Indoor Air 2006; 16: 328–334
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INDOOR AIR
doi:10.1111/j.1600-0668.2006.00437.x

What is IAQ?

Abstract In spaces for human occupancy indoor air quality (IAQ) is often defined as the extent to which human requirements are met. But what requirements do people have in relation to indoor air? The desire is that the air be perceived as fresh and pleasant, that it has no negative impact on their health, and that the air is stimulating and promotes their work, i.e. it increases their productivity and the learning of their children in the classroom at school. Present ventilation standards and guidelines do not care about productivity and learning and have the very modest requirement that the indoor air shall be 'acceptable,' meaning that the most sensitive group of persons (usually 20%) perceive the air as unacceptable while the remaining less sensitive persons may find the air barely acceptable. With such a modest aim it is not surprising that comprehensive field studies in many countries in buildings in which ventilation standards are met show high percentages of dissatisfied persons and of those suffering from sick building syndrome symptoms. Recent studies show that improvement of IAQ by a factor of 2–7 compared with existing standards increases office productivity and school learning significantly, while decreasing the risk of allergic symptoms and asthma in homes. To make indoor air acceptable, even for the most sensitive persons, an improvement of 1–2 orders of magnitude may be required. The paper will discuss the development of new methods that can provide such substantial improvements of IAQ while maintaining or even decreasing ventilation and energy usage. A paradigm shift is required and further future shifts are foreseen where we learn how to make indoor air equally fresh and pleasant as outdoors when it is best. Or even better, i.e. 'out of this world.'

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Key words: Indoor air quality; Perceived air quality; Productivity; Asthma; Allergy; Learning.

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Received for review 2 December 2005. Accepted for publication 12 March 2006.

Practical Implications
The paper estimates an enormous potential for improving IAQ in practice utilizing new emerging technologies. This will enable us to provide IAQ which is acceptable even for the most sensitive persons. Already modest improvements compared to present minimum standards and typical conditions in practice can significantly decrease the risk of asthma/allergy in homes, improve learning in schools and increase productivity.

Introduction

The philosophy behind this paper is that indoor air quality (IAQ) in spaces for human occupancy be defined by its effect on humans: IAQ is the extent to which human requirements are met. But what requirements do we have? It is obvious that we want to breathe indoor air that does not have a negative effect on our health; we also appreciate that the air is perceived as acceptable or even better: fresh and pleasant; we want indoor air to have a positive impact on our work performance or on our productivity; and we want IAQ in the classroom to improve the performance of our children at school.

Can we express the human requirements in chemical terms? We know that it is chemicals emitted from people, materials and processes that decrease the IAQ. Can we not just make sure that the concentration of each chemical in the air is below a certain guideline value? Unfortunately, this method does not work well in non-industrial buildings, the reason being that there are typically hundreds or even thousands of chemicals in the air, each in very small concentrations, and we have only limited information on their impact on health and comfort. Guideline values are available for only a few dozen chemicals which only apply when they occur alone. How about using odor or irritation thresholds that are available for a larger number of chemicals? The thresholds given in the literature for a certain chemical may often vary considerably, however, and provide information on only the concentration where 50% of people can perceive that specific chemical when it occurs alone. The most sensitive people may perceive the chemical at a concentration that is several orders of magnitude lower and may perceive a cocktail of hundreds of chemicals at even lower concentrations. Furthermore, some chemicals, although above an odor threshold, may be perceived as pleasant while others may be very unpleasant. A further obstacle is that many chemicals are difficult to measure at the very small concentrations where they still have a negative impact on people.

An alternative is to use the human sensory response directly to define IAQ. Using this definition, high IAQ would be air that is perceived as acceptable by a large percentage of people. To this end, sensory measurements using human panels have already been used to evaluate IAQ by Yaglou in the 1930s (Yaglou et al., 1936) and later by Fanger (1988) to introduce sensory units: the perceived IAQ is expressed in decipol or percent dissatisfied while the sensory pollution load is expressed in olf. The sensory units allow a calculation of the ventilation required to obtain a certain desired perceived air quality. Sensory measurements have often been shown to be superior to chemical measurements and they have formed for decades the basis for ventilation standards and guidelines (CEN, 1998; ASHRAE, 2004). These standards and guidelines typically define acceptable IAQ as air with which $<15\%$, 20% or 30% of people are dissatisfied and specify the corresponding required ventilation. In practice, this philosophy of the standards led to mediocre air with rather large numbers of dissatisfied persons, as predicted. This is documented in numerous field studies in buildings all over the world that have been designed to accord to the standards.

The present paper will discuss the impact of indoor air on people in three examples of premises where many people spend most of their lives: at home, at school, and at the office. We know from numerous field studies that indoor air in these premises is often quite mediocre. The good news is that recent studies document that there are substantial benefits in terms of human health, comfort, productivity and learning, by improving indoor air by a factor of 2–7 compared with present practice. To make indoor air acceptable even for the most sensitive persons, a much greater improvement of 1–2 orders of magnitude is required.

The paper will discuss methods that have the potential to provide such large improvements of IAQ while saving energy. This will allow much needed future paradigm shifts in IAQ and in indoor environmental engineering.

Homes, allergy and asthma

The incidence of allergic and asthmatic diseases has doubled in developed countries over the past two decades. These diseases comprise one of the greatest current problems for public health, involving enormous costs in medicine, treatment and absenteeism.

Bornehag et al. (2004) hypothesized that the worsening of IAQ in dwellings in developed countries is a primary reason for the increment in these diseases. IAQ has declined because of comprehensive energy conservation campaigns and because high energy prices have motivated people to tighten their dwellings and reduce the rate of ventilation, so that the air change in many homes is at a historically low level. Other factors contributing to poor IAQ are the many new materials, especially polymers, and the numerous electronic devices that have been introduced indoors in recent decades, especially in children's rooms.

Bornehag et al. (2004, 2005) studied the relation between IAQ and asthma/allergy in a Scandinavian investigation comprising 11,000 children, and detailed chemical, physical, biological and medical measurements have been performed in 200 homes with asthmatic children and 200 homes with healthy children. These homes were situated in areas with excellent outdoor air quality.

The results show that allergic symptoms are related to ventilation (Figure 1). Improving the ventilation rate and thereby the IAQ by a factor of 4 decreased the risk of allergic symptoms by a factor of 2. The results also showed a relation between the concentration of phthalates and the risk of asthma (Figure 2). Phtha-

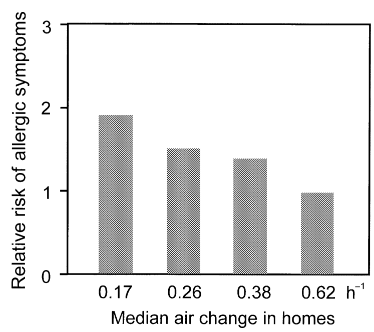


Fig. 1 Low ventilation rates in dwellings increase the risk of allergic symptoms among children. Each column represents about 90 dwellings (Bornehag et al., 2005)

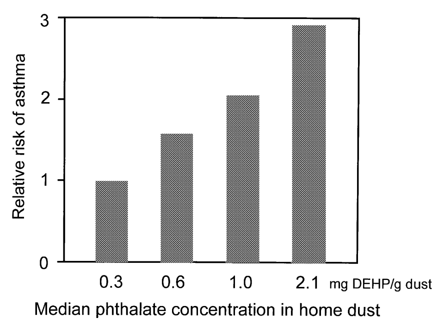


Fig. 2 Plasticizers, e.g. from polyvinyl chloride in dwellings, increase the risk of asthma among children. Each column represents about 90 dwellings. DEHP: di(2-ethylhexyl)phthalate (Bornehag et al., 2004)

lates are widely used as plasticisers in a wide range of polymers occurring in homes, e.g. polyvinyl chloride. Decreasing the concentration of phthalates by a factor of 7, decreased the risk of asthma to one-third. Improving the IAQ in homes by a factor 4–7 has thus been shown to have a dramatic positive impact on decreasing the risk of asthma and allergic symptoms.

Productivity in offices

Seppänen and Fisk (2005) have discussed different potential benefits of high IAQ on office workers, including the reduced costs in connection with absenteeism and medical treatment; but the most important benefit is the direct impact on productivity.

A series of recent independent studies document that an improvement in the quality of indoor air has a significant and positive influence on the productivity of office workers. In one study, a well-controlled normal office (field lab) was used in which two different air qualities were established by including or excluding a commonly used carpet as an extra pollution source, invisible to the occupants (Wargocki et al., 1999). The two cases corresponded to a low-polluting and a non-low-polluting building as specified in the European guidelines for the design of indoor environments (CEN, 1998). The same subjects worked for 4.5 h on simulated office work in each of the two air qualities. The productivity of the subjects was found to be 6.5% higher ($P < 0.003$) in good air quality and they also made fewer errors and experienced fewer sick building syndrome symptoms. This study performed in Denmark has later been repeated in Sweden with similar results (Wargocki et al., 2002a). A third study was performed in the Danish field lab with the same pollution sources present at three different ventilation rates: 3, 10, and 30 l/s per person (Wargocki et al., 2000a). The productivity increased significantly with increased ventilation. The three studies involving seven experimental conditions and 90 subjects have been analyzed as a whole, relating productivity to perceived air quality. Results show a significant positive influence of high IAQ on productivity in offices.

In another blind study with a similar experimental set-up as the one described above, the air was polluted by 3-month-old personal computers as an extra pollution source (Bakó-Biró et al., 2004). In this study the productivity was 9% lower ($P < 0.01$) when the extra computers were present and three times as many of the occupants were dissatisfied with the air quality. Each of the PCs polluted the air corresponding to 3 olf. This study was later extended to include the most common brands of PCs with CRT monitors and TFT (flat) screens. It showed results very similar to the previous study on sensory pollution and also showed that PCs with flat screens pollute much less.

The positive impact of high IAQ on productivity has recently been validated in a blind intervention study in the field in a call center in Denmark where the ventilation rate could be increased and particulate filters were new (Wargocki et al., 2004b). A significant positive effect of increased ventilation on productivity was documented in this study in a moderately cold climate but a similar study has recently been performed in the Tropics (Tham and Willem 2005; Tham et al., 2003). This study showed a very similar positive effect of increased ventilation on office productivity. The results of the two studies are combined in Figure 3. No positive effect of increased ventilation was found when used filters were present.

In the field lab studies mentioned above showing a positive impact of ventilation on productivity, *no* filters were present. Federspiel et al. (2002) also conducted an intervention study in a call center where ventilation rates were increased. As old used filters were employed throughout the study, this may explain why the authors found only a marginal positive impact of increased ventilation on productivity. These studies indicate, as shown in several previous investigations, that particulate filters in the HVAC system can be a serious source of pollution.

Based on these studies it is estimated that improving IAQ by a factor of five, compared with the mediocre air that is present in many existing office buildings worldwide, may increase productivity by 5–10%. An annual gain of this magnitude has an enormous economic impact which may cover all the capital and running costs of operating a building. Any life-cycle cost analysis of office buildings should therefore include the productivity gain resulting from improved high IAQ. This gain could often be greater than all other costs relating to the construction and operation of the building. The life-cycle cost will thus be a life-cycle gain of the building. It pays to provide high IAQ!

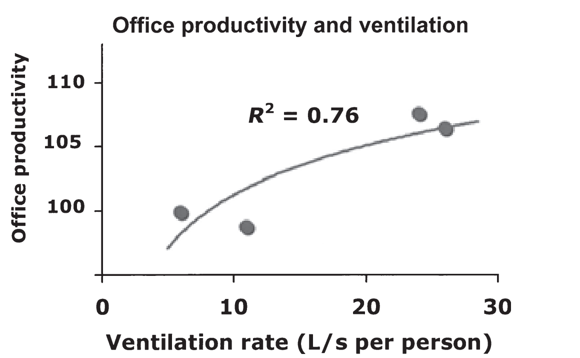


Fig. 3 Performance of call-center operators as a function of outdoor air supply rate; the dots exemplify the normalized performance of operators in 2 studies carried out in call-centers located in moderate climate (Wargocki et al., 2004b) and in the Tropics (Tham et al., 2003); a normalization factor in each study was an average performance of the call-center operators independently of the outdoor air supply rate

Learning in schools

It is well documented that IAQ in schools is often poor. Ventilation has in many cases been decreased to save energy, and operation and maintenance of systems are often insufficient. It has been suspected that poor IAQ in the classroom could have a negative impact on children's learning.

This has recently been investigated by Wargocki et al. (2005) who studied parallel classes of 10-year-old children and measured the impact of increased ventilation on the children's performance of school work. In appropriate lessons each week, the children's usual teachers administered parallel versions of performance tasks representing different aspects of school work from reading to mathematics. Clean filters were used in the ventilation systems. By increasing the ventilation rate from 5 to 10 l/s, the performance of school work improved significantly by more than 15%. An improvement of IAQ by a factor of two caused thus a remarkable improvement of the children's school performance and learning.

IAQ acceptable for the most sensitive

Standards and guidelines acknowledge that they prescribe IAQ which the most sensitive 15–30% of the population will not find acceptable. It is quite frustrating that we deliberately design buildings with so many dissatisfied persons. How much would it take to decrease the dissatisfied from 20% to a negligible number, e.g. $<1\%$? According to Fanger's model for perceived air quality (1988), used in European guidelines (CEN, 1998), such an improvement would require an increase in IAQ by a factor of 20 or more. If this should be obtained by increased ventilation, enormous rates would be required and such rates would of course be prohibitive because of cost and energy use. But fortunately, alternative methods are available to improve IAQ:

- source control,
- air cleaning,
- personalized ventilation, and
- cool and dry air.

These methods will be discussed in the following.

Source control

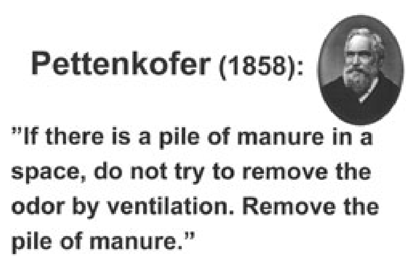
An obvious preferred method to improve IAQ is to reduce pollution sources in the building, including the HVAC system. Source control was already advocated in the mid 1800s by Pettenkofer (1858), the founder of modern hygiene and environmental science (Figure 4). There are three pollution sources that are of special concern indoors: loaded particle filters, building materials (including carpets), and PCs.

Particle filters are particularly serious as the air quality is degraded even before it is supplied to the ventilated space. Furthermore, increased ventilation, i.e. a higher airflow through the filter, increases, as mentioned previously, the emission of pollutants from the particles in the filter so that the air quality downstream of the filter does not improve (Alm et al., 2000; Beko et al., 2003; Clausen et al., 2002a,b; Pejtersen et al., 1989; Strøm-Tejsen et al., 2003). This may help explain why increased ventilation in mechanically ventilated spaces in some cases improves IAQ only slightly or not at all. It may also explain why, in some cases, the air quality in mechanically ventilated or even air-conditioned buildings has been found to be worse than in naturally ventilated buildings (during winter). It is therefore recommended that traditional particle filters in HVAC systems should be changed very frequently or better, substituted by alternative equipment that can remove particles from the air to protect the HVAC system without accumulating the polluting dust in the airflow. R&D is obviously required.

The second source of pollution is building materials. It is recommended that materials and processes emitting phthalates, especially DEHP, be avoided. It is suggested that carpets in general should be avoided unless they have been very carefully tested. It is suggested that requirements for carpets and other materials in the future should be much higher than those specified at present by various recommendations and labeling criteria. Strict sensory requirements should be included in the testing of materials.

Following the above recommendations for filters, materials and carpets, it is suggested that a realistic goal for the sensory load for low-polluting buildings that at present is 0.1 olf/m^2 floor in the building (CEN, 1998) be lowered to 0.02 olf/m^2 floor. For extra-low-polluting buildings Wargocki et al. (2004a) documented in a field study in six non-smoking modern office buildings that such a level can be reached if materials are selected very carefully.

It should also be considered that surface materials in spaces can function as a sink by sorbing pollutants in the air. Sakr et al. (2006) demonstrated, by using sensory methods, that gypsum plates and specially prepared sorbing materials can significantly improve IAQ by decreasing the sensory pollution load on the air in the space.



An important pollution source is common brands of PCs with CRT screens. It is recommended to stop buying the common brands of PCs with CRT screens and instead purchase low-polluting PCs and use TFT (flat screens) that generate only a negligible pollution. As a PC generation lasts only 3 years and the pollution decreases with a half life of 4–5 months (Beko et al., 2003), the load from the existing stock of PCs would quickly decrease if the above recommendation is followed.

Following the above recommendations for source control, it is estimated that the total sensory pollution load in many existing offices may be reduced by a factor of 4 (Fanger, 2003).

Air cleaning

Cleaning of indoor air from gaseous pollutants is a method with a promising potential for improving IAQ and partly substituting ventilation. Different methods, including sorption and photocatalysis, are being investigated. The latter method has been shown to provide interesting filtering efficiencies, documented in relation to individual chemicals in the air (Zhao and Yang, 2003). For the typical cocktail of hundreds of chemicals occurring indoors in very low concentrations, a cleaning efficiency of the two methods above 80% may be feasible (Fang et al., 2005), i.e. air cleaning may decrease concentrations and improve IAQ by a factor of 5. But further R&D of the technologies is obviously needed and further studies to demonstrate cleaning efficiencies in perceived IAQ for typical indoor pollution sources are recommended.

Personalized ventilation

If, for example, 10 l/s · person of outdoor air is supplied to the office, only 0.1 l/s · person, or 1%, is inhaled. The rest, i.e. 99% of the supplied air, is not used. What a huge waste! And the 1% of the ventilation air being inhaled is not even clean. It is polluted by bioeffluents, building materials, PCs and other pollution sources in the space.

According to traditional engineering practice, full mixing of clean supply air and pollutants in the room air has typically been regarded as an ideal solution. What is needed in the future are systems that supply rather small quantities of clean air direct to the breathing zone of each individual. The idea is to serve to each occupant, clean air that is as unpolluted as possible by the pollution sources in the space. In an office, this personalized ventilation may be provided from an individual, easily movable outlet. Under ideal conditions, each person can inhale clean air from the core of the jet where the air is unmixed with polluted room air and has a low velocity and turbulence which do not cause draught. Such systems are now being developed and studied (Bolashikov et al., 2003; Kaczmarczyk et al., 2002; Melikov et al., 2002). Based on these studies, it seems realistic to envisage that a properly developed outlet may reach a ventilation effectiveness as high as 10 or more, i.e. personalized ventilation may increase the quality of the inhaled air by one order of magnitude. An essential feature is that each person has easy control over the position of the outlet, of the flow and even of the temperature of the supply air.

Cool and dry air

Comprehensive studies by Fang et al. (1998a,b, 1999) and Toftum et al. (1998) have shown that perceived air quality is also influenced by the humidity and temperature of the air we inhale. People prefer rather dry and cool air. They like a sensation of cooling of the respiratory tract each time air is inhaled. This causes a sensation of freshness which is felt pleasant. A high enthalpy of the air means a low cooling power of the inhaled air and therefore an insufficient convective and evaporative cooling of the respiratory tract, in particular the nose. This lack of proper cooling is closely related to poorly perceived air quality.

Fang's studies indicate that decreasing the air temperature 2–3 K, e.g. from 23–24 to 21°C may improve the perceived IAQ by a factor of two. Decreased humidity has also a beneficial effect on perceived IAQ down to 20% rh. Below that, dry air may have negative effects on the eye blinking rate and on productivity (Fang et al., 2003; Wyon et al., 2002).

Combined effect of all methods

What happens if we simultaneously use all methods to improve the IAQ? We do not know, as we have no data from studies, where all the methods were simultaneously used. But we may make a rough theoretical estimate. Compared with many typical existing offices at 23–24°C, a ventilation rate of 10 l/s · person, and a pollution load around 0.2 olf/m^2 floor, we may by source control, air cleaning and personalized ventilation, decrease the pollutant concentration in the inhaled air by a factor of $4 \times 5 \times 10 = 200$, without increasing the ventilation rate. All the three methods contribute to dilute the pollution concentration, and the effects can be multiplied provided the source emission and the filtering efficiency are independent of pollution concentration. It is also assumed that the personalized ventilation system is able to supply clean ventilation air.

By decreasing the temperature (and humidity), we may furthermore improve perceived IAQ by a factor of two, i.e. to a level 400 times better than the reference.

We do not need such a dramatic improvement of the IAQ. Less is required to satisfy even the most sensitive persons. There may therefore be room for simultaneous energy savings by reduced ventilation. But further studies are required to validate these very rough estimates.

Conclusions and future predictions

- IAQ should be defined in relation to its impact on human health, comfort, productivity, and learning.
- Improving IAQ by a factor of 2–7, compared to typical present practice and to standards, decreased the risk of asthma/allergy in homes, increased productivity in offices, and improved learning in schools. The potential benefits for society are enormous.
- To decrease the percentage of dissatisfied from the 15–30% allowed in existing standards and guidelines, to a negligible figure may require an improvement of IAQ by a factor of 20 or more.
- Methods are suggested that may provide such large improvements of IAQ without increasing ventilation. Applying these methods simultaneously may even allow for a reduced ventilation rate and energy usage.
- To reach a level of IAQ where even the most sensitive persons find the air acceptable will require a future paradigm shift. Further paradigm shifts are foreseen when we learn how to treat indoor air so that people perceive it as being equally pleasant and fresh as outdoors when it is best, e.g. in the mountains or at the sea. A further shift may teach us how to create indoor air that is even better than anywhere in nature: truly out of this world!

Acknowledgement

The Danish Technical Research Council is acknowledged for its support to the International Centre for Indoor Environment and Energy.

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