Estimation of endotoxin inhalation from shower and humidifier exposure reveals potential risk to human health

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ABSTRACT

This paper investigates potential exposure to endotoxin in drinking water through the inhalation of aerosols generated by showers and humidifiers. Adverse health effects attributable to the inhalation of airborne endotoxin in various occupational settings are summarized, as are controlled laboratory inhalation studies. Data from investigations estimating aerosolization of particulate matter by showers and humidifiers provide a basis for similar analyses with endotoxin, which like minerals in water, is nonvolatile. A theoretical assessment of the inhalation of aerosolized endotoxin showed that while the likelihood of an acute response while showering is minimal, the same is not true for humidifiers. Ultrasonic and impeller (cool mist) humidifiers efficiently produce large numbers of respirable particles. It is predicted that airway inflammation can occur if humidifier reservoirs are filled with tap water, sometimes even at typical drinking-water distribution-system endotoxin concentrations. Higher endotoxin levels occasionally found in drinking water (>1,000 EU/ml) are very likely to induce symptoms such as chills and fever if used as humidifier feed water. While it is unlikely that treated drinking water would contain extremely high endotoxin levels occasionally observed in cyanobacterial blooms (>35,000 EU/ml), the potential for serious acute health consequences exist if used in humidifiers.

Key words | drinking water, endotoxin, impeller humidifier, inhalation, shower, ultrasonic humidifier

INTRODUCTION

Endotoxins are a component of the lipopolysaccharide (LPS) complexes which make up a part of the outer layer of the cell walls of most Gram-negative bacteria (Prescott et al. 2002) and some cyanobacteria (Buttke & Ingram 1975; Sykora & Keleti 1981). LPS complexes are macromolecules composed of three main regions: lipid A, core polysaccharide, and “O” antigens (Braude 1982). The lipid A component is critical for all biological responses to endotoxin (Morrison et al. 1994; Prescott et al. 2002). Potential pathways of water-associated endotoxin exposure in humans include direct introduction into the blood stream by passage through semi-permeable dialysis membranes (in the case of haemodialysis patients) and by intravenous injection solutions contaminated with endotoxin. The significance of endotoxin in the bloodstream is well understood and measures are in place in the medical and pharmaceutical communities to limit the risk of such occurrences (British Pharmacopeia 1994; United States Pharmacopeia 1995). Although solutions for injection are made with drinking water, it is always pretreated, usually culminating in membrane filtration to remove endotoxin.

Endotoxin contact from drinking water through dermal abrasions is not well documented, although it is well known that bacterial penetration into wounds can lead to infection with associated complications. It is unlikely that endotoxin can penetrate intact human skin. Even if it were assumed...
that it could, the surface area of the alveolar region of the lungs (300 m²; Weibel 1985) and the lung’s efficiency with regard to transfer into blood far exceeds that of the dermis (2 m²; Rao & Brown 1993). While the most obvious route of endotoxin exposure from drinking water is ingestion, very little information concerning occurrence exists. Endotoxin has been detected in the plasma of otherwise healthy patients with irritable bowel disease but it is unclear if this originates from endotoxin uptake from water, food, or bacteria in the gut (indigenous or otherwise) (Caradonna et al. 2000). Virtually all patients suffering from cirrhosis of the liver also suffer, to some degree, from systemic endotoxemia (Bauer et al. 2002). The cause has been identified as overgrowth of bacteria in the small intestine, characterized by 10⁵ or more total colony forming units per milliliter of jejunal secretions (Bauer et al. 2002). In this case it would appear that endotoxin originates from localized bacterial growth as opposed to direct ingestion of endotoxin in food or water. There have been reports of an increased incidence of diarrhea in sewage treatment plant workers who have inhaled endotoxin but this response is not universal (Thorn & Rylander 1998; Rylander 1999). Rylander (1999) speculates that particles associated with sewage water aerosols are larger than those associated with dry organic dusts, resulting in substantial deposition in the nasopharyngeal area and transport to the gastrointestinal tract with subsequent inflammatory response in the gut mucosa.

This paper summarizes events associated with inhalation of endotoxin from drinking water, occupational airborne endotoxin exposure, data from recent studies involving controlled endotoxin inhalation experiments in humans, and endotoxin levels in water. A brief discussion of issues related to the formation and inhalation of aerosolized water droplets is followed by several theoretical assessments of the potential for adverse impacts to human health as a result of endotoxin inhalation while showering and in humidifier treated environments.

Inhaled endotoxin events associated with water

Rylander et al. (1978) were among the first to theorize that endotoxin was the causal agent in unexplained cases of fever after exposure to contaminated water in humidifiers and in a sauna (Kohler et al. 1976; Metzger et al. 1976; Pickering et al. 1976). This was accomplished by measuring endotoxin O antigen antibody titers in three subjects who developed ‘humidifier disease’ from a humidifier contaminated with two unidentified species of Flavobacterium. Endotoxin exposure-related symptoms such as breathing difficulties, cough, and fever were accompanied by increased white blood cell counts, increased proportions of segmented leukocytes, and increased levels of IgG immunoglobulins and antibodies (Rylander et al. 1978).

The earliest confirmed human exposures related to the inhalation of endotoxin from drinking water appear to have occurred in association with a ‘bathing fever’ epidemic of initially unknown etiology among 100 of the 1,000 inhabitants of Tampere, Finland in 1978 (Aro et al. 1980). Symptoms included cough, breathing difficulties, chills, fever, muscle pain, and aching of the joints. Muittari et al. (1980a, b) calculated that Tampere inhabitants who had experienced fever received a total inhaled endotoxin dose of 1.0 to 4.0 µg, or assuming a 70 kg human, 0.01 to 0.03 µg endotoxin/kg body weight. The endotoxin concentration in the contaminated water system ranged from 0.2 to 1.0 µg/ml. This converts to 200 to 1,000 ng/ml or about 2,000 to 10,000 endotoxin units (EU)/ml assuming 1 ng = 10 EU based on actual factors ranging from about 4 to 17 EU/ng (e.g. Burger et al. 1989; Chang et al. 2001). This factor (1 ng = 10 EU) has been applied to convert ng to EU throughout this paper, when actual conversions were not provided, because a uniform factor must be utilized in order to roughly standardize data collected prior to the implementation of EU. Following the outbreak, four of the previously affected subjects were given 2 x 2 ml (inhalation challenge) of contaminated tap water; within 4 h each developed a fall in single breath lung diffusion capacity as well as a fever with coughing and shortness of breath. The calculated doses of 0.01 to 0.03 µg/kg (10 to 30 ng/kg) are consistent with intravenous bacterial endotoxin doses which will induce fever (1 to 10 ng/kg weight, Anderson et al. 2002).

Humidifier disease has been documented in an occupational setting where airborne endotoxin levels ranged from 150 to 390 ng/m³ (Rylander & Haglund 1984). It was characterized by fever, chills, and chest tightness in affected
employees when a humidifier contaminated with *Pseudomonas* was operating.

A hypersensitivity pneumonitis event attributable to endotoxin inhalation at a community recreation complex in Westminster, Colorado is described by McGregor et al. (1993). Lifeguards reported symptoms including dry cough, chest tightening, shortness of breath, and sluggishness. The problem was traced to a deep pool with features including a water levitator, fan sprays, and wall spouts, some or all of which could have contributed to the aerosolization of endotoxin. After an ozone treatment system was installed, pool water endotoxin concentrations dropped from 95–120 ng/ml to less than 1 ng/ml; the symptoms in lifeguards subsequently disappeared. It is not clear whether the ozone controlled biological growth, removed the endotoxin directly, or involved some combination of the two.

Overall, while there are few studies describing outbreaks of adverse health effects associated with aerosolized endotoxin, they clearly occur on occasion. It is likely that given the generic symptoms at low doses (impaired breathing, cough, and quickly resolving fever) most incidents go unreported. All reported incidents have been associated with substantial bacterial contamination and/or the presence of high levels of aqueous endotoxin, along with an effective delivery vector.

### OCCUPATIONAL EXPOSURE TO INHALED ENDOTOXIN

In order to put the risk associated with waterborne aerosolized endotoxin into perspective it is useful to survey other airborne endotoxin exposure sources. Potential settings for endotoxin exposure are diverse and include: sawmills, paper recycling (repulping and deinking), fiberglass manufacturing, animal handling, grain handling, manure handling, cotton/textile milling, hemp processing, potato sorting, and cigar and cigarette manufacturing, among others (Rylander et al. 1985; Castellan et al. 1987; Dahlqvist et al. 1992; Christiani et al. 1993; Walters et al. 1994; Zejda et al. 1994; Milton et al. 1996; Rix & Lyne 1996; Louhelainen et al. 1997; Zock et al. 1998; Douwes et al. 2000; Reiman & Uitti 2000; Chang et al. 2001; Fishwick et al. 2001; Melbostad & Eduard 2001; Su et al. 2002). Aerosolized endotoxin concentrations vary widely both between and within occupational settings. For example, within swine enclosures, airborne endotoxin concentrations have been found to range from 438 to 41,307 EU/m³ (Zejda et al. 1994). The highest recorded concentration observed in the above referenced studies was 59,801 EU/m³ in a hemp processing plant (Fishwick et al. 2001). It should be noted though that some measurements were made in areas where there is limited human activity or at levels above or below breathing zones.

Several studies have shown that human health effects can be linked to aerosolized endotoxin in the workplace (Rylander et al. 1985; Castellan et al. 1987; NIOSH 1994; Smid et al. 1994; Milton et al. 1996; Keman et al. 1998; Vogelzang et al. 1998; Zock et al. 1998; Mandryk et al. 1999, 2000). An analysis of these studies suggests that as test methods and statistical analyses become more rigorous, endotoxin levels at which effects are observed are decreasing. The lowest dose resulting in a statistically significant health effect (FEV₁, forced expiratory volume or volume of air exhaled in 1.0 s—the first second) is 0.1 to 2 ng/m³ (Mandryk et al. 1999, 2000). Assuming that 1 ng = 10 EU, then this would correspond to 1 to 20 EU/m³ which is consistent with other studies showing effects at 40 to 53 EU/m³ (Milton et al. 1996; Zock et al. 1998).

In addition to changes in lung function measures, Mandryk et al. (2000) found that sawmill workers suffered from specific adverse health related symptoms when compared to a control population. The increased occurrence of chronic symptoms/conditions in green mill (fresh undried wood) workers was statistically significant in all cases and included cough, chronic bronchitis, regular blocked nose, sinus problems, flu-like symptoms, eye irritation, and throat irritation. Workers in both green and dry mills experienced statistically higher frequencies of regular runny nose, regular sneezing, and frequent headaches. Melbostad & Eduard (2001) surveyed Norwegian farmers for a variety of symptoms related to the eyes, nose, throat, and lower airway. They found a higher prevalence of at least one symptom in farmers that carried out tasks such as grain handling (34–55%), and handling of hay and tending of swine and poultry (26–35%). The prevalence of work-related symptoms in allergic farmers was 87% compared to 61% in those without allergies and 71% in...
male farmers versus 56% in female farmers. Observations in these studies are confounded by the fact that there are other constituents in dusts and aerosols found in certain occupational environments. For example, symptoms associated with endotoxin exposure are similar to those associated with fungal mycotoxicosis. Mycotoxins are not detected in the endotoxin assays but fungal-derived glucans do interfere. A test is available for glucans.

At least two studies have shown that outdoor air endotoxin concentrations can be substantially lower than those found in some indoor occupational settings. Hartung & Seedorf (1999) found that the median endotoxin concentration in outside air in twenty-two rural and eight urban settings was 0.36 ng/m$^3$, with the highest maximum concentration of 1.80 ng/m$^3$ occurring in the summer. No significant differences were found between rural and residential outdoor areas. Similarly, Su et al. (2002), while investigating airborne endotoxin concentrations in textile mills in Taiwan, measured endotoxin concentrations in a courtyard just outside the mills. They found outdoor concentrations of 1.6 and 3.4 ng/m$^3$ (16–34 EU/m$^3$) in Year 1 of the study and 0.4 and 41 ng/m$^3$ (4 and 410 EU/m$^3$) in Years 2 and 3, respectively. It is clear that indoor endotoxin levels may be orders of magnitude higher than would normally occur outdoors. Not surprisingly, there can also be substantial variability between buildings. Teeuw et al. (1994) showed endotoxin levels in buildings associated with ‘sick building syndrome’ to be six to seven times higher than those in control buildings (254 vs. 46 ng/m$^3$).

**Laboratory endotoxin inhalation studies in humans**

Endotoxin response can vary widely between individuals. There is a disconnect between the levels of endotoxins some people can tolerate without reporting symptoms and those which can clearly be measured or characterized in human studies. This could be attributable to the species of bacteria generating the endotoxin, the amount of endotoxin actually respiried, the size of particles with which the endotoxin is associated, and/or individual response variability (e.g. Laude-Sharp et al. 1990; Hansen et al. 1999; Koyama et al. 2000). Table 1 summarizes some controlled laboratory studies involving human volunteers. All studies used E. coli endotoxin with 4 of 5 using that from strain O26:B6 while the fifth used O11:B4. Although indicators of immunological activity and mild symptoms such as shortness of breath occur at inhaled doses around 5 μg, a dose of about 50 μg is required to elicit symptoms such as chills and fever (at least for E. coli O26:B6 endotoxin). For comparative purposes these doses have been assumed to correspond to roughly 50,000 and 500,000 EU, respectively.

Symptoms that were observed significantly more frequently 24 h following exposure to 40 μg (roughly 400,000 EU) of endotoxin than before, were breathlessness (29% of subjects), irritation in the throat (38%), dry cough (33%), headache (62%), heaviness in the head (71%) and unusual tiredness (57%) (Thorn & Rylander 1998). On the other hand, Michel (1998) indicates that the no-response threshold to acute inhalation of endotoxin is less than 0.5 μg, corresponding to 50 ng/m$^3$ (roughly 500 EU/m$^3$) of airborne endotoxin. The threshold may be lower for allergy and asthma sufferers. Eldridge & Peden (2000) demonstrated that an interaction between allergens and endotoxin in allergy sufferers produces a significant increase in total and differential inflammatory cell counts and in IL-6 and ECP concentrations. E. coli O26:B6 endotoxin was administered to volunteers at a dosage of 1,000 ng (roughly 10,000 EU). The allergen used was dust mite allergen (D. farinae at a dose of 100 AU).

**PROPOSED STANDARDS FOR INHALED ENDOTOXIN**

A few jurisdictions have proposed standards for inhaled dust borne endotoxins. The Health Council of the Netherlands has proposed an occupational exposure limit of 50 EU/m$^3$ (roughly 5 ng/m$^3$), based on inhalable dust exposure, measured as an eight hour time-weighted average (Health Council of the Netherlands 1998). This recommendation was based on observed decreases in FEV$_1$ (forced expiratory volume or volume of air exhaled in 1.0 s). Palchak et al. (1988) are quoted by Laitinen et al. (1992) as stating that a proposed occupational exposure limit for endotoxin is 30 ng/m$^3$ as an 8 h time-weighted average (no further details provided).

A 1993 endotoxin criteria document, prepared by the International Commission on Occupational Health
## Table 1

Survey of responses to inhaled endotoxin under laboratory conditions. All responses were statistically significant. Endotoxin was administered in 5% hypertonic saline water.

<table>
<thead>
<tr>
<th>Dose (μg)</th>
<th>Delivery system</th>
<th>Endotoxin origin</th>
<th>Response</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Jet nebulizer(^1)</td>
<td><em>E. coli</em> O26:B6</td>
<td>Decrease in sputum PMN(^2)</td>
<td>Michel <em>et al.</em> 1997</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td><em>E. coli</em> O26:B6</td>
<td>Increase in blood CRP(^3), blood PMN, sputum PMN, monocytes, MPO(^4)</td>
<td>&quot;</td>
</tr>
<tr>
<td>50</td>
<td>&quot;</td>
<td><em>E. coli</em> O26:B6</td>
<td>Increase in temperature(^5), blood PMN, blood &amp; urine CRP, sputum PMN, monocytes, lymphocytes, MPO, TNF-α(^6), ECP(^7)</td>
<td>&quot;</td>
</tr>
<tr>
<td>40</td>
<td>Nebulizer(^8)</td>
<td><em>E. coli</em> O26:B6</td>
<td>Decrease in FEV(_1)(^9) and FVC(^10); increase in MPO(^4) and ECP(^7)</td>
<td>Thorn &amp; Rylander 1998</td>
</tr>
<tr>
<td>≥ 6.5</td>
<td>Nebulizer(^11)</td>
<td><em>E. coli</em> O11:B4</td>
<td>≥ 20% decline in FEV(_1)</td>
<td>Kline <em>et al.</em> 1999</td>
</tr>
<tr>
<td>5</td>
<td>Closed-circuit ultrasonic nebulizer(^12)</td>
<td><em>E. coli</em> O26:B6</td>
<td>Induced neutrophil influx to airway, decreased phagocytosis in both airway and circulating cells, modified CD11b expression-no fever, myalgia, malaise, shortness of breath, chest tightness or hypotension observed</td>
<td>Alexis <em>et al.</em> 2003</td>
</tr>
<tr>
<td>5</td>
<td>Jet nebulizer(^3)</td>
<td><em>E. coli</em> O26:B6</td>
<td>Airway inflammation that correlated with CD14 expression and eosinophil numbers-asthmatics more sensitive</td>
<td>Alexis <em>et al.</em> 2001</td>
</tr>
</tbody>
</table>

---

\(^1\)Generated heterodisperse droplets with a mass median aerodynamic diameter of 1 to 4 μm, 9 μl per dose (Mefar MB3 dosimeter [Mefar, Brescia, Italy]).

\(^2\)Polymorphonuclear neutrophil luminol-enhanced chemiluminescence (could reflect a process of margination and/or extravascular sequestration of activated PMN); also referred to as airway neutrophilic inflammation (Alexis *et al.* 2001).

\(^3\)CRP = C-reactive protein.

\(^4\)MPO = myeloperoxidase.

\(^5\)Temperature increase was 0.7 °C.

\(^6\)TNF = tumor necrosis factor.

\(^7\)ECP = eosinophil cationic protein.

\(^8\)"Pari Boy" nebulizer (20 puffs [4 μl per dose] of endotoxin [500 μg/ml] up to a total of 40 μg).

\(^9\)Forced expiratory volume in one second (the first second).

\(^10\)Forced vital capacity.

\(^11\)DeVilbiss 646 powered by compressed air at 30 psi.

\(^12\)DeVilbiss 99 (total fluid volume = 10 ml).
DROPLETS AND AEROSOLS

Understanding exposure to endotoxins via inhalation of aerosolized water can be further complicated (relative to dust) by the nature of aerosols. Inhalation exposure for a nonvolatile compound such as endotoxin is a function of the volume of aerosol produced, the size distribution of the aerosols, growth, or shrinkage of aerosols, aerosol transport within the exposure area and the concentration of endotoxin in the water (Weisel et al., 1999).

Aerosols can be present in liquid form and can be formed when water droplets completely evaporate, leaving only particles that were contained in the droplet. Within the context of this study, aerosols are defined as airborne particles sufficiently small (diameter Dp ≤ 10 μm) that they do not rapidly settle out of air (as opposed to water droplets which are >10 μm) (Pandis & Davidson, 1999). Droplets are rapidly removed from inhalation environments by gravity (settling velocity of a 50 μm droplet is ~11 cm/s vs. ~0.3 cm/s for a 10 μm aerosol; Hinds, 1982), while aerosols (<10 μm) can persist in respirable indoor environments for hours (Pandis & Davidson, 1999). This delineation is important because droplets are too large to be respirable; the aerosol concentration needs to be estimated. Aerosols produced when droplets evaporate are expected to be liquid only at relative humidities exceeding 60% at ambient temperatures (Seinfeld & Pandis, 1997). Therefore, droplets larger than 10 μm are only important in the context of being aerosol precursors. In addition to evaporation, however, droplets can produce aerosols by impacting other solid or liquid surfaces (e.g., the human body, sink or shower surfaces etc.) (Seinfeld & Pandis, 1997). Gunderson & Witham (1988, as quoted in Pandis & Davidson, 1999) indicate that the effect of the collision of water droplets with human bodies is likely to be significant and probably cannot be neglected in estimating exposure.

If particles ≤10 μm are considered to be aerosols but water droplets >10 μm can evaporate, then is aerosol production quantified? Owen et al. (1992) indicated that the diameter of an aerosol particle (da) resulting from the complete evaporation of a droplet tap water with a diameter (dwp) will be given by da = 0.05 dwp. The authors assumed that the tap water contained 300 mg/L of total dissolved solids, and that the dissolved material had a density of 2.5 g/cm². Given the calculation, droplets with a diameter >200 μm can be ignored when quantifying aerosol exposure since those droplets will yield aerosol particles with a diameter >10 μm i.e. particles which are not respirable. As such, these authors assume, for the purposes of estimating inhalation exposure to aerosols, droplets with diameters larger than 200 μm can be ignored (i.e. larger droplets will produce nonrespirable, da > 10 μm, dry particles even if they completely evaporate).

Furthermore, from a settling perspective, water droplets in high humidity environments (e.g., in a shower) larger than 50 μm can be neglected for aerosol exposure estimates and those larger than 100 μm can be neglected in most other indoor environments (Pandis & Davidson, 1999). Droplets in excess of these values settle too rapidly to form substantial quantities of aerosols. During water evaporation, the mass concentration of nonvolatile aerosol components remains constant (as opposed to volatile components, which are transferred to the gas phase during volatilization). In some respects this simplifies the determination of inhaled endotoxin.

FACTORS INFLUENCING ENDOTOXIN EXPOSURE AND UPTAKE

Several factors should be considered when estimating human exposure to endotoxins: body weight, sources of inhalation, endotoxin concentrations in those sources, inhalation rates, as well as both exposure frequency and duration. Potential household water-related exposures include: bathing, dish washing (manual or automatic), clothes washing, beverage and food preparation, personal
washing, toilet use, household cleaning, cooking, and outdoor use. While all of these may contribute to airborne contaminant loading (particularly in the case of volatile compounds), most would not be important from the point of view of aerosolization of a nonvolatile compound such as endotoxin under conditions of typical usage. In high use environments such as stadium or theme park settings the risk to the occupationally-exposed from activities such as toilet flushing may be somewhat increased. Additional water-related exposures which would be more likely to include endotoxin aerosolization include showers, humidifiers, hot tubs, saunas, and pools in which fountains, showers, or aeration are present.

AEROSOLS IN SHOWERS

Although there is very little information in the literature related to aerosol inhalation exposure associated with most of the sources noted above, some information is available for showers and humidifiers. If inhalation exposure to aerosols is to be estimated one must know the rates of droplet/aerosol production (mass of droplets per unit of time per mass of water), other activity-related parameters (flux of water, showerhead type, etc.), and the size distribution of the droplets (Pandis & Davidson 1999). The characterization of shower generated aerosols is discussed in more detail by Keatin & McKone (1992; in Mercer 1999).

There are several sources of information for exposure assumptions associated with showering, and respiration rates and tidal volumes for humans of different ages at various levels of activity (James & Knuiman 1987; Hofmann et al. 1989; USEPA 1989; USEPA 1992; AIHC 1994; Page 1994; USEPA 1996; Mills et al. 1998) These are not discussed here but a summary can be found in Anderson (2004).

Aerosols produced by humidifiers

In a study investigating aerosol emissions in humidifiers, Highsmith et al. (1988, 1992) observed that PM10 concentrations (the concentration of particles with an aerodynamic diameter <10 μm) exceeding 400 and 7,000 μg/m³ were emitted when an ultrasonic humidifier was operated under whole-house and single room conditions, respectively. Humidifier water had a total dissolved solids content of 300 mg/L and hardness of 145 mg/L. It was noted that more than 90% of the particles generated were in the respirable range, and virtually all had diameters <1 μm). The authors also examined impeller type (cool mist) humidifiers and traditional steam models. The impeller units generated less than half of the aerosol mass generated by the ultrasonic units and a steam unit generated no increase in PM10 (Highsmith et al. 1988). Approximately 60 to 75% of the particles generated by impeller humidifiers were in the respirable range. The particle constituents were primarily calcium, silica, and sulfur with sodium, magnesium, and copper present in minor amounts. Calcium carbonate and aluminosilicate particles were observed. All of these are characteristic of what would be expected if tap water were to be aerosolized. The authors expressed concern that occupational standards for respirable nuisance particulates were being exceeded. They did not consider aerosolization of microorganisms or microbial constituents such as LPS/endotoxin. As endotoxin is nonvolatile and extremely environmentally resilient, it would be reasonable to assume that it would behave similarly with respect to aerosolization as the inorganic constituents found in tap water.

Respiratory uptake

As discussed above, only particles/aerosols with a diameter <10 μm are respirable. The majority of particles with a diameter of 5 to 10 μm are removed in the upper respiratory tract. Of the remaining particles with a diameter of >5 μm, only approximately 20% are in fact deposited throughout the entire respiratory tract (Schlesinger 1985). The alveolar-capillary barrier (gas exchange region) of the human lung consists of a 0.2 μm thick epithelial cell layer and lumen through which gases and particles are exchanged into red blood cells. Larger particles are removed in the upper respiratory tract and conducting airways by deposition and subsequent clearance by ciliated cells in a mucus layer (Mercer et al. 1991). The cells move particles and inhaled bacteria upward to the glottis, where mucous and particles are removed by swallowing. This process does not occur in the alveolar gas exchange region but it is known that, on
average, each alveolus in the lung contains an average of 12 macrophages which are thought to process all particles making it to that point (Stone et al. 1992). It is these macrophages that are responsible for initial pulmonary responses to the inhalation of endotoxin (Davis et al. 1980; Rylander 1989).

THEORETICAL ASSESSMENT OF ENDOTOXIN EXPOSURE FROM SHOWER AND HUMIDIFIER AEROSOLS

For this and the following assessments only those conditions resulting in acute health outcomes are considered. Chronic effects in occupational settings have been documented but will not be investigated here. Endotoxin exposure from shower aerosols and two types of humidifiers (ultrasonic and impeller) are assessed.

Shower

This assessment uses a previously established formula for estimating concentrations of a target compound in air when the concentration in water is known. Gunderson & Witham (1988, as quoted in Pandis & Davidson 1999), working with mannequins, found that the expected respirable particulate concentration for a nonvolatile species, Ca, at a concentration Cw in showers can be approximated by:

$$C_a(\mu g \cdot m^{-3}) = A C_w (mg \cdot L^{-1})$$

where A is an empirical constant with values varying from 0.03 to 0.2.

Using this equation, two worst-case scenarios with respect to endotoxin in treated drinking water were evaluated. Previous work has shown that following shutdown of biological drinking water filters, endotoxin concentrations can be as high as 750 EU/ml (Peppler et al. 1995; Anderson 2004). This value was rounded up to 1,000 EU/ml as a benchmark for the calculations below. In a study by Rapala et al. (2002) it was observed that the highest endotoxin concentration found in untreated surface water was 38,000 EU/ml at the site of a cyanobacterial bloom. These two concentrations will be used in this assessment and those to follow.

Table 2 provides airborne endotoxin concentrations (Ca) obtained by solving Equation 1 for aqueous endotoxin concentrations of 1,000 and 38,000 EU/ml (using the low and high constant [A] values provided).

At the lower aqueous endotoxin concentration (1,000 EU/ml) the estimated aerosol concentrations range from 30 to 200 EU/m$^3$ while at 38,000 EU/ml the aerosol concentrations range from 1,140 to 7,600 EU/m$^3$. Three of the four calculated concentrations are above the Health Council of the Netherlands (1998) proposed occupational exposure limit of 50 EU/m$^3$ based on personal inhalable dust exposure, measured as an eight hour time-weighted average. It should be noted that much shorter times are spent in the shower. One way of ‘normalizing’ these concentrations is to determine how much would be inhaled during a shower and compare this to the amount inhaled at an 8-h exposure to 50 EU/m$^3$. This does not take into account the amount of endotoxin that actually deposits in the respiratory system and assumes that endotoxin accumulates over the 8-h period without significant clearance. It also assumes that some threshold value for shorter periods of time is not exceeded.

The 50th and 90th percentile residence times while showering were selected (corresponding to 7.2 min [0.12 h] and 12 min [0.20]) based on those provided by the USEPA (1989). Sedentary and maximal activity respiration rates for a 20-year old were assumed to be 7 L/min and 122 L/min, respectively (Hofmann et al. 1989). These correspond to 0.42 m$^3$/h and 7.32 m$^3$/h based on the 0.12 and 0.20 h shower residence times.

Table 2 | Calculated endotoxin concentrations in shower air from Equation 1 (Ca)

<table>
<thead>
<tr>
<th>Constant value used</th>
<th>1,000 EU/ml (100 ng/ml)</th>
<th>38,000 EU/ml (3,800 ng/ml)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = 0.20</td>
<td>200</td>
<td>7,600</td>
<td>EU/m$^3$</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>760</td>
<td>ng/m$^3$</td>
</tr>
<tr>
<td>A = 0.03</td>
<td>30</td>
<td>1,140</td>
<td>EU/m$^3$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>140</td>
<td>ng/m$^3$</td>
</tr>
</tbody>
</table>
Using data provided in Table 2, the total amount of endotoxin inhaled in 0.12- and 0.20-h showers at sedentary, midpoint and maximal breathing rates can be calculated (Table 3). Table 4 summarizes total endotoxin inhalation over a period of 8 h at a background concentration of 50 EU/m³ (roughly 5 ng/m³). This roughly normalizes brief exposures while showering to the 8-h proposed occupation exposure limit.

The total volume of endotoxin inhaled over 8 h would range from 168 to 2,928 EU depending upon respiration rate, at a constant airborne endotoxin concentration of 50 EU/m³ (rougishly 5 ng/m³). This roughly normalizes brief exposures while showering to the 8-h proposed occupation exposure limit.

The total amount of endotoxin inhaled over 8 h would exceed the 5,000 EU required to induce symptoms (Table 1) or the 1,380 EU value shown in Table 4.

Using data provided in Table 2, the total amount of endotoxin inhaled in 0.12- and 0.20-h showers at sedentary, midpoint and maximal breathing rates can be calculated (Table 3). Table 4 summarizes total endotoxin inhalation over a period of 8 h at a background concentration of 50 EU/m³ (roughly 5 ng/m³). This roughly normalizes brief exposures while showering to the 8-h proposed occupation exposure limit.

The total volume of endotoxin inhaled over 8 h would range from 168 to 2,928 EU depending upon respiration rate, at a constant airborne endotoxin concentration of 50 EU/m³. It is probably reasonable to assume that respiration rates would be on the higher side in occupational settings. If it were assumed that the actual respiration rate was the midpoint of the sedentary and maximal rates (3.45 m³/h) then the total amount of endotoxin inhaled in 8 h would be 1,380 EU (Table 4).

Examination of Table 3 shows that at airborne endotoxin concentrations of 30 and 200 EU/m³ (which correspond to an aqueous concentration of 1,000 EU/ml) none of the inhaled endotoxin concentrations exceed 1,380 EU. This is reassuring in that drinking water distribution system endotoxins are typically below 1,000 EU/ml. If, however, water was pumped into a system without treatment, or solely with chlorination, and this occurred during a period of high cyanobacterial activity near the intake (i.e. 38,000 EU/ml), endotoxin levels could be high enough to induce low-level endotoxicosis. This is demonstrated by the fact that the calculated total endotoxin inhaled midpoint concentrations, 3,156 and 5,244 EU, exceed the calculated 1,380 EU 8-h total exposure at the occupational limit of 50 EU/m³ (Table 3). The upper values also approach or slightly exceed 0.5 μg, which has been demonstrated to initiate inflammatory responses in laboratory studies (Table 1). Nonetheless, even the highest predicted endotoxin concentration should not result in health outcomes that would cause more than temporary discomfort.

### Ultrasonic humidifier

Highsmith et al. (1988) proposed the following steady-state Equation (2) to determine humidifier fine particle formation based on the mass balance approach of Alzona et al. (1979):

\[
C_{\text{air}} = \frac{C_w \times WCR \times F \times 1,000 + C_h}{V \times M \times (AER + K_L)} \tag{2}
\]

This equation was solved using inputs both listed and defined in Table 5, assuming that endotoxin and minerals in water behave similarly. As with showers, aqueous endotoxin concentrations of 1,000 EU/ml (0.1 mg/L) and 38,000 EU/ml (3.8 mg/L) were used in this scenario. In Table 5, assuming that endotoxin and minerals in water behave similarly. As with showers, aqueous endotoxin concentrations of 1,000 EU/ml (0.1 mg/L) and 38,000 EU/ml (3.8 mg/L) were used in this scenario. In

#### Table 3

<table>
<thead>
<tr>
<th>Airborne endotoxin (EU/m³)</th>
<th>30</th>
<th>200</th>
<th>1,140</th>
<th>7,600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhalation rate (m³/h)⁴</td>
<td>0.42</td>
<td>3.45</td>
<td>7.32</td>
<td>0.42</td>
</tr>
<tr>
<td>0.12 h in shower</td>
<td>2b</td>
<td>12</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>0.20 h in shower</td>
<td>3</td>
<td>21</td>
<td>44</td>
<td>17</td>
</tr>
</tbody>
</table>

Values in bold exceed the 5,000 EU required to induce symptoms (Table 1) or the 1,380 EU value shown in Table 4.

⁴0.42, 3.45 and 7.32 m³/h are sedentary, midpoint, and maximal respiration rates.

**Example:** 0.12 h × 30 EU/m³ × 0.42 m³/h = 2 EU (rounded up).

#### Table 4

<table>
<thead>
<tr>
<th>Activity level</th>
<th>Respiration rate (m³/h)</th>
<th>Total air inhaled in 8 h (m³)</th>
<th>Total endotoxin inhaled over 8 h period assuming concentration is 50 EU/m³ (EU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedentary</td>
<td>0.42</td>
<td>3.36</td>
<td>168</td>
</tr>
<tr>
<td>Midpoint</td>
<td>3.45</td>
<td>27.6</td>
<td>1,380</td>
</tr>
<tr>
<td>Maximum</td>
<td>7.32</td>
<td>58.6</td>
<td>2,928</td>
</tr>
</tbody>
</table>

Values in bold exceed the 5,000 EU required to induce symptoms (Table 1) or the 1,380 EU value shown in Table 4.
addition, a more typical drinking water distribution level of 25 EU/ml (0.0025 mg/L) was assessed. Whole-house endotoxin concentrations were calculated for an ultrasonic humidifier (Table 6) and separate assessments using two different values for M (degree of mixing factor) for a single bedroom are shown in Table 7.

The data (Table 6) show that at high aqueous endotoxin levels respirable endotoxin concentrations exceed those known to cause moderate to severe health impacts. Even at typical distribution system endotoxin concentrations, the 0.5 μg threshold (for those without allergies and asthma) can be exceeded in 8 hours. At an endotoxin concentration of 1,000 EU/ml, which occasionally occurs in distribution systems, it is possible to inhale between 1.25 and 22 μg of endotoxin in 8 hours (12,528 to 218,347 EU). At extremely high endotoxin concentrations, which would only rarely be seen, up to 104 μg (1,037,150 EU) could be respired in 1 hour and anywhere from about 48 to 830 μg (476,069 to 8,297,203 EU) could be respired in 8 hours. As discussed previously, in human endotoxin inhalation challenges, symptoms such as breathlessness, throat irritation, dry cough, headache, and heaviness in the head are observed at around 40 μg and chills and fever are observed above 50 μg.

The above was a whole-house assessment; if the humidifier were located in a small room, airborne endotoxin levels could arguably be higher. The calculations were repeated for a smaller room (27 m³), such as a bedroom, at two ‘degree of mixing factors’ (M = 0.53 and 1.0) (Table 7). The concentrations were approximately 30 times higher in the small room vs. the whole house when M = 1.0. At typical distribution system levels, approximately 1 to 15 μg (∼8,600 to 150,000 EU) of endotoxin could be inhaled over an 8-h period. If the background aqueous endotoxin concentration were to increase to 1,000 EU/ml, 1-h inhalation exposure would range from 4 to 75 μg (43,000 to 749,568 EU), while 8-h exposure would range from 34 to 600 μg (344,064 to 5,996,544 EU). At an aqueous endotoxin concentration of 38,000 EU/ml inhaled endotoxin concentration levels at both 1 and 8 h of exposure exceeded fever inducing endotoxin exposure concentrations of around 50 μg (160 to 23,000 μg; 1,634,304 to 227,868,672 EU).

**Impeller humidifier**

A similar theoretical exercise was carried out for impeller (cool-mist) humidifiers, which generate droplets and aerosols by using a spinning impeller to draw water from a reservoir and force it at high speeds against a ring of staggered baffles. The same assumptions provided in Table 5 were used except for the proportion of particles generated

---

**Table 5 | inputs for equation 2a**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Abbreviation</th>
<th>Value(s) assumed</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne endotoxin concentration</td>
<td>C&lt;sub&gt;air&lt;/sub&gt;</td>
<td>solve for</td>
<td>μg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Endotoxin content of water</td>
<td>C&lt;sub&gt;w&lt;/sub&gt;</td>
<td>0.0025; 0.1; 3.8</td>
<td>mg/L</td>
</tr>
<tr>
<td>Humidifier water consumption rate</td>
<td>WCR</td>
<td>0.48</td>
<td>L/h</td>
</tr>
<tr>
<td>Proportion of particles generated in the collected size fraction</td>
<td>F</td>
<td>0.9</td>
<td>–</td>
</tr>
<tr>
<td>Background airborne endotoxin</td>
<td>C&lt;sub&gt;b&lt;/sub&gt;</td>
<td>ignored</td>
<td>μg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Volume of whole house/room</td>
<td>V</td>
<td>395; 27</td>
<td>m³</td>
</tr>
<tr>
<td>Unitless factor for degree of mixing</td>
<td>M</td>
<td>0.53; 1.0</td>
<td>–</td>
</tr>
<tr>
<td>Room/house air exchange rate</td>
<td>AER</td>
<td>0.5</td>
<td>h&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Loss rate of particles due to settling (fine particles)</td>
<td>K&lt;sub&gt;L&lt;/sub&gt;</td>
<td>0.14</td>
<td>h&lt;sup&gt;−1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>aInput values obtained from Highsmith et al. (1988), except for endotoxin concentrations.</sup>
in the fine (respirable) size fraction (F): 0.9 was used for ultrasonic humidifiers while values of 0.6 and 0.75 were used for impeller humidifiers. This represents the range of formation of fine/respirable particles measured by Highsmith et al. (1992). The total estimated endotoxin inhaled was 15 to 30% less than that calculated for an ultrasonic humidifier at corresponding conditions (Tables 8 and 9). In 1 hour, at typical aqueous endotoxin concentrations (25 EU/ml), it is possible to inhale in excess of 0.5 mg and with an 8-h exposure the 5 mg symptom level is exceeded at both midpoint and maximal respiration levels.

To help visualize the significance of the calculated inhaled endotoxin concentrations, Table 10 shows the conditions under which total inhaled endotoxin exceeds 0.5 μg (the no observed effects level-NOEL), 50 μg (the level at which body aches and fever are induced), and 500 μg, a level for which human trials have not been conducted. The degree of mixing factor is 1.0 for all data reported. This table also includes midpoint respiration rate categories, data not shown in previous tables.

**DISCUSSION**

A number of uncertainties plague researchers trying to accurately assess risks associated with endotoxin inhalation. Although there are numerous studies that look at airborne endotoxin in a variety of environments, absolute comparisons are difficult. Studies report results in different units (ng or μg vs. EU). Many studies, including recent ones, report results in terms of chemical concentration as opposed to units of activity. It would be useful if all studies reported in EU relative to a standard endotoxin and provided the conversion factor to calculate the actual concentration in ng/m³. Equal concentrations of endotoxin from different species can produce differing endotoxic responses; a switch to endotoxin units would at least partially overcome this problem. For example, based on the most common method used to measure endotoxin concentration, the Limulus amoebocyte lysate (LAL) assay, Hansen et al. (1999) found that LPS from *Escherichia coli* and *Salmonella enteritis* was about four times more potent than that from *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*. Laude-Sharp et al. (1990) found that *E. coli* LPS is about 100 times more potent than *Shigella flexneri* LPS and *Pseudomonas testosteroni* LPS is about 60% more active than *E. coli* LPS. Even within species there can be wide variations in LAL potency with a 625-fold range in some *E. coli* serotypes (Koyama et al. 2000).

Not surprisingly, structural differences in LPS also play a major role in the degree of cytokine production in human monocytes. This is significant in terms of the severity of an immune response in that unlike pathogens, which set up...
<table>
<thead>
<tr>
<th>Table 7</th>
<th>Small bedroom endotoxin loading (ultrasonic humidifier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Parameters</td>
<td></td>
</tr>
<tr>
<td>Endotoxin in water (EU/ml)</td>
<td>25</td>
</tr>
<tr>
<td>Inhalation rate (m$^3$/h)$^a$</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m$^3$)$^b$**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Endotoxin in air (EU/m$^3$)</td>
<td>1,357</td>
</tr>
<tr>
<td>Total endotoxin inhaled in 1 h (EU &amp; [μg])</td>
<td>570 [0.06]</td>
</tr>
</tbody>
</table>

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m$^3$)$^c$**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Endotoxin in air (EU/m$^3$)</td>
<td>2,560</td>
</tr>
<tr>
<td>Total endotoxin inhaled in 1 h (EU &amp; [μg])</td>
<td>1,075 [0.1]</td>
</tr>
<tr>
<td>Total endotoxin inhaled in 8 h (EU &amp; [μg])</td>
<td>8,602 [0.9]</td>
</tr>
</tbody>
</table>

Values in bold exceed 0.5 μg threshold for symptoms related to endotoxin inhalation.

$^a$For a 20 year old; 0.43 m$^3$/h = sedentary, 7.32 m$^3$/h = maximal.

$^b$Degree of mixing factor (M) = 0.53.

$^c$Degree of mixing factor (M) = 1.0.
Table 8 | Small bedroom endotoxin loading (impeller humidifier, F = 0.75)

<table>
<thead>
<tr>
<th>Fixed Parameters</th>
<th>25</th>
<th>25</th>
<th>1,000</th>
<th>1,000</th>
<th>38,000</th>
<th>38,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endotoxin in water (EU/ml)</td>
<td>25</td>
<td>25</td>
<td>1,000</td>
<td>1,000</td>
<td>38,000</td>
<td>38,000</td>
</tr>
<tr>
<td>Inhalation rate (m³/h)ᵃ</td>
<td>0.42</td>
<td>7.32</td>
<td>0.42</td>
<td>7.32</td>
<td>0.42</td>
<td>7.32</td>
</tr>
</tbody>
</table>

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m³)ᵇ**

| Endotoxin in air (EU/m³) | 1,131 | 1,131 | 45,227 | 45,227 | 1,718,613 | 1,718,613 |
| Total endotoxin inhaled in 1 h (EU & [µg]) | 475 [0.05] | 8,276 [0.8] | 18,995 [1.9] | 331,059 [33] | 721,818 [72] | 12,580,250 [1,258] |

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m³)ᶜ**

| Endotoxin in air (EU/m³) | 2,133 | 2,133 | 85,333 | 85,333 | 3,242,667 | 3,242,667 |

Values in bold exceed 0.5 µg threshold for symptoms related to endotoxin inhalation.

ᵃFor a 20 year old; 0.43 m³/h = sedentary, 7.32 m³/h = maximal.
ᵇDegree of mixing factor (M) = 0.53, F = 0.75.
ᶜDegree of mixing factor (M) = 1.0, F = 0.75.
Table 9 | Small bedroom endotoxin loading (impeller humidifier, \( F = 0.6 \))

<table>
<thead>
<tr>
<th>Fixed Parameters</th>
<th>25</th>
<th>25</th>
<th>1,000</th>
<th>1,000</th>
<th>38,000</th>
<th>38,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endotoxin in water (EU/ml)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inhalation rate (m³/h)(^a)</td>
<td>0.42</td>
<td>7.32</td>
<td>0.42</td>
<td>7.32</td>
<td>0.42</td>
<td>7.32</td>
</tr>
</tbody>
</table>

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m³)\(^b\)**

<table>
<thead>
<tr>
<th>Endotoxin in air (EU/m³)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total endotoxin inhaled in 1 h (EU &amp; [µg])</td>
<td>380 [0.04]</td>
<td>6,621 [0.7]</td>
<td>15,196 [1.5]</td>
<td>264,847 [26]</td>
<td>577,454 [58]</td>
<td>10,064,200 [1,006]</td>
</tr>
<tr>
<td>Total endotoxin inhaled in 8 h (EU &amp; [µg])</td>
<td>3,059 [0.3]</td>
<td>52,969 [5.3]</td>
<td>121,569 [12]</td>
<td>2,118,779 [212]</td>
<td>4,619,633 [462]</td>
<td>80,513,597 [8,051]</td>
</tr>
</tbody>
</table>

**Calculated Endotoxin in Air and Total Endotoxin Inhaled; Bedroom (27 m³)\(^c\)**

<table>
<thead>
<tr>
<th>Endotoxin in air (EU/m³)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total endotoxin inhaled in 1 h (EU &amp; [µg])</td>
<td>1,707</td>
<td>1,707</td>
<td>68,267</td>
<td>68,267</td>
<td>2,594,133</td>
<td>2,594,133</td>
</tr>
<tr>
<td>Total endotoxin inhaled in 8 h (EU &amp; [µg])</td>
<td>717 [0.07]</td>
<td>12,493 [1.3]</td>
<td>28,672 [2.9]</td>
<td>499,712 [50]</td>
<td>1,089,536 [109]</td>
<td>18,989,056 [1,899]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Values in bold exceed 0.5 µg threshold for symptoms related to endotoxin inhalation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^a)For a 20 year old; 0.43 m³/h = sedentary, 7.32 m³/h = maximal.</td>
</tr>
<tr>
<td>(^b)Degree of mixing factor (M) = 0.53, F = 0.6.</td>
</tr>
<tr>
<td>(^c)Degree of mixing factor (M) = 1.0, F = 0.6.</td>
</tr>
</tbody>
</table>
infection, a dramatic response to endotoxin can be an over
reaction in terms of the actual threat posed by the
endotoxin. Caroff et al. 2002 (summarizing several studies)
placed the cytokine-inducing capacity (CIC) of bacterial
species into three categories: weak, enterobacterial-
strength, and strong, with some species falling into more
than one category. This arises since some LPS can have
different CIC on different cytokines. Even if the issue of CIC
were not so complex, information on CIC is not complete,
especially when it comes to environmental strains. Infor-
mation on the species origin of endotoxin being measured
in air is often not available. To complicate matters further,
LPS also stimulates other cells such as dendritic cells to
undergo a maturation process that involves the expression
of co-stimulatory molecules, HLA molecules, and pro-
duction of cytokines and chemokines (Caroff et al. 2002).
It would, therefore, be useful for future research to specify
from which species the endotoxin being studied originated.
Realistically this may be difficult to do.

A related problem is variable response in test subjects.
Asthmatics and those with other breathing-related con-
ditions are often more susceptible to endotoxin. Endotoxin
exposure can also make these hypersensitive individuals
more susceptible to allergens (Boehlecke et al. 2003;
Michel 1998) notes that exposure to domestic allergen
provokes extravasation of LPS-binding protein and sCD-14.
The presence of these compounds in the bronchoalveolar
compartment may greatly enhance the capacity of inhaled
endotoxin to activate the inflammatory cascade, leading to
air way disease. This suggests that in certain allergy
sufferers, the no-response threshold value of endotoxin
exposure is probably substantially less than the 0.5 µg
inhaled no-response threshold to acute inhalation of LPS
which has been calculated for non-allergic individuals
(Michel 1998). This could, to some extent, be overcome by
selecting highly susceptible individuals for testing and
setting guidelines or regulations to protect the most easily
affected individuals.

The fact that there are two mechanisms leading to
human endotoxicosis is often understated in the occu-
pational literature. The primary and most widely invoked
mechanism results in toxicity when endotoxin encounters

| Conditions under which inhaled endotoxin is calculated to be \( \geq 0.5\) µg\(^{\dagger}\), \( \geq 50\) µg\(^{\ddagger}\), and \( \geq 500\) µg\(^{\ddagger\ddagger}\). |
|-----------------|------------------|------------------|------------------|
| **Humidifier type** | **Ultrasonic** | **Impeller (F = 0.75\(^{\dagger}\))** | **Impeller (F = 0.6\(^{\dagger}\))** |
| Aqueous endotoxin (EU/ml) | 25 | 1,000 | 38,000 | 25 | 1,000 | 38,000 | 25 | 1,000 | 38,000 |
| 1 h exposure |
| Sedentary\(^{e}\) | • | • | • | • | • | • |
| Midpoint | • | • | • | • | • | • |
| Maximal | • | • | • | • | • | • |
| 8 h exposure |
| Sedentary | • | • | • | • | • | • |
| Midpoint | • | • | • | • | • | • |
| Maximal | • | • | • | • | • | • |

\(^{a}\)No observed effect limit for specified humidifier types.

\(^{b}\)Fever-inducing inhaled endotoxin dose for specified humidifier types.

\(^{c}\)10 times fever-inducing inhaled endotoxin dose for specified humidifier types.

\(^{d}\)Proportion of respirable particulate (<2.5 µm).

\(^{e}\)Respiration rates: sedentary = 0.42 m\(^3\)/h, midpoint = 3.45 m\(^3\)/h, maximal = 7.32 m\(^3\)/h.
CD14 and lipopolysaccharide-binding-protein (LBP) in plasma. The second mechanism (DeLucca et al. 1988) involves the binding of LPS to pulmonary surfactants. This can result in altered surface tension in the lung and changes in pulmonary function. Overall, additional work on the second mechanism, and the relative importance of the two, is warranted.

The final major area of uncertainty in airborne endotoxin risk assessment involves variability in the quantification of exposure by the currently available sampling and analytical methods. Sampling, which often involves elution of airborne endotoxin from filters, may suffer from relatively unquantified losses at each point in the process (sampling, elution, adsorption, and storage). Douwes et al. (1995) showed a seven-fold higher endotoxin yield when 0.05% v/v of Tween-80 was added to the elution medium (endotoxin-free water). If this observation is generally applicable, endotoxin concentrations in many studies conducted to-date could be substantially underestimated.

The evaluation performed above shows that ultrasonic and impeller type humidifiers can theoretically produce sufficient levels of endotoxin to facilitate the inhalation of endotoxin above the NOEL of 0.5 μg. This can occur even at typical distribution system endotoxin levels (25 EU/ml). Calculations also show that, for scenarios where higher endotoxin levels in water are present, the inhaled doses are well beyond what would elicit chills and fever. While it could be argued that definitive conclusions cannot be drawn on the basis of uncertainties in the above discussion it would be prudent to minimize exposure to high levels of aerosolized endotoxin. This could be accomplished by introducing procedures or treatments to ensure that levels in drinking water are low. However, it will not be possible to completely keep endotoxin out of treated drinking water as biofilms are present in the distribution system. Another alternative would be to use deionized water for humidifiers but even deionized water can contain endotoxin.

The total amount of endotoxin inhaled is dependent on inhalation rate, which would normally be lower in a bedroom (assuming that the primary activity is sleep). However, humidifiers are often used when someone is suffering from illnesses such as colds or influenza. These subjects are already compromised and may be breathing more heavily if they are experiencing discomfort. It should also be recalled that these calculations were done assuming breathing rates of a healthy 20 year old. This was done to compare with findings from controlled inhalation studies. A necessary follow-up from this work will be to demonstrate that predicted respirable endotoxin concentrations can be verified in controlled laboratory tests. This was beyond the scope of the present study due to the requirement for a test environment in which air flow can be monitored and controlled.

CONCLUSIONS

Airborne endotoxin originating in water has been previously linked to adverse human health effects. Identified episodes are typically linked to secondary use of drinking water (e.g. in air around swimming pools, baths, and saunas). Saunas, humidifiers, and to some extent showers, can produce sufficient quantities of aerosolized products to be of concern, particularly with respect to volatile organic compounds. Endotoxin is, however, nonvolatile and becomes airborne only in association with dust particles and water droplets, either in small aggregates/membrane vesicles, or in association with bacteria.

On the basis of this theoretical exercise the following conclusions can be drawn:

- Ultrasonic humidifiers are potentially capable of discharging large amounts of respirable endotoxin in short periods of time, even without accounting for potential growth of bacteria in tanks or reservoirs.
- While not as efficient as ultrasonic humidifiers, impeller-type humidifiers are nonetheless capable of significantly increasing respirable endotoxin concentrations in short periods of time.
- Even at typical distribution system endotoxin concentrations (25 EU/ml) the potential for adverse health effects associated with humidifier use exists.
- At endotoxin concentrations that can occur following shutdown and subsequent restart of biological drinking water filters, and those associated with cyanobacterial blooms, it is theoretically possible to inhale sufficient quantities to cause chills and fever, and potentially more severe symptoms.
- It would appear that the quantities of endotoxin that are aerosolized in showers are not substantial enough to be
of human health concern at typical distribution system endotoxin concentrations.

- If drinking water was drawn in the vicinity of a cyanobacterial bloom containing high levels of endotoxin, short-term health consequences such as those associated with airway inflammation could occur from showering. Chills and fever would not be expected.

- In order to keep endotoxin levels in finished drinking water low it is suggested that drinking water biofilters be operated in such a manner as to preclude activities that will allow endotoxin to accumulate in biological processes. One of the most important mechanisms by which endotoxin can accumulate is the shutdown of biologically active filters, followed by subsequent restarting without immediately backwashing or sending the first 5 pore volumes to waste (Anderson 2004).

- If controlled laboratory studies show that the risks of endotoxin exposure associated with ultrasonic and impeller type humidifiers are as substantial as predicted, humidifier operation and potential design should be re-examined.

- This study did not consider aerosolization of bacteria. Given the efficiency of humidifiers to produce respirable particles this may be worth investigating.

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Available online May 2007