thermal plume created by the patient. Hence at low air change rates the buoyancy force is stronger than the momentum force. What it does not do is to behave in any way as a LEV system, and hence there is no removal of a quantity of gas at source. Clearly, the more we look to reduce the number of air changes, the more we have to be specific about the design solution, and its ability to perform effectively.

Additional modelling considerations

There are a number of other questions associated with the CFD models to be considered. The first is what is the implication of reducing the extract grille face velocity, as this parameter is not explicitly considered in the guidance, but is implicitly referred to when the use of LEV is mentioned (Fig. 4)? The second is whether there is an operational benefit in installing the extract grille at skirting level (Fig. 5). The third is the effectiveness of the ventilation system when the patient moves from the normal position on the bed, to the middle of the bed (Figs. 6a & 6b).

When comparing the graphic representation shown in Figure 4 with the model illustrated in Figure 3b, we can see a real improvement in the operational effectiveness of Figure 3b. This shows that a higher extract grille face velocity enhances the operational effectiveness of the system. This comparison of operational effectiveness was tested in all volume flow rate conditions, and there was a consistency of results.

Figure 5 indicates that the operational effectiveness is reduced when the extract grille is placed at skirting level when compared with a grille positioned at gas terminal level. In this scenario neither an LEV, nor a displacement approach, is achieved, and the 7.5 air changes/hour are not enough to provide effective dilution.

The analysis so far has concentrated on a patient remaining in a normal position on the bed. However this may not be the case in practice, with the patient moving towards the middle of the bed. For the purposes of this analysis we have assumed that the patient movement is constrained by the length of the gas tube. Figure 6 shows the contamination levels for three cases. The difference in cases 6a and 6b involve the position of the extract grille from gas terminal position to high level in the ceiling, while 6c illustrates a reduced number of air changes, with an extract grille at high level in the ceiling reflecting a displacement design appproach.

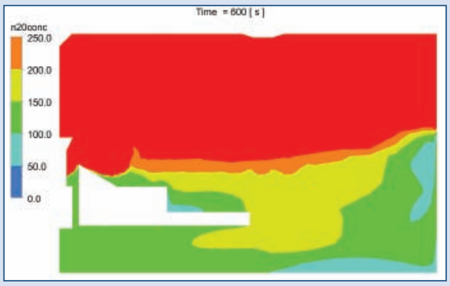
Discussion

We have assumed that the patient uses the gas 'on demand'. As far as we know the gas use over time per patient is not

Figure 4: The effect of reducing the extract grille face velocity.

Air change rate	7.5
Supply type	Passive supply
Extract face velocity	0.5 m/s
Extract location	Gas terminal level

Reducing the face velocity of the grille creates an unsatisfactory solution, even though there is a passive supply. Displacement is occurring, but general contamination is high.



monitored or recorded. We can extrapolate the gas use and re-apply that to the models that we have developed to show the maximum gas input that can be maintained below the COSHH threshold for each of the given ventilation arrangements. Importantly, however, there needs to be further work done to monitor accurately the gas use in a birthing room, as this is key data that currently is being assumed, and may be leading to an unnecessary number of air changes.

Opening a window

A further consideration is the impact of opening a window in the birthing room, and allowing the incoming air to disturb the influence of the extract grille. This may happen even with a higher face velocity and an LEV system, but it is extremely difficult to model with any certainty. This should be the subject of further studies, and indeed if it is found that the operational effectiveness is reduced to an unacceptable level if and when a window is opened, then consideration should be given to a birthing room being an air-conditioned space with non-openable windows. Although not a preferred solution, given the legal requirements of the COSHH Regulations, there may be no other option, and it will remove any ambiguity in the design solutions.

Conclusions

- There can be ambiguity in the design of the birthing room ventilation system. This analysis shows three possible design approaches – LEV, displacement, and mixing/dilution. The second approach can be successfully achieved with a lower air change rate.
- The extract system is the key to the operational effectiveness of the overall system. In order for the extract system to impose its authority on the gas levels,

Figure 5: Extract grille positioned at skirting level on the bedhead wall.

Air change rate	7.5
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Skirting level

Placing the extract grille at skirting level creates a high level of contamination, even though there is a low air change rate, passive supply, and a high extract grille face velocity. The thermal plume counteracts the authority of the extract system.

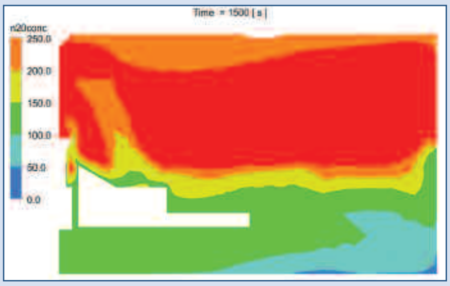
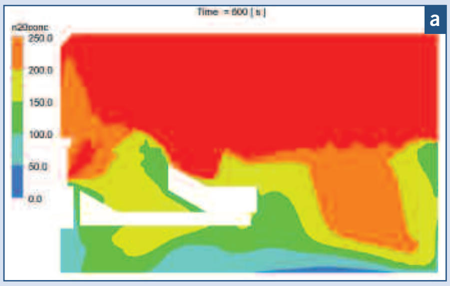


Figure 6: Example of change to concentration levels when a patient moves toward the centre of the bed.

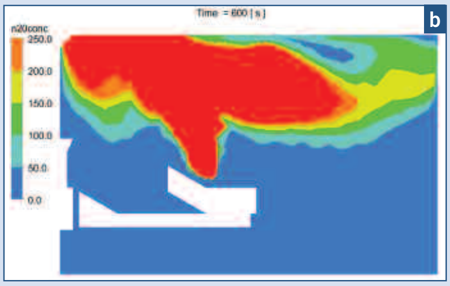
Air change rate	10.0
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	Gas terminal level

Checking the sensitivity of the model to changes in patient position shows a low contamination level in the lower part of the room, but a higher level in the working area (head height).



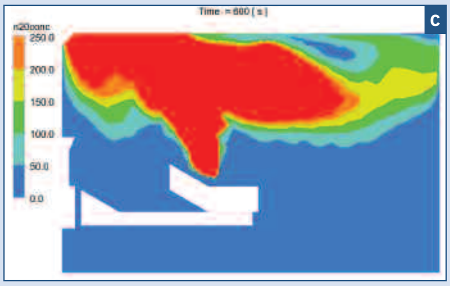
Air change rate	10.0
Supply type	Passive supply
Extract face velocity	3.0 m/s
Extract location	High level in ceiling

Changing the position of the extract grille to ceiling level creates a much reduced contamination level around the patient. This is created by the thermal plume buoyancy forces driven by the patient.



Air change rate	7.5
Supply type	Passive supply
Extract face velocity	3.0 m / s
Extract location	High level in ceiling

Reducing the air change rate maintains a displacement system with what appears to be a reduced contamination level.



an extract grille face velocity of not less than 3 m/s is preferred.

- For the LEV system to work in any acceptable way, an extract grille must be placed behind the patient at gas terminal level.
- For the extract system to impose its authority on the system as a whole, it is important that the supply air make-up is introduced into the room at a low velocity, and does not create an aggressive mixing characteristic.
- The LEV system works well with 15 air changes per hour of supply and extract air, providing that there is a passive supply air input created.
- Fifteen air changes per hour is a significant amount of air to pass through a typical birthing room. Unless designed sensitively, draughts from the supply air, and air noise from the extract grille, could create an unsatisfactory experience, and co-ordination could be challenging.
- A thorough understanding of the density of the gas being used is vital, particularly when using the buoyancy to overcome the momentum force.
- To avoid confusion, Entonox should be described as an analgesic, and not an anaesthetic gas.
- To ensure that past guidance is still operationally effective, and respecting the fact that updated guidance is not retrospective on existing facilities, we have modelled a number of conditions using 10 air changes per hour. A passive supply air input, extract face velocity of 3m/s, and an extract grille at gas terminal level, appear to be the minimum design requirements.
- An analysis which considered 7.5 air changes per hour was carried out, and was considered to be effective under certain design conditions. These included designing towards a displacement solution with the extract grille being positioned at high level in the ceiling above the bed with a 3 m/s face velocity and a passive make-up air supply. There are a number of reasons for investigating the 7.5 air change solutions – including reduced system capital cost; reduced energy use, carbon emissions, and air noise; physically smaller ducting, and reduced co-ordination.
- It is imperative that we have a greater understanding of the gas quantities used in a birthing room by the mother, to enable designers to design effective ventilation systems that satisfy the operational requirements of the COSHH Regulations.
- The disturbance on air flow patterns by operable windows needs to be further investigated, and, if found to be a serious impediment to the effective operation of the system, the option of sealing the room may be the only option.
- The gas cycle of use by the mother needs to be better understood.

- *The authors would also like to thank Dr Peter Fitzgerald – senior consultant anaesthetist at the Royal Glamorgan Hospital, for contributing to this article.*

References

1 The Control of Substances Hazardous to Health Regulations 2002 (COSHH).
2 HTM 2025 Ventilation in Healthcare Premises – Design considerations.
3 HTM 03-01Specialised Ventilation for Healthcare Premises.
4 HBN 21 Maternity Department Health Building Note.
5 Health Building Note 09-02 (Crown Copyright 2008) – Maternity Care Facilities.
6 Health Technical Memorandum 02-01 (Crown Copyright May 2006) Medical Gas Pipeline Systems.
7 Robertson A. Nitrous Oxide – no laughing matter. *MIDIRS Midwifery Digest* 2006: **16** (1).
8 Anaesthesia UK – various information.

About the authors

Phil Nedin

Phil Nedin CEng FIMechE FIHEEM MCIBSE MEI, is a Chartered Engineer, a Fellow of IHEEM, and a Past President of the Institute. Having worked for Arup for 25 years, he recently left his role as director and global healthcare business leader with the company, and now works as a consultant.

Dr Anna Coppel

Dr Anna Coppel CEng MIMechE, is a Chartered Engineer, based at Arup's Advanced Technology and Research team in London. An environmental physicist, she joined Arup after completing a MEng degree in Aeronautical Engineering, and a PhD in the application of computational fluid dynamics to sports equipment design. She has worked on a diverse range of commercial and technical projects involving challenging building physics design elements, and advanced computational fluid dynamics methods.