Is ventilation duct cleaning useful? A review of the scientific evidence

Sultan, Z. M.

Publisher’s version / Version de l'éditeur:
https://doi.org/10.1111/j.1600-0668.2010.00672.x
Indoor Air, 20, 6, pp. 445-447, 2010-12-01

Is ventilation duct cleaning useful? A review of the scientific evidence

NRCC-53529

Sultan, Z.M.

2010-12-01

A version of this document is published in / Une version de ce document se trouve dans:

Indoor Air, Volume 20, Issue 6, pages 445–457, December 2010.
http://dx.doi.org/10.1111/j.1600-0668.2010.00672.x

IS VENTILATION DUCT CLEANING USEFUL? A REVIEW OF THE SCIENTIFIC EVIDENCE

Zuraimi MS.

Indoor Environment Research Program,
Institute for Research in Construction, National Research Council Canada.
Rm 217C, Bldg M-24, 1200 Montreal Road,
Ottawa, Ontario, Canada, K1A 0R6.

613-991-0891 (DID)
613-954-3733 (Fax)
zuraimi.sultan@nrc-cnrc.gc.ca (E-mail)
http://www.nrc-cnrc.gc.ca/eng/ibp/irc.html

IS VENTILATION DUCT CLEANING USEFUL? A REVIEW OF THE SCIENTIFIC EVIDENCE

ABSTRACT

Ventilation duct cleaning is widely advocated to provide good IAQ, health benefits, cost savings, and enhance ventilation system performance. The aim of the present review is to evaluate the scientific evidence as shown in the literature. There is evidence that under normal operating conditions, ventilation ducts can be contaminated with dusts and serve as reservoirs for microbials to proliferate. While controlled experiments noted that contaminants resuspension can elevate exposure levels indoors, no field studies have correlated poor IAQ with duct contamination. Despite high efficiencies of contaminant removal within the ducts during cleaning, reductions for different indoor air pollutants vary widely, where, post-cleaning air pollutants concentrations can be higher than pre-cleaning levels. Further, there are health concerns in the use of biocides, sealants and encapsulants. There is inadequate evidence to show that duct cleaning can improve air flow in ducts and reduce energy consumption. Although epidemiological studies indicate suggestive evidence that improperly maintained ducts are associated with higher risks of symptoms among building occupants, this review finds insufficient evidence that duct cleaning can alleviate occupant's symptoms. In summary, the need for duct cleanliness has to be properly balanced by the probable generation of indoor pollution resulting from duct cleaning and subsequent potential health risks.

PRACTICAL IMPLICATIONS

Existing evidence is insufficient to draw solid conclusions regarding positive impact of duct cleaning on IAQ, health benefits, cost savings and HVAC performance. Maintaining duct cleanliness has to be properly balanced by the probable generation of indoor pollution and potential health risks.

KEY WORDS:

Review; Duct cleaning; Performance; Indoor air quality; Benefits.

INTRODUCTION

Ventilation duct cleaning has been commercially advocated to remove pollutant sources inside the HVAC system (Brosseau et al., 2000a, b). Over the years, many companies are claiming that duct cleaning (DC) is capable of improving indoor air quality and occupant health, enhancing ventilation system performance and their operating life, as well as providing energy and maintenance cost savings (Brosseau et al., 2000a; EPA, 1997; NEMI, 2002). The aim of this paper is to systematically review the scientific evidence for these claims.

METHODS

A literature search using the key terms *duct cleaning, cleanliness or hygiene* was performed limiting the search to title or abstract of papers on residential and non-industrial commercial building applications. Scientific literature, published in journals was searched through a number of electronic databases including Airbase from the Air Infiltration and Ventilation Center; Current Contents; Inspec; Medline; PubMed; and Sciencedirect. Conference papers were excluded and articles published from January 1980 to January 2009 were considered.

The abstracts were then reviewed and papers accepted for consideration based on the following inclusion criteria: (1) dust measurements and characteristics in ducts, (2) DC performance, and (3) health benefits and risk of DC. Full-text versions of the papers were then obtained and carefully reviewed. Pertinent references cited in the papers or reports but not identified by earlier search were also obtained and reviewed. Studies with clear deficiencies and flaws in methodologies and those which incorporated other interventions (e.g. new filters) together with duct cleaning were excluded.

When studying research reports dealing with health associations related to DC or duct cleanliness, several criteria was assessed. The evaluation criteria were based on the design of the study, methods of health assessments, presence of bias, use of randomization and/or 'blinding', accounting for confounders, and size of the study population (Cook and Campbell, 1979; Gordis, 1996).

In discussing DC performance, the concept of efficiencies and effectiveness provided by Miller-Leiden et al. (1996) was adopted. Here, efficiency describes the likelihood of DC in removing pollutants from duct surfaces. Effectiveness describes the impact of DC on reducing indoor pollutant concentrations in actual settings. Thus, effectiveness is more relevant when discussing pollutant exposure and health risk impact. The efficiency (η) and effectiveness (ε) are given by equations 1 and 2, respectively:

$$\eta = 1 - \frac{C_{s,A}}{C_{s,B}} \qquad (1)$$

$$\varepsilon = 1 - \frac{C_{i,A}}{C_{i,B}} \qquad (2)$$

Where $C_{s,\ B}$ and $C_{s,\ A}$ are the duct surface pollutant concentrations before and after DC respectively and $C_{i,\ B}$ and $C_{i,\ A}$ are the indoor pollutant concentrations before and after DC respectively. Studies providing only illustrations of pollutant levels before and after cleaning make it difficult for this review to evaluate efficiencies objectively. Thus, estimated ranges of values will be reported.

To facilitate comparisons, reported concentrations of surface and airborne pollutants were converted to common units. To quantitatively assess benefits of DC on interior surface pollution and indoor air quality, we evaluate if proper statistical tests of concentration differences were conducted. Findings are considered significant if the p value of the difference is less than 0.05 and confidence intervals (CI) are 95% CI.

RESULTS

A flow chart detailing the results of the systematic review process and categories of articles identified is given in Fig. 1. As shown, of 104 papers initially identified, 48 were found to fulfill the inclusion and exclusion criteria. Two broad groups of articles falling into those covering dust measurements and characteristics in ducts and those dealing with duct cleaning performance and benefits were noted.

Figure 1 Stages of systematic analysis and categories of articles

Duct measurements and characteristics in ducts

Duct soiling

There are different sources of pollutants which can accumulate in ducts during two building phases: 1) particles from construction and oil residues from duct manufacture in newly installed units during construction phase (Pasanen, 1998; Pasanen et al., 1995, Holopainen et al., 2002b); and 2) pollutants from outdoor air and recirculated air during operation and maintenance (O&M) phase (Pasanen, 1998).

The estimated annual accumulation rate for dust in commercial supply air ducting is normally set at 1 g/m^2. However, Pasanen (1998) reported an average accumulation level of 5.1 g/m^2 in supply air ducts of buildings occupied less than a year while Holopainen et al., (2002b) measured dust levels as high as 4.9 g/m^2 in new constructions. Holopainen et al., (2002b) noted that with proper protection methods, lower dust accumulation levels can be attained compared to those without protection (0.4–2.9 g/m^2 vs 1.2–4.9 g/m^2). Asikainen et al., (2003) noted that the amount of residual oil in spiral ducts and other duct components ranged from 0.014 to 0.196 g/m^2 while galvanised sheet metal that had been covered with corrosion protection oil contained 0.5–1.0 g/m^2 of oil.

Simulation studies on dust deposition during building's O & M phase showed that duct deposition was negligible for particles smaller than 1 µm and complete for particles larger than 50 µm (Sippola and Nazaroff, 2003). Dust deposition onto the floor of ventilation ducts is about 2 orders of magnitude larger than that onto other duct surfaces due to gravitational settling (Zhao and Chen, 2006). Others noted that duct surface orientation is less important as turbulence increases – a phenomenon where turbulent impaction and diffusion processes dominate the deposition of large and small particles, respectively (Kvasnak et al., 1993). High air velocities, surface roughness or flow obstruction (bends, diffusers, dampers etc.) increase dust deposition (Miguel et al., 2004; Sippola and Nazaroff, 2003).

There is no field study evidence to show that dust accumulation can cause higher energy consumption, poor HVAC system performance or decreased air flow rates.

With increasing humidity, dust deposition can be enhanced presumably due to two factors: 1) adsorbed water molecules on surfaces have higher affinity to hygroscopic particles; 2) greater particle growth from higher relative humidity increases their gravitational settling velocity (Arundel et al., 1986). No studies have been performed to evaluate bioaerosol deposition onto duct surfaces. However, research in a room chamber (Kanaani et al., 2008) showing similar deposition rates of fungal spores (*Aspergillus niger* and *Penicillium* spp) and inanimate particles (canola oil and talcum powder). This indicates that the process may be similar in ducts. Both the aerosol and the bioaerosol deposition rates were found to be a function of particle size.

Microbes

Pasanen et al. (1997) noted no concentration difference for total fungal spores in supply and exhaust air ducts. They attributed this to unfavorable microenvironment conditions in ventilation ducts for fungal spore viability. However, higher viable fungi concentrations were collected on exhaust ducts compared to supply ducts. Presumably, more stable moisture conditions and nutrients for fungi survival are found in the exhaust ducts. In an experimental set-up, Pasanen et al., (1993) noted that water condensation on ducts facilitate germination and sporulation of fungal spores on dusty steel surfaces of a HVAC system.

Chang et al. (1996) demonstrated the importance of dust accumulation control to prevent fungal growth at high humidity conditions (97%). Moderate soiling (4-7 g/m ^{2}) resulted in fungal growth on fibrous glass ductboard and flexible duct, but not galvanized steel. Higher levels of soiling (90-180 g/m ^{2}) resulted in fungal growth on galvanized steel as well. Likewise, Foarde et al. (1996) observed fungal growth on fiberglass duct liner when heavily soiled (10-20 g/m^2) at humidity levels above 90%. However, no growth was observed under the same conditions with no duct soiling. They added that low temperature (12^{0}C) may delay onset of fungal growth but do not arrest growth. Ezeonu et al. (1994) noted fungal growth on fiberglass insulation only above 85% RH with no soiling. With soiling, none of the fiberglass materials showed evidence of colonization at humidities below 50%.

Dust sampling

Prior to dust sampling, various dust loosening techniques are employed. These include using a trowel, a razor blade as well as plastic blades (Nielsen et al., 1990; Pasanen, 1998). Further, various techniques have been utilized to sample dust in ventilation ducts. Studies have shown that results may be dependent on the specific sampling method employed (Holopainen et al., 2002a; Fransson et al., 1995). Table 1 provides a brief description of these methods.

Table 1 Surface dust sampling methods

Table 2 summarizes the results of dust profile studies from duct surfaces. Mean dust surface concentrations ranged from 0.2 to 13.2 g/m^2 with deposits reaching as high as 158 g/m^2. Yearly dust accumulation ranged between <0.1 to 1.0 g/m^2 per year. An overview of the data shows higher levels in office compared to residential buildings. Under the O&M phase, factors such as presence and quality of filtration, building age, intake location, HVAC operation time and particle deposition mechanisms are potential determinants of dust levels (Pasanen, 1998).

Table 2 Summary of the results on dust settled in the inner surfaces of building air ducts (n=number of buildings studied).

Dust composition

Collected dusts have been analyzed with respect to elemental (Fransson et al., 1995; Foarde et al., 1996), organic (Asikainen et al., 2003), microbial (Nyman and Sandström, 1991) or allergenic composition (Tsay et al., 2000).

For fungi and bacteria, various techniques employed include direct cultivation of dusts, contact plates and swab. Bacteria concentrations range from 1 to 320 000 CFU/m^2 while fungi concentrations range from 1 to 250 000 CFU/m^2 (Table 3). Nyman and Sandström, (1991) documented lower bacterial contamination in ducts compared to other HVAC components (rotating heat exchangers, cooling coils or humidifiers) with concentrations decreasing along the supply air duct. Some factors are associated with higher levels of microorganisms. These include temperature and air recirculation, moist or wet insulation material as well as dust loading (see below). Pasanen et al., (1997) reported that the viable proportion was less than 5 % of the total fungi in dust.

Table 3 Summary of the results on viable fungi and bacteria settled in the inner surfaces of building air ducts (n=number of buildings studied).

Tsay et al. (2000) studied allergens analyzed from dusts collected from supply and return air ducts in homes where pets are present. They found higher levels of allergens in the return (cat allergen: range <0.5- 339 μg/g dust; dog allergen: range <0.5- 213 μg/g dust) compared to the supply air ducts (cat allergen: range <0.5- 10.8 μg/g dust; dog allergen: range <0.5- 24 μg/g dust). The authors noted that filters present in the HVAC system dramatically reduce allergen levels passing back into rooms via the supply air ducts. They reported little or no accumulation of mite allergen in air ducts, suggesting that the conditions in air ducts are not suitable for mite growth.

Dust accumulated in supply air ducts has been reported to contain 16-20% organic matter, inorganic elements with composition amounting to 12% iron, 0.4 % magnesium 4% zinc and 14% silicon (Foarde et al., 1996). Pasanen (1998) found that the content of the dust was similar to the dust in outside air.

Dust resuspension and effects on IAQ

Yoshizawa et al. (1997) studied the effects of fans being turned on and off intermittently on airborne dust levels in supply ducts. Airborne particle number concentration increased by about an order of magnitude within a period of five minutes after the fan was turned on. The authors attributed this effect to the resuspension of deposited dust. After DC, this effect was greatly reduced, especially for particles greater than 2 microns.

Air velocities can affect microbial resuspension from duct surfaces and thus enable them to be reentrained into the airstream. In the indoor environment, Pasanen et al. (1991) noted that at air velocity of 0.5 ms^{-1}, *A. fumigatus* and *Penicillium* spp. spores were released from their conidiophores, whereas *Cladosporium* spores required at least a velocity of 1.0 ms^{-1}. High air velocities (above 0.4 – 10.2 ms^{-1}) resulted in increased fungal fragmentation (Górny et al., 2002; Kanaani et al., 2009). Kanaani et al., (2009) noted that fungal fragmentation percentage increases with air velocities. Submicron fragmented parts were found to increase by up to 400 times, 9.4 times and 6.3 times for *Penicillium*, *Aspergillus* and *Cladosporium*, respectively, during fragmentation.

Relative humidity can also influence spore release from duct surfaces. *A. fumigatus* and *Penicillium* spp. airborne spore counts were usually higher in dry than moist air, being minimal at relative humidities above 70% (Pasanen et al., 1991).

Very few systematic field investigations have been conducted to examine the correlation between duct surface contaminant levels and elevated pollutants levels indoors. Morey (1988) reported a case building study where the ducts contained about 1 million viable fungi per gram of dust with the air at the affected site measured over 3000 CFU/m^3 of *Penicillium*, more than 10 times the level outdoors. Another case study (Bernstein et al., 1983) reported higher airborne fungi levels in an office exposed to "contaminated HVAC system" compared to a "control" office

Duct cleaning performance and benefits

Techniques

Techniques to clean ducts can be categorized into dry or wet methods (Brosseau et al., 2000b; CEN, 1997; HVCA, 2005). Table 4 provides a summary of the various techniques.

Table 4 Summary of duct cleaning techniques

Performance – efficiencies and effectiveness

In general, DC efficiencies for dust reduction using compressed air and mechanical brush methods range from 50 to 99% (Table 5). Results from field studies are somewhat lower compared to data from laboratory studies. The contact vacuum method showed lower efficiencies (Foarde et al., 1997) although Fugler and Auger (1994) noted no differences in their evaluation of 33 houses. DC efficiencies for surface fungi and bacteria was 27% with wide variation (-36 to 99%) noted in laboratory studies (Foarde et al., 1997). Laboratory studies reported high residual oil removal efficiencies (95 to 99%). Only the study by Fugler and Auger (1994) evaluated statistical significance for surface pollutant removal ($P<0.05$).

Table 5 Duct cleaning performance in reducing surface dusts, microorganisms and residual oil

Table 6 summarizes study findings regarding the calculated effectiveness of DC in reducing IAQ contaminants. The studies did not mention any changes in operating conditions or parameters pre and post DC. For particles, wide variations in the calculated effectiveness can be observed (from -473% to 62%). DC method and particle size do not affect the effectiveness. DC is associated with viable fungi removal effectiveness ranging from -103 to 99%. Only two studies evaluated statistical differences between pre and post DC pollutant levels. Significant reduction was observed for airborne viable fungi and bacteria (Fugler and Auger, 1994).

Table 6 Duct cleaning performance in reducing indoor air pollutants

Impact of duct cleaning on other parameters

Although Auger (1994) did not notice any air flow effects with DC in the supply ducts of residences, they contained little dust originally. Heavily contaminated return ducts however, recorded a non-significant mean post cleaning increase of 8% in airflows. Wallin (1991) reported a 20-30 % increase in exhaust air flows. It is also unclear if any increased airflow rates would result in higher ventilation or air velocity indoors. Researchers have noted no significant difference in air velocities or carbon dioxide (a crude indicator of ventilation) in pre and post cleaning measurements (Kolari et al., 2005).

Auger (1994) reported no significant difference in HVAC fan current (5.06 versus 4.92 amps) and voltage (126 versus 127 V) indicating that DC does not significantly reduce energy consumption. The researcher added that there was no statistically significant increase in pressure differences available for the HVAC fan.

Foarde and Menetrez (2002) researched the use of 3 commonly used antifungal coatings on regrowth on fibreglass ducting and galvanized steel in a static chamber study. The authors reported that the coating helped limit, but did not fully contain, regrowth on fibreglass ducting. No regrowth was found on the coated galvanized steel.

Health benefits of duct cleanliness and duct cleaning

Three types of studies were identified linking duct cleanliness with health: 1) perceived air quality (PAQ) using sensory panels; 2) sick building syndrome prevalence studies; and 3) studies linked to mold-contaminated HVAC materials.

Laboratory studies showed that residual oil and accumulated dusts in air ducts can influence PAQ of the supply air (Pasenen et al., 1995). The odor emission of oil residues from mineral and vegetable oils was evaluated with the aid of a trained panel for eight months. It was reported that odor emissions from the oil residues were high for both types of oils. Odor emissions continued to increase for vegetable oil.

Kolari et al. (2005) studied 410 occupants in 10 non-problem office buildings that were selected from assignments of DC companies. The authors noted that dust deposition was significantly correlated with increased prevalence of nasal symptoms but decreased prevalence of difficulty in concentration. In a NIOSH study involving 2435 occupants from 80 US office buildings with health complaints, Sieber et al. (1996) reported that dirty ductwork (one of the indicators of poor HVAC cleanliness) was significantly associated with increased risk of multiple respiratory symptoms (adjusted relative risk: 2.1) and non-significantly associated with increased risk of multiple atopic symptoms (adjusted relative risk: 1.2). They added that the relative risks of exposure to supply air from ductwork that has never been cleaned were significantly high for multiple lower respiratory symptoms and multiple atopic symptoms (adjusted relative risks: 2.8 and 1.8 respectively). In a cross-sectional US EPA BASE study, Mendell et al. (2008) analyzed the conditions of the HVAC system and how they were associated with symptoms among 4326 office building occupants. They noted that fair or poor liner conditions in air handler housing and duct were associated with increased odds (adjusted odds ratio: 1.43) of upper respiratory outcomes among the occupants.

2 employees exposed to “contaminated ventilation system” in a US office building reported symptoms compatible with hypersensitive pneumonitis (HP) (Bernstein et al., 1983). Their symptoms were noted to increase in severity during the workday, recur during the workweek but diminish over the weekends or on holidays. Retrospective epidemiological analysis revealed higher incidences of non-specific respiratory illness among employees in the “exposed office” compared to those in the “control office” (10.8 versus 6.3 person-years at risk, relative risk: 1.71). Due to the small sample size (n=25) or non-specific respiratory diseases, statistical significance was not attained.

Ezeonu et al. (1994) managed to isolate heavily mold-contaminated duct liners and boards from eight buildings where occupants complained of moldy odors. In a different study, fourteen fungal species isolates obtained from HVAC equipment were used as a skin prick test on 150 patients (Schata et al., 1989). All the patients were present with allergic diseases whose symptoms mainly occurred in air-conditioned rooms – no ‘healthy’ patients were used as controls. The authors reported that 90% of the patients displayed positive reactions to the skin tests.

Only 1 study was identified that evaluated the independent effects of ventilation duct cleaning on occupant’s health. Bernstein et al. (1983) reported that HP symptoms of an affected employee persisted even after remedial duct cleaning. They reported that the employee could have been sensitized such that even low exposure levels to contaminants after DC may trigger HP episodes.

Health risk – negative impact associated with duct cleaning

DC has been reported to increase indoor air pollution in several intervention and case studies. In a carefully designed intervention study with control samples from homes without DC, indoor particle concentrations observed in homes during duct cleaning activities exceeded those measured before cleaning (Ahmad et al., 2001). Further, particles concentrations were higher not only during but after cleaning had taken place (Auger, 1994; Ahmad et al., 2001). These suggest that dirt, debris and other pollutants may become airborne as a result of disturbances caused by the cleaning processes. The vacuum collection device for duct cleaning itself might be a significant source of pollutants in the building (Puhakka et al., 1992), particularly if the exhaust air is supplied back into the occupied space during duct cleaning work.

To date, toxicity of sealants and biocidal products for DC application is unclear (EPA, 1997). Research reports have documented potential risk of biocides application as well as the use of ozone (Hubbard, 2006; EPA, 2001; 2006). For common biocides (hypochlorides, quaternary ammonium compounds, phenols, aldehydes and iodides), risks associated with their use include irritation to the eyes, skin, nose and mucous membranes, toxic irritancy and even carcinogenesis

(Brosseau et al. 2000a; EPA, 2001; 2006). Figley (1994) reported 'relatively low' concentrations of biocide products measured in the air of 5 houses that had been duct cleaned followed by continuous fan operation and windows opening for at least 6 hours. Still, there were no specific chemical concentration standards to compare with.

DISCUSSION

Are there IAQ and health benefits associated with duct cleanliness?

There is good evidence that ventilation ducts can be contaminated during the construction and O & M phases of the building. Considerable information is available on dust and fungi, and to a lesser extent, bacteria and residual oil accumulation in ducts. During the O & M phase, microenvironment conditions within the ducts such as high air velocities and flow obstruction facilitate dust accumulation. Dust accumulations in ducts in turn, support the growth of fungi at RH above 50%. For pollutants resuspension however, laboratory studies have identified air velocity and relative humidity as important parameters. The mechanism for this is hypothesized to be due to a combination of higher turbulence and vibrations in the duct system that induce a lift-off drag force vector needed to break particle surface adhesion. Dry conditions further encourage reduction of particle surface adhesion making them more susceptible to convection by subsequent local, turbulent eddies introduced by air movements. While controlled laboratory research (Yoshizawa et al. 1997) showed that pollutant accumulation in ducts is associated with increased concentration of particles indoors, no field surveys have confirmed the correlation of poor IAQ with dust levels in contaminated ducts. Likewise, no study has conclusively shown that dust accumulation is associated with higher energy consumption, lower HVAC system performance or airflow rates.

Review of laboratory experiments showed that surface fungi dispersion into the air occurred at air velocities typically found in ventilation ducts. Further, cyclical RH conditions may trigger deposited spores to be released. Despite reported case studies (Bernstein et al., 1983; Morey, 1988), no systematic field investigation was found linking fungal contamination of duct surfaces to higher indoor exposure levels of fungi. Viable fungal concentrations collected from ducts (Table 3) were only slightly higher than those reported in house dust (Hyvarinen et al., 1993) but lower than in office dust (Mølhave et al., 2000). The main fungal genera in dust from air ducts (*Penicillium*, *Cladosporium* and *Aspergillus*) are mostly of outdoor origin (Pasanen et al., 1997; Pasanen, 1998). The same fungal genera were observed in dust accumulated in air ducts (Pasanen et al., 1997), settled on the floors (Hyvarinen et al., 1993) and sampled in the air (Toivola et al., 2004; Shelton et al., 2002).

Previous analyses of epidemiological studies (Seppanen and Fisk, 2002) which showed significantly higher symptom prevalence rates in air-conditioned buildings compared to naturally ventilated buildings suggest that the ventilation system itself may be a source of contaminants. Seppänen and Fisk (2002) hypothesized that pollutants emitted by HVAC ductwork or surface contamination, are transferred with supply air to the occupied spaces where they elicit symptoms. In this review, out of the three SBS symptom studies, the findings from complaint (Sieber et al., 1996) and non-complaint buildings (Mendell et al., 2008) provide suggestive evidence to support the above hypothesis. The large data collection of indoor environments and occupants symptoms using a cross sectional approach ensures precision of the risk estimates while the results have been adjusted for relevant confounding variables. Also, the studies linked health outcomes data reported by building occupants with descriptive information related to duct cleanliness from inspection by field researchers. This method excludes the frequent drawback of dependence between exposure and health outcomes faced by cross-sectional studies in which information on health and exposure comes from the same source (Kristensen, 1992). Information bias that could explain the findings under these conditions are minimized. Still, the data merely present an association of duct cleanliness with health outcome and does not provide a causal interpretation. It is also unknown what are the likely mechanisms (biologic, chemical, or particulate pollutant exposures) that duct cleanliness exposure are linked to negative health effects.

In many studies, viable fungi concentration was reported. Viable fungi concentration does not, however, reflect the total fungal contamination in accumulated dust. All fungal spores may not be viable due to unfavorable conditions in ventilation systems for their survival. Pasanen et al. (1997) reported that less than 5 % of the total fungi in dust was viable. Still, this proportion is higher than that reported for air samples (0.6 %) (Toivola et al., 2004). Dusts dislodged from the ventilation surfaces thus have a higher microbial load than the airstream carrying them. This suggests that the full health potential of dust settled in air ducts have not been understood. Indeed, most fungal spores may retain their allergenic properties even when the spores are no longer culturable (Levetin, 1995) while some dead fungi may even be toxic (EPA, 2001). Elsewhere, researchers studying the effects of fungi and health outcomes have relied on other alternative approaches to culture methods including immunodetection (Immonen et al., 2002), extracellular polysaccharides (Douwes et al., 1999), fungal biomass such as 1-3 b-d-glucan or ergosterol (Szponar et al., 2000; Rylander, 1999) and chemical mycotoxins or microbial volatile organic compounds (Nielsen et al., 1999; Schleibinger et al., 2008). Some of these techniques have been used to associate fungi exposure with SBS symptoms, asthma and allergies and respiratory outcomes (Wan and Li, 1999; Douwes et al., 1999; Park et al., 2008).

Odor emissions of contaminants from ‘dirty’ ducts have been reported (Pasanen et al., 1995; Asikainen et al 2003). Weschler and Nazaroff (2008) provided a theoretical analysis which showed that equilibrium partitioning of semi volatile organic compounds from the air onto dust particles can be achieved easily especially on a thick sorptive reservoir. Subsequent desorption could serve as a secondary contaminant source and odor. Depending on the olfactory characteristics of these organic compounds, odors may be perceived differently by the building occupants. However, the panels performing the odor evaluations in the reviewed studies may not be blind to the conditions of the ducts. More research is needed to study these effects leading to odor complaints.

Is duct cleaning *efficient* and *effective* in removing pollutants?

In general, pollutant removal efficiency via DC can be very high, however, wide variations in the efficiencies are also noted. More importantly, most studies did not evaluate removal efficiencies statistically. Thus, significance of efficiencies values cannot be ascertained with confidence. Researchers have reported that various methods used to assess dust levels in ducts can provide very different outcomes (Holopainen et al., 2002a; Fransson et al., 1995). Also, uneven dust distribution on duct surfaces can affect surface dust sampling measurements leading to considerable discrepancies (Holopainen et al., 2002a). Indeed, uncertainties arising from these two factors need to be accurately characterized during efficiency calculations.

After cleaning, the duct might be recontaminated through deposition or in the case of microbials, regrowth. According to Wallin (1991), DC should be performed every 1-2 years depending on the quality of the outside air and the activities in the building. Foarde et al. (1997) demonstrated that post-cleaning fungal contamination returned to pre-cleaning levels within 6 weeks. Their studies showed that mechanical cleaning alone produced only temporary reduction in surface fungal load. Subsequent experiments (Foarde and Menetrez, 2002) revealed that even the use of antifungal coating did not fully control regrowth on fibreglass ducting. A case study involving the use of encapsulant in a 15-year-old building (Groen, 1995) documented that microbial growth reappeared as quickly as one year after cleaning. Although subsequent coating of sealants on the duct liner was applied, growth recurred within a season.

Concentrations of indoor air pollutants are dynamic and are a function of various parameters such as their outdoor levels, source strengths, surface deposition and ventilation. During DC, the parameter that is reduced is the pollutant source strength within the ducts. From the point of view of human exposure, even a complete removal of a pollutant source within the duct (100% efficient) does not mean that other indoor sources of that particular pollutant don't exist or its ingress from outdoors may not occur. Thus, in terms of effectiveness, duct cleaning *alone* may not be sufficient. In keeping with this, some DC intervention studies include post-cleaning installation of new filters (Kolari et al., 2005) or new electrostatic precipitators (Garrison et al., 1993). Under these scenarios, any indoor particle concentration reduction will not be due the independent effects of DC. Installing new filters or electrostatic precipitators to replace old and dirty filters can enhance the removal of particles or volatile contaminants released from soiled filters and decrease indoor levels. This is further evidence which demonstrate that it may be very difficult to effectively reduce indoor pollutants via DC alone.

Are there health benefits of duct cleaning?

Despite suggestive evidence linking improperly maintained ducts with SBS symptoms, little scientific evidence was found to support the hypothesis that DC can have a positive health effect on building occupants. The reason for this is due to the limited number of studies that have been conducted and to flaws in the intervention study designs. For example, the positive health benefits of DC study by Kolari et al (2005) was excluded from the review because installation of new filters can improve occupants SBS symptoms (Mendell et al., 2002).

DC effectiveness displayed very wide variations with negative effectiveness presented at the lower ranges. The latter indicates that duct cleaning itself could be a source of indoor pollutants. Increased particle exposure during and after DC has negative health implications. Indeed, fine particles exposure has been linked to morbidity and mortality outcomes (Schwartz and Neas, 2000).

Further, some biocides used in DC are classified as pesticides (Godish, 2003; Sondossi, 2004). The USEPA noted that exposures to airborne biocides that have not been approved for use in HVAC systems may cause detrimental health effects equal to or worse than those caused by the bio-contaminants exposure that the biocides are intended to control (EPA, 2006). Other disinfectants used during DC, notably ozone, are also problematic (Hubbard, 2006; EPA, 2001). Reactions of ozone emitted indoors during these activities can provide a large source of secondary pollutants, some which are known irritants and listed as toxic air contaminants (Weschler, 2006). Post-cleaning ventilation system operation may increase the spread of the biocides or disinfectants and their byproducts throughout occupied building zones.

Limitations

Conference papers on this topic are numerous and potentially informative. Their exclusion from this review was primarily based on their lack of fully peer-reviewed status, but also due to the difficulty in finding all relevant papers in conference literature. This study was conducted by one reviewer – thus, there is no blinding or panel arbitration to minimize bias. Other limitations are biases that are actually inherent in the published studies such as bias from selection of problem buildings (a substantial issue in some of the reviewed studies) and generalizability of the results.

Future research

Standardized dust contamination measurement is needed considering DC performance requires accurate characterization of pre and post cleaning measurements. More research is required to assess whether duct cleanliness or cleaning can indeed improve IAQ, reduce energy consumption, increase air flow rates and enhance HVAC system performance. To gain more information about mechanisms associating poor duct cleanliness and health effects, future research should test new hypothesis such as effects of specific physical, chemical or microbial agents. Further research is advocated for studying the health benefits of DC in a controlled study; DC activities should be performed using a blind study design such that the researchers who assess the outcomes are not be able to distinguish between intervention and control groups. DC health risks associated with particle resuspension, use of biocides, sealants and encapsulant should also be studied.

CONCLUSION

Ventilation duct cleaning is widely advocated to provide good indoor air quality, health benefits, enhance ventilation system performance and operating life, and offer energy and maintenance cost savings. This review found that there is clear evidence that under normal operating conditions, ventilation ducts can be contaminated with dusts and serve as reservoirs for microbials to proliferate. While no field studies have correlated good IAQ with duct cleanliness, controlled experimental studies revealed that resuspension of deposited contaminants on the duct surfaces can translate to higher exposure levels indoors. However, this scientific review concludes that there is poor evidence that duct cleaning can improve or provide good indoor air quality. Despite the high efficiencies in contaminant removal within the ducts, cleaning effectiveness in reducing different indoor air pollutants vary widely, and in many cases, post-cleaning air pollutants concentrations were higher than pre-cleaning levels. There are also health concerns in the use of biocides, sealants and encapsulants during some cleaning process. This review also concludes insufficient evidence exists that duct cleaning can alleviate sick building syndrome symptoms of occupants, improve air flow in ducts and reduce energy consumption. On the basis of this review, the need for duct cleanliness has to be properly balanced by the probable generation of indoor pollution and subsequent potential health risks.

ACKNOWLEDGMENTS

This work is funded by the Canadian government's Clean Air Agenda, NRC-IRC Indoor Air Initiative research grant. The author appreciates the excellent ideas and comments from the Indoor Air Initiative Technical Advisory Committee and Duct Cleaning Workshop participants. The author is grateful to Robert Magee and Don Fugler for the contribution in the initial draft of this manuscript. The author also greatly benefited from the helpful and constructive comments provided by the reviewers.

REFERENCES

Ahmad, I., Tansel, B., Mitrani, J.D. (2001) 'Effectiveness of HVAC duct cleaning procedures in improving indoor air quality', *Environ. Monit Assess*, 72, 265-276.

Arundel, A.V., Sterling, E.M., Biggin, J.H., Sterling, T.D. (1986) 'Indirect health effects of relative humidity in indoor environments', *Environ Health Perspect*.65, 351-361.

Asikainen, V., Pasanen, P., Liesivuori , J. (2003) 'Mineral oil residues on HVAC components: measuring methods', *Build Environ*, 38, 1057−1061.

Auger, M. (1994) 'Efficiency of residential duct cleaning.' Project No. 93-2-001. Canada Mortgage and Housing Corporation, Ottawa, Canada.

Bernstein, R.S., Sorenson, W.G., Garabrant, D., Reaux, C., Treitman, R.D. (1983) 'Exposures to respirable, airborne Penicillium from a contaminated ventilation system: clinical, environmental and epidemiological aspects', *Am Ind Hyg Assoc J*, 44, 161-169.

Brosseau, L.M., Vesley, D., Kuehn, T.H., Melson, J., Han, H.S. (2000a) 'Duct cleaning: A review of associated health effects and results of company and expert surveys', *ASHRAE Trans*, 106, 180-187.

Brosseau, L.M., Vesley, D., Kuehn, T.H., Melson, J., Han, H.S. (2000b) 'Methods and criteria for cleaning contaminated ducts and air-handling equipment', *ASHRAE Trans*, 106, 188-189.

CEN. (1997) 'Ventilation for buildings − Ductwork − Requirements for ductwork components to facilitate maintenance of ductwork systems' European Committee for Standardization, Brussels, European Prestandard, (ENV 12097).

Chang, J.C.S., Foarde, K.K., VanOsdell, D.W. (1996) . 'Assessment of fungal (*Penicillium chrysogenum*) growth on three HVAC duct materials', *Environ Int*, 22, 425-431.

Cook, T.D., Campbell, D.T. (1979). *Quasi experimentation: Design and analysis for field settings,* Chicago, Rand McNally College Publishing Company.

Douwes, J., van der Sluis, B., Doekes, G., van Leusden, F.,Wijnands, L., van Strien, R., Verhoeff, A., Brunekreef, B. (1999) 'Fungal extracellular polysaccharides in house dust as a marker for exposure to fungi: relations with culturable fungi, reported home dampness, and respiratory symptoms', *J Allergy Clin Immunol*, 103, 494-500.

EPA. (1997) 'Should you have the air ducts in your home cleaned?' EPA-402-K-97-002. Research Triangle Park: U.S. Environmental Protection Agency, Indoor Environment Division, Office of Air and Radiation.

EPA. (2001) 'Mold remediation in schools and commercial buildings. Investigating, evaluating, and remediating moisture and mold problems'. EPA-402-K-01-001. Research Triangle Park: U.S. Environmental Protection Agency, Indoor Environment Division, Office of Air and Radiation.

EPA. (2006) 'Pesticide Registration (PR) Notice 2006-A Draft: Draft Pesticide Registration Notice Use of Antimicrobial Pesticide Products in Heating, Ventilation, Air Conditioning and Refrigeration Systems (HVAC&R)'. U.S. Environmental Protection Agency, Office of Pesticide Programs. http://www.epa.gov/opppmsd1/PR_Notices/prdraft_hvacr_2006.htm

Ezeonu, I. M., Noble, J.A., Simmons, R.B., Price, D.L., Crow, S.A., Ahearn, D.G. (1994) 'Effect of relative humidity on fungal colonization of fiberglass insulation', *App Environ Microbiol*, 60, 2149-2151.

Figley, D. (1994) 'Use of biocides by residential duct cleaners'. Canada Mortgage and Housing Corporation, Ottawa, Canada.

Fitzner, K., Müller, B., Lußky, J., Küchen ,V. (2000) 'Final report task 2 of AIRLESS. Design, operation and maintenance criteria for air handling systems and components for better indoor air quality and lower energy consumption'. Pre-Norminative Research. Research funded in part by the European Commission in the framework of the Non Nuclear Energy Programme Joule III. Hermann-Rietschel-Institute for Heating and Air-Conditioning of the Technical University of Berlin (Contract JOR3- CT97–0171).

Foarde, K.K., VanOsdell, D.W., Chang, J.C.S. (1996) 'Evaluation of fungal growth on fiberglass duct materials for various moisture, soil, use, and temperature conditions', *Indoor Air*, 6, 83-92.

Foarde, K.K., VanOsdell, D.W., Myers, E., Chang, J.C.S. (1997) 'Investigation of contact vacuuming for remediation of fungally contaminated duct materials', *Environ Int*, 23, 751-762.

Foarde, K.K., Menetrez, M.Y. (2002) 'Evaluating the potential efficacy of three antifungal sealants of duct liner and galvanized steel as used in HVAC systems', *J Ind Microbiol Biotech,* 29, 38 –43.

Fortmann, R., Gentry, G., Foarde, K.K., VanOsdell, D.W., Kulp, R.N. (1997) 'Results of a pilot field study to evaluate the effectiveness of cleaning residential heating and air conditioning systems and the impact on indoor air quality and system performance'. EPA Contract No. 68-D4-0005, Work Assignment No. 2-030, Research Triangle Institute, US Environmental Protection Agency, Office of Research and Development, Washington D.C.,USA.

Fransson, J.I., Ruud, S.H., Rosell, L. (1995) 'Rena ventilationskanaler'. SP-Rapport:38, Sveriges Provnings- och Forskningsinstitut (SP), Energiteknik/Kemisk Analys, Borås, Sweden.

Fugler, D., Auger, M. (1994) 'A first look at the effectiveness of residential duct cleaning', *JAWMA*, 44, 2- 16.

Garrison, R.A., Robertson, L.D., Koehn, R.D., Wynn, S.R. (1993) 'Effect of heating-ventilation-air conditioning system sanitation on airborne fungal populations in residential environments', *Ann Allergy*, 71, 548-556.

Godish, T. (2003) *Air quality*, US. Fourth edition, Lewis publishers.

Górny, R.L., Reponen, T., Willeke, K., Schmechel, D., Robine, E., Boissier, M., Grinshpun, S.A. (2002) 'Fungal fragments as indoor air biocontaminants', *App Environ Microbiol*, 68, 3522–3531.

Gordis, L. (1996) *Epidemiology*, Philadephia, W.B. Saunders Company.

Groen, D. (1995) 'A case study in the use of mechanical insulation repair coatings', *Healthy Buildings*, pp. 23-24.

HVCA. (2005) 'Guide to good practice: Internal cleanliness of ventilation systems. (HVCA TR19)'. Heating and Ventilating Contractors' Association (HVCA). London. UK.

Holopainen, R., Asikainen, V., Pasanen, P., Seppänen, O. (2002a) 'The field comparison of three measuring techniques for evaluation of the surface dust level in ventilation ducts', *Indoor Air* 12, 47-54.

Holopainen, R., Tuomainen, M., Asikainen ,V., Pasanen, P, Säteri, J., Seppänen, O. (2002b) 'The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations', *Indoor Air*, 12, 191-197.

Holopainen, R., Asikainen, V., Tuomainen, M., Björkroth, M., Pasanen, P., Seppänen, O. (2003) 'Effectiveness of duct cleaning methods on newly installed duct surfaces', *Indoor Air,* 13, 212-222.

Hubbard, H.F. (2006) 'Building disinfection chemistry: heterogeneous consumption of gaseous disinfecting agents and resulting by-product formation'. PhD thesis. The University of Texas at Austin.

Hyvarinen, A., Reponen, T., Husman, T., Ruuskanen, J., Nevalainen, A. (1993) 'Characterizing mold problem buildings – concentrations and flora of viable fungi', *Indoor Air* , 3, 337-343.

Immonen, J., Laitinen, S., Taskinen, T., Pekkanen, J., Nevalainen, A., Korppi, M. (2002) 'Mould-specific immunoglobulin G antibodies in students from moisture- and mould-damaged schools: a 3-year follow-up study', *Ped Allergy Immunol*. 13, 125-128.

JADCA-02, (1997) 'Light transmission measurement method'. Research report of the Japan Air Duct Cleaners Association, Tokyo, Japan, JADCA.

Kanaani, H., Hargreaves, M., Ristovski, Z., Morawska, L. (2008) 'Deposition rates of fungal spores in indoor environments, factors effecting them and comparison with non-biological aerosols', *Atmos Environ*, 42, 7141-7154.

Kanaani, H., Hargreaves, M., Ristovski, Z., Morawska, L. (2009) 'Fungal spore fragmentation as a function of airflow rates and fungal generation methods', *Atmos Environ*, 43, 3725-3735.

Kolari, S., Heikkilä-Kallio, U., Luoma, M., Pasanen, P., Korhonen, P., Nykyri, E., Reijula, K. (2005) 'The effect of duct cleaning on perceived work environment and symptoms of office employees in non-problem buildings', *Build Environ*, 40, 1665-1671.

Kristensen, P. (1992) 'Bias from nondifferential but dependent misclassification of exposure and outcome', *Epidemiology*, 3, 210–215

Kvasnak, W., Ahmadi, G., Bayer, R., Gaynes, M. (1993) 'Experimental investigation of dust particle deposition in turbulent channel flow', *J Aerosol Sci*, 24, 795-815.

Levetin, E. (1995) 'Fungi'. In: *Bioaerosols*, Boca Raton, Lewis Publishers: 87-120.

Luoma, M., Pasanen, A-L., Pasanen, P., Fan, Y. (1993) 'Duct cleaning - a literature survey'. *Air Infiltration Review*. 14, 1-5.

Mendell, M.J., Fisk, W.J., Petersen, M.R., Hines, C.J., Dong, M., Faulkner, D., Deddens, J.A., Ruder, A.M., Sullivan, D., Boeniger, M.F. (2002) 'Indoor particles and symptoms among office workers: results from a double-blind cross-over study', *Epidemiology*, 13, 296-304.

Mendell, M.J., Lei-Gomez, Q., Mirer, A.G., Seppänen, O., Brunner, G. (2008) 'Risk factors in heating, ventilating, and air-conditioning systems for occupant symptoms in US office buildings: the US EPA BASE study', *Indoor Air* 18, 301-316.

Miguel, A.F., Reis, A.H., Aydin, M. (2004) 'Aerosol particle deposition and distribution in bifurcating ventilation ducts.' *J Hazardous Materials*, 116, 249-255.

Miller-Leiden, S., Lobascio, C., Nazaroff, W.W., Macher, J.M. (1996) 'Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control', *JAWMA*, 46, 869-882.

Mølhave, L., Schneider, T., Kjærgaard, S.K., Larsen, L., Norn, S., Jørgensen, O. (2000) 'House dust in seven Danish offices', *Atmos Environ*, 34, 4767-4779.

Morey, P.R. (1988) ‘Experience on the contribution of structure to environmental pollution’. In R. B. Kundisin (ed.), Architectural design and indoor microbial pollution. Oxford University Press, New York: 40-79.

NADCA. (2006) ‘Assessment, cleaning and restoration of HVAC systems (ACR 2006)’. NADCA National air duct cleaners association. Washington, D.C

NEMI. (2002) ‘Indoor air quality (IAQ) market research’. National Energy Management Institute (NEMI). Report by Management Consultants to the Construction Industry (FMI).

Nielsen, J.B., Valbjorn, O., Gravesen, S., Molhave, L. (1990) ‘Stov i ventilationsanlaeg Horsholm’. Statens Byggeforskningsinstitut.34 pp. SBI-Rapport 206. (in Danish)

Nielsen, K.F., Gravesen, S., Nielsen, P.A., Andersen, B., Thrane, U., Frisvad, J.C. (1999) ‘Production of mycotoxins on artificially and naturally infested building materials’, *Mycopathologia*, 145: 43-56.

Nyman, E., Sandstrom, N. (1991) ‘Mikroorgansme i ventilations system Sweden’. Byggforskningsrdet. 38 pp. R45 (in Swedish).

Park, J.H., Cox-Ganser, J.M., Kreiss, K., White, S.K., Rao, C.Y. (2008) ‘Hydrophilic fungi and ergosterol associated with respiratory illness in a water-damaged building’, *Environ Health Perspect,* 116, 45-50.

Pasanen, A-L., Pasanen, P., Jantunen, M.J., Kalliokoski, P. (1991) ‘Significance of air humidity and air velocity for fungal spore release into the air’, *Atmos Environ.* 25, 459-462

Pasanen, P., Pasanen, A-L., Jantunen, M.J., (1993) ‘Water condensation promotes fungal growth in ventilation ducts. *Indoor Air*, 3, 106-112.

Pasanen, P., Pasanen, A-L., Kalliokoski, P. (1995) ‘Hygienic aspects of processing oil residues in ventilation ducts’, *Indoor Air*, 5, 62–68.

Pasanen, A-L., Kujanpää, L., Pasanen. P,, Kalliokoski, P., Blomquist, G. (1997) ‘Culturable and total fungi in dust accumulated in air ducts in single-family houses’, *Indoor Air* 7, 121-127.

Pasanen, P. (1998) ‘Emissions from the filters and hygiene of air ducts in the ventilation systems of office buildings’. Doctoral dissertation, Department of Environmental Sciences, University of Kuopio, Kuopio, Finland.

Puhakka, E., Kärkkäinen, J., Jyrkiäinen, J. (1992) ‘Tuloilmakanaviston puhdistustyön seuranta esimerkkitapauksen avulla (Monitoring the cleaning of supply air ducts using a case study)’ . LVIS 2000, Report 14, Espoo, pp. 82−88. (In Finnish).

Rylander, R. (1999) ‘Indoor air-related effects and airborne (1→3)-beta-D-glucan’, *Environ Health Perspect,* 107 (suppl 3), 501-503.

Schata, M., Jorde, W., Elixmann, J.H., Linskens, H.F. (1989) ‘Allergies to mold caused by fungal spores in air conditioning equipment’, *Environ Int*, 15, 177-179.

Schleibinger, H., Laussmann, D., Bornehag, C-G., Eis, D., Rueden, H. (2008) ‘Microbial volatile organic compounds in the air of moldy and mold-free indoor environments’, *Indoor Air*, 18, 113-124.

Schneider, T., Kildesø, J., Petersen, O.H., Kloch, N.P., Løbner, T. (1996) ‘Design and calibration of a simple instrument for measuring dust on surfaces in the indoor environment’, *Indoor Air*, 6, 204-210.

Schwartz, J., Neas, L.M. (2000) ‘Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren’, *Epidemiology*, 11, 6–10.

Seppänen, O., Fisk, W.J. (2002) ‘Association of ventilation system type with SBS symptoms in office workers’, *Indoor Air* 12, 98-112.

Shelton, B.G., Kirkland, K.H., Flanders, W.D., Morris, G.K. (2002) ‘Profiles of airborne fungi in buildings and outdoor environments in the United States’, *App Environ Microbiol*, 68, 1743-1753.

Sieber, W.K., Staynor, L.T., Malkin, R., Petersen, M.R., Mendell, M.J., Walligford, K.M., Crandall, M.S., Wilcox, T.G., Reed, L. (1996) ‘The National Institute for Occupational Safety and Health Indoor Environmental Evaluation Experience, Part Three: Associations between environmental factors and self-reported health conditions’, *App Occ Environ Hyg*, 11, 1387–1392.

Sippola, M.R., Nazaroff, W.W. (2003) ‘Modeling particle loss in ventilation ducts’, *Atmos Environ,* 37, 39-40: 5597-5609.

Sondossi, M. (2004) ‘Biocides: Nonpublic health, nonagricultural microbials’. In (Eds) Schaechter M, Lederberg J. *The desk encyclopedia of microbiology*. Oxford, UK, Elsevier Academic Press.

Szponar, B., Larsson, L. (2000) ‘Determination of microbial colonisation in water-damaged buildings using chemical marker analysis by gas chromatography- mass spectrometry’, *Indoor Air,* 10: 13-18.

Toivola, M., Nevalainen, A., Alm, S. (2004) ‘Personal exposures to particles and microbes in relation to microenvironmental concentrations’, *Indoor Air* 14, 5: 351-359

Tsay, A., Roman, M.C., Chapman, E.L., Chapman, M.D. (2000) 'Air duct cleaning to reduce allergen levels in the home - is it worthwhile?' *J Allergy Clin Immunol*, 105, 1, Part 2, S271.

Wallin, O. (1991) 'Klimat och byggnader. Nr 1/1991'. Second edition. Stockholm, Kungliga tekniska hgskolan. Intitutionen fr uppvrmnmgs- och ventilationsteknik (in Swedish).

Wan, G.H., Li, C.S. (1999) 'Indoor endotoxin and glucan in association with airway inflammation and systemic symptoms', *Arch Environ Health*, 54 , 172-179.

Weschler, C.J. (2006) 'Ozone's impact on public health: contributions from indoor exposures to ozone and products of ozone-initiated chemistry', *Environ Health Perspect*, 114, 1489-1496.

Weschler, C.J., Nazaroff, W.W. (2008) 'Semivolatile organic compounds in indoor environments', *Atmos Environ*, 42, 9018-9040.

Yoshizawa, S., Ito, H., Kumagai, K., Shizawa, K., Shimizu, S., Abe, S., Ichiki, T. (1997) 'Methods to evaluate duct cleaning efficiency'. JADCA-01, Japanese Air Duct Cleaners Association, Tokyo, Japan.

Zhao, B., Chen, J.J. (2006) 'Numerical analysis of particle deposition in ventilation duct', *Build Environ*, 41, 710-718.

Table 1 Surface dust sampling methods

Evaluation method	Application	Measurement units	Reference
Gravimetric			
Gravimetric vacuum test method is commonly used as a reference method for evaluating the dust accumulation on the duct surface.	Evaluation of cleaning work	g/m^2	NADCA, 2006; Brosseau et al., 2000b
Gravimetric wiping method uses non-woven cloth or cloth applied with solvent, is an efficient method of collecting dust on the duct surface.	Evaluation of cleaning work	g/m^2	Fitzner et al., 2000; Brosseau et al., 2000b
Gravimetric tape method is fast and applicable to relatively low dust accumulation in the field.	Evaluation of cleaning work	g/m^2	Fransson et al., 1995; Pasanen, 1998; Brosseau et al., 2000b
Optical			
Sampling using gelatine tapes or or semi-transparent engineering adhesive tapes- determining percentage reduction of light transmission through a transparent adhesive tape contaminated with dust compared to its clean state	Evaluation of cleaning work	%	Schneider et al., 1996; JADCA-02, 1997; Fransson et al., 1995; Brosseau et al., 2000b
Thickness mesurement			
Sampling by determining dust deposit thickness test (D.T.T.) method with an instrument or with a comb.	Evaluation of cleaning work	µm	HVCA, 2005; Brosseau et al., 2000b
Visual			
Visual inspection by trained and experienced inspectors, surface comparison test with the contact vacuum equipment, as well as use of special tools such as borescopes, mirrors and remote-controlled video-camera robots with illumination capability.	Evaluation of cleaning work Commissioning for new air ducts	–	NADCA, 2006; HVCA, 2005; Brosseau et al., 2000b

Table 2 Summary of the results on dust settled in the inner surfaces of building air ducts (n=number of buildings studied).

Study	Building types	Building age (years)	n	Method	Filter class	Mean (range) dust concentration (g/m^2)	Annual dust accumulation (g/m^2)
Nielsen et al. (1990)	Office, schools	3 to 29	13	Razor blade, vacuum method	…	6.8 (1.1-50.9)	0.7
Auger (1994)	Residential	0 to 45	33	Vacuum method	…	0.2 (< DL-2.7)	<0.1
Pasanen et al. (1995)	Office	3 to 34	14	Plastic blade, vacuum method	EU2-7	13.2 (1.2-158)	1.0
Fransson et al. (1995)	Residential	19 to 37	5	Tape method	EU2-6	2.6 (1.9-3.0)	0.2
Fortmann et al. (1997)	Residential	9 to 35	9	Vacuum method	…	6.4 (1.5-26.0)	…
Holopainen et al. (2002b)	Office, schools, daycare[a]	0 (new construction)	9	Vacuum method	…	0.9 (0.4-2.9)	…
	Cinema, office, schools, daycare[b]	0 (new construction or recently renovated)	9	Vacuum method	…	2.3 (1.2-4.9)	…
Kolari et al. (2005)	Office	4 to 26	10	Vacuum method	EU4-8	8.8	…

[a] buildings with proper cleanliness category or protection methods; [b] buildings with no specific requirements for protection methods;
DL: detection limit
…: data not available

Table 3 Summary of the results on viable fungi and bacteria settled in the inner surfaces of building air ducts (n=number of buildings studied).

Study	Building types	Building age (years)	n	Method	Filter class	Viable fungi concentration range (x10^3)	Viable bacteria concentration range (x10^3)
Nyman and Sandstrom (1990)	Office, daycare centers	…	6	Swab	EU2-7	0.001 – 0.015 CFU/m^2	0.001 – 0.022 CFU/m^2
Auger (1994)	Residential	0 to 45	33	contact plates	…	< DL-80 CFU/m^2	<DL-320 CFU/m^2
Fortmann et al. (1997)	Residential	9 to 35	9	Swab	…	13-250 CFU/m^2	0.005-1.5 CFU/m^2
Kolari et al. (2005)	Office	4 to 26	10	Direct cultivation	EU4-8	8-17 CFU/m^2	0.012 CFU/m^2
Pasanen et al. (1995)	Office	3 to 34	14	Direct cultivation	EU2-7	0.3-24 CFU/g	…
Pasanen et al. (1997)	Residential	2 to 16	24	Direct cultivation	EU3-5	2-6100 CFU/g	…

DL: detection limit
…: data not available
[a] total microbial counts

Table 4 Summary of duct cleaning techniques

Technique	Method of removing dust	Reference
Dry method		
Contact vacuuming	Suction and brushing using a brush head to transfer dirt to a collection point.	Auger, 1994; Foarde et al., 1997; Ahmad et al., 2001;
Compressed air cleaning	Dust is dislodged from surfaces using airflow movement (via air nozzle) and collected using a vacuum collector.	Ahmad et al., 2001; Holopainen et al., 2003;
Mechanical brushing	A brushing or mechanical action is used to dislocate dust from surfaces and transferred to a vacuum collector. The most commonly used is the rotating brushes.	Auger, 1994; Ahmad et al., 2001; Holopainen et al., 2003;
Wet method		
Hand washing	Cleaning components surfaces by hand using tools such as brushes, sponges, cloths and a source of water with a cleaning agent.	Brosseau et al., 2000b
Water jet spray	Liquid solutions are sprayed or wet-fogged to adhere, bond, or fibre- fixed particles that were not removed by mechanical cleaning	Luoma et al, 1993; Brosseau et al., 2000b
Chemical disinfection	The use of biocides and sealants to coat and encapsulate duct surfaces. Some duct cleaning contractors introduce ozone as part of the disinfection process.	Luoma et al, 1993; Figley, 1994; Brosseau et al., 2000b; EPA, 1997.

Table 5 Duct cleaning performance in reducing surface dusts, microorganisms and residual oil [a]

Study	Setting	Duct cleaning method	Pollutant	Pre- cleaning concentration (unit)	Post- cleaning concentration (unit)[b]	Efficiency (%)
Surface dust						
Fugler and Auger (1994)	Field studies – residential	mechanical brush	Dust [c, d]	2 (g/m^2)	1 (g/m^2)	50.0
Foarde et al. (1997)	Laboratory	contact vacuum	Dust	7.3 to 96.5 (g/m^2)	3.5 to 13.3 (g/m^2)	32.1 to 93.6
Holopainen et al. (2003)	Field studies - New Office, Schools	mechanical brush	Dust	0.6 to 0.9 (g/m^2)	0.1 to 0.2 (g/m^2)	66.6 to 87.5
	Field studies - New Office, Schools	compressed air	Dust	5.4 (g/m^2)	0.3 (g/m^2)	94.4
Holopainen et al. (2003)	Laboratory	mechanical brush	ASHARE Test Dust	6.0 to 8.6 (g/m^2)	0.2 to 0.8 (g/m^2)	95.0 to 97.7
		compressed air	ASHARE Test Dust	5.3 to 7.2 (g/m^2)	0.1 to 1.0 (g/m^2)	86.1 to 98.6
		mechanical brush	Construction Site Dust	1.0 to 10.1 (g/m^2)	<DL (g/m^2)	95.0 to 99.5
		compressed air	Construction Site Dust	3.5 (g/m^2)	<DL (g/m^2)	98.6
Microorganisms						
Fugler and Auger (1994)	Field studies – residential	mechanical brush, compressed air	Fungi and Bacteria [c]	3.2 (CFU/cm^2)	2.3 (CFU/cm^2)	26.6
Foarde et al. (1997)	Laboratory	contact vacuum	*P. chrysogenum*	0.01 to 41 (CFU/cm^2)	0.08 to 4.8(CFU/cm^2)	-35.7 to 99.7
	Laboratory	contact vacuum	*A. versicolor*	0.01 to 1800 (CFU/cm^2)	0.01 to 0.1 (CFU/cm^2)	0 to 99.9
Residual oil						
Holopainen et al. (2003)	Laboratory	mechanical brush	Residual Oil	33 to 119 (mg/m^2)	16 to 52 (mg/m^2)	95.0 to 99.0
Holopainen et al. (2003)		compressed air	Residual Oil	9 (mg/m^2)	15 (mg/m^2)	98.6

[a] Studies where the intervention uses only duct cleaning are tabulated; [b] A value of half the detection limit is used; [c] statistical tests performed; [d] statistically significant reduction between pre and post cleaning ($P<0.05$); …: data not available

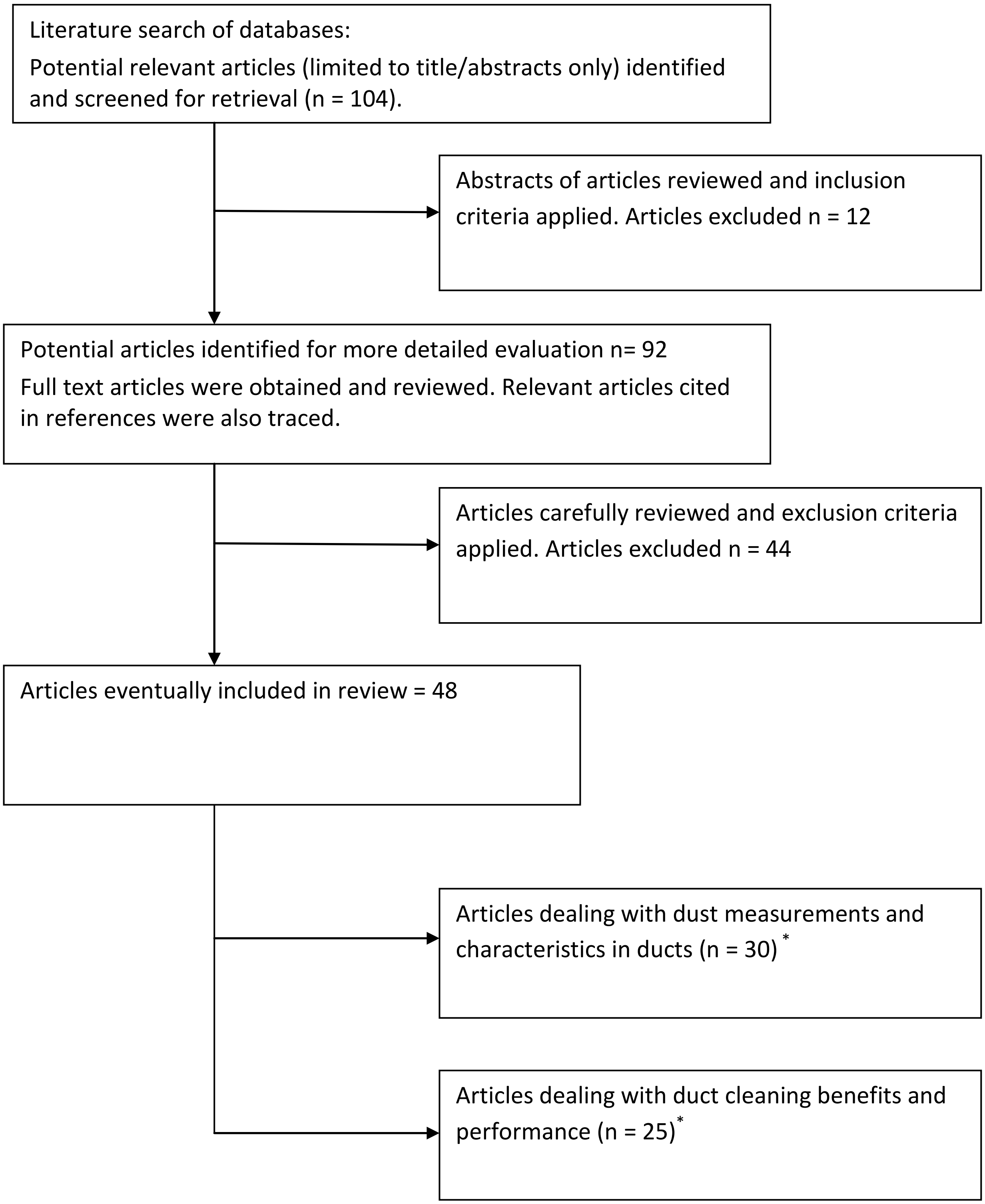
Table 6 Duct cleaning performance in reducing indoor air pollutants. [a]

Study and building types	Duct cleaning method	Pollutant (unit)	Pre- cleaning indoor concentration	Post- cleaning indoor concentration [b]	Pre- cleaning outdoor concentration [e]	Post- cleaning outdoor concentration [e]	Effectiveness (%) [f] based only on indoor levels	Effectiveness (%) [g] considering in/out levels	Comments [h]
Ahmad et al. (2001) Residence	contact vacuum	Particles: > 0.3 μm ($x10^3$ no/L)	14.4 to 44.3	3.7 to 5.1	2.4	3.2	-158 to 38.6	-11 to 70	Post - DC samples were taken two days after pre – DC measurements.
	mechanical brush		40.4 to 175.6	180.0 to 231.8	49.9	207.2	-473 to -2.5	-38 to 75	
	compressed air		28.2 to 52.0	64.9 to 198.9	40.4 to 40.6	33.4	-282 to -130	-363 to -180	
	contact vacuum	Particles: > 1.0 μm ($x10^3$ no/L)	9.4 to 3.4	3.7 to 5.1	2.4	3.2	-49 to 62	-11 to 70	
	mechanical brush		6.9 to 7.3	3.5 to 6.3	3.1	1.0	8 to 51	-181 to -41	
	compressed air		4.7 to 5.3	2.6 to 4.7	1.7	1.9	11 to 45	20 to 50	
	contact vacuum	viable fungi (CFU/m^3)	300 to 410	200 to 610	…	…	-103 to 51	…	
	mechanical brush		280 to 300	180 to 300	…	…	0 to 36	…	
	compressed air		560 to 820	130 to 280	…	…	66 to 77	…	
Auger (1994) Residence	mechanical brush, compressed air	Particles: ($\mu g/m^3$) [c]	120	310	…	…	-158	…	Pre-cleaning tests were less than a week before DC while post-cleaning tests were 2 to 7 days after DC.

Bernstein et al. (1983) Office	No information provided	viable fungi (CFU/m^3)	90 to 6000	20 to 40	…	…	78 to 99	…	Post - DC measurements were taken two and half months after pre – DC measurements
Fugler and Auger(1994) Residence	mechanical brush, compressed air	viable fungi and bacteria (CFU/m^3) [c, d]	513	380	…	…	26	…	Pre-DC tests were less than a week before cleaning while post-DC tests were 2 to 7 days after DC.

[a] Studies where the intervention uses only duct cleaning are tabulated; [b] A value of half the detection limit is used; [c] statistical tests performed; [d] statistically significant reduction between pre and post cleaning ($P<0.05$); [e] …: outdoor data not given. [f] Effectiveness calculated using indoor concentrations only; [g] Because co-varying outdoor pollutant concentrations can have an influence on the indoor pollutant concentrations, effectiveness using indoor -outdoor ratio concentrations are provided as well; [h] No report of any changes in the operating conditions or parameters pre and post-cleaning.

Figure 1 Stages of systematic analysis and categories of articles.



*articles from both categories are not mutually exclusive