Release of airborne particles and Ag and Zn compounds from nanotechnology-enabled consumer sprays: Implications for inhalation exposure

Leonardo Calderón a, Taewon T. Han a, Catriona M. McGilvery b, Letao Yang c, Prasad Subramaniam c, Ki-Bum Lee c, Stephan Schwander d,e, Teresa D. Tetley f, Panos G. Georgopoulos d,e, Mary Ryan g, Alexandra E. Porter b, Rachel Smith h, Kian Fan Chung f, Paul J. Lioyd d,e, Junfeng Zhang h, Gediminas Mainelis a,d,e

a Rutgers University, Department of Environmental Sciences, New Brunswick, NJ 08901, USA
b Department of Materials and London Center for Nanotechnology, Imperial College London, United Kingdom
c Department of Chemistry and Chemical Biology, Rutgers University, Piscataway, NJ 08854, USA
d Environmental and Occupational Health Sciences Institute (EOHSI), Rutgers University, Piscataway, NJ, USA
e Rutgers School of Public Health, Department of Environmental and Occupational Health, Piscataway, NJ, USA
f National Heart and Lung Institute, Imperial College London, London, UK
g Centre for Radiation, Chemical and Environmental Hazards, Public Health England, UK
h Nicholas School of the Environment and Duke Global Health Institute, Duke University, Durham, NC, USA

Highlights
- Eighteen consumer sprays with Ag and Zn nanoparticles analyzed for possible exposure.
- All sprays produced nanoscale (<100 nm) and coarse aerosol particles (>2.5 μm).
- Presence of silver, zinc and various other metals determined in sprays and aerosol.
- Presence of nanoparticle and agglomerates in liquid and airborne state confirmed.

Article info
Article history:
Received 9 August 2016
Received in revised form 10 January 2017
Accepted 7 February 2017
Available online 8 February 2017

Keywords:
Nanotechnology
Nanotechnology-enabled consumer products
Consumer sprays
Nanoparticles
Exposure
Metals

Abstract
The increasing prevalence and use of nanotechnology-enabled consumer products have increased potential consumer exposures to nanoparticles; however, there is still a lack of data characterizing such consumer exposure. The research reported here investigated near-field airborne exposures due to the use of 13 silver (Ag)-based and 5 zinc (Zn)-based consumer sprays. The products were sprayed into a specially designed glove box, and all products were applied with equal spraying duration and frequency. Size distribution and concentration of the released particles were assessed using a Scanning Mobility Particle Sizer and an Aerodynamic Particle Sizer. Inductively coupled plasma mass spectrometry (ICP-MS) was used to investigate the presence of metals in all investigated products. Spray liquids and airborne particles from select products were examined using transmission electron microscopy (TEM) and Energy Dispersive X-ray Spectroscopy (EDS). We found that all sprays produced airborne particles ranging in size from nano-sized particles (<100 nm) to coarse particles (>2.5 μm); however, there was a substantial variation in the released particle concentration depending on a product. The total aerosol mass concentration was dominated by the presence of coarse particles, and it ranged from ~30 μg/m³ to ~30,000 μg/m³. The TEM verified the presence of nanoparticles and their agglomerates in liquid and airborne states. The products were found to contain not only Ag and Zn compounds – as advertised on the product labeling – but also a variety of other metals including lithium, strontium, barium, lead,
1. Introduction

Nanotechnology, manipulation of materials on the nanoscale (1–100 nm), has a variety of applications in medicine, consumer goods, electronics, communication, computing, energy, agriculture, water treatment, aerospace industry and many other areas (Aschberger et al., 2011; Ferreira et al., 2013; Maynard, 2006; Maynard, 2007; Newman et al., 2009; Ordidge et al., 2012; Som et al., 2011; Stone et al., 2010; Thomas et al., 2013; von Goetz et al., 2013; Wijnhoven et al., 2010). As a result, application of nanomaterials has increased not only in industrial and commercial products, but also in consumer products. A comprehensive inventory of consumer products that contain nanoparticles is provided by the Project on Emerging Nanotechnologies (Project on Emerging Technologies, 2015). As of this writing, the database contains more than 1800 products from 30 countries. While this database might not describe all relevant consumer products due to a very dynamic nature of the market, it does provide an excellent idea about the wide-spread application of nanoparticles in consumer markets. In addition, recent research indicated that nanosized materials might even be present in consumer products not labeled as nanotechnology-based (Nazarenko et al., 2011, 2012b).

Among the nanomaterials introduced into the consumer products, Ag, TiO2, ZnO, Pt and SiO2 nanoparticles seem to be the most commonly used (Frohlich and Roblegg, 2012). Ag nanoparticles are commonly used in products due to their antimicrobial characteristics (Quadros and Marr, 2011), while TiO2 and ZnO nanoparticles are employed in sunscreens (Newman et al., 2009), Pt in cosmetics, and SiO2 in various coatings, among other applications (Project on Emerging Technologies, 2015).

While the introduction of nanomaterials into consumer products provides various desired or claimed properties, because of their widespread use there is concern regarding the potential environmental and human health effects due to the release of and exposure to nanoparticles (Beddow et al., 2014; Dunphy Guzman et al., 2006; Hansen et al., 2008; Lioy et al., 2010; Majestic et al., 2010; Maynard and Aitken, 2007;McCall, 2011; von Goetz et al., 2013). Concerns about nanoparticles in consumer products are amplified by studies showing toxicological potential of Ag, ZnO, and TiO2 nanoparticles (Cho et al., 2011; De Jong et al., 2013; Elsässer and Howard, 2012; Kao et al., 2012; Sung et al., 2008; Warheit et al., 2009; Zhang et al., 2014). Therefore, it is essential to assess exposures of the general public to nanoparticles and then use the information to improve our understanding of environmental and human health risks (Elsässer and Howard, 2012; Lioy et al., 2010; Thomas et al., 2006).

Consumer exposure to nanoparticles can occur via inhalation, ingestion, and dermal pathways, but inhalation is considered the most likely way to introduce nanoparticles into the human body (Biskos and Schmidt-Ott, 2012). Among the available consumer product groups, use of sprays and cosmetic powders is most likely to result in inhalation exposures because the emissions are likely to occur close to the consumer’s breathing zone and inevitably lead to aerosol particle production (Hansen et al., 2008; Nazarenko et al., 2012a, 2012b). Due to their exposure potential, nanoparticle-containing sprays were even called a critical class of consumer products (Losert et al., 2015). The US EPA indicated that studies of nano-Ag present in disinfectant products are one of the best ways to inform about potential ecological and health implications of nano-Ag (USEPA, 2012). A recent review identified Ag-containing products as the most prevalent sources of exposure to manufactured nanoparticles indoors (Vance and Marr, 2015). Thus, there is a clear need to examine consumer exposures to most common nanoparticle types, especially focusing on a realistic simulation of the exposure processes.

Quadros and Marr (2011) manually sprayed three Ag-containing sprays into a chamber and found a wide distribution of aerosol particles, ranging from nanoparticle size to 10 μm (and assumed even larger) for all products. Lorenz et al. (2011) examined four commercial sprays (two were labeled as containing silver) and observed the release of large amounts of airborne nanoparticles. However, the presence of nanosized particles in the resulting aerosol did not always correlate with the presence of engineered nano-objects in the original spray liquid. A similar observation was made by Nazarenko et al. (2011). Hagendorfer et al. (2009) examined one commercial nanosilver spray and found that no measurable particles were released when a pump sprayer was used, but a substantial amount of single nanoparticles and nanosized clusters was released using a propellant sprayer.

All studies mentioned above showed that consumers using nanotechnology-based sprays would be exposed to nano-sized as well as larger particles, most likely via inhalation. However, some issues remain unresolved to date. First, it is not always clear if the nanosized particles derived from consumer products are indeed manufactured nanoparticles, or result from product matrix, or, possibly, are a combination of both. Second, while data on the composition of nano-aerosols released by commercial spray products are beginning to emerge (Losert et al., 2015), there is still insufficient data when it comes to sprays based on materials of concern (such as compounds of Ag and Zn). Third, the nanotechnology-based consumer product market is very dynamic with a rapid turnover of available products; thus, as new products are introduced they should be examined for potential exposures to nanoparticles and related health risks.

This study focused on investigating sprays with Ag and Zn compounds to help provide answers to the above questions. We examined thirteen Ag-containing and five Zn-containing consumer sprays produced in six countries and determined the produced size distributions and aerosol particle concentrations when the sprays were used. In addition, the presence of solid nanoparticles and agglomerates, as well as their composition in airborne state and liquid state, were examined for select products.

2. Materials and methods

2.1. Selection of products

Thirteen Ag-based products and five Zn-based products have been chosen and acquired for testing. The Ag-based products were chosen due to being advertised as nanotechnology-based either in the Consumer Product Inventory (Project on Emerging Technologies, 2015), or on product websites, or product labels. All spray products were compressed air canisters. Some of the Ag product labels indicated that the products contained nano-Ag,
while others listed Ag ingredient as being colloidal Ag, i.e., Ag particles dispersed in a liquid. Different from nanotechnology-based Ag products, Zn-based sprays were not explicitly advertised as containing nanoparticles. The presence of particles in nano-size range or close to that range was inferred from product description and properties, as described below.

Tables S1 and S2 in Supplemental Materials describe the investigated sprays, including product descriptions and contents as provided by their manufacturers. Products were assigned a four symbol code based on their described function. The letter “S” or “Z” at the beginning of the code indicates whether a product is Ag or Zn-based; the second symbol enumerates products; the letters C, H, or O following the number indicate a product’s suggested application: cosmetic, health or other (e.g. cleaning surfaces), respectively; the last letter indicates whether the product is intended to be sprayed (S) or administered orally, i.e., ingested (O).

Two Ag products that were designated to be ingested orally (S2HO and S4HO) and were investigated for comparison with Ag-based sprays. Since sunscreens with microfine zinc oxide (Z-cote) (Mitchnick et al., 1999) were found to contain nano-sized particles (SCCS, 2012), and micronization (pulverization of material into fine particles) of Zn is known to produce particles in or close to nano-sized range, products Z1CS (described as containing Z-cote) and Z4CS (containing micronized zinc) were included in the study. Interestingly, Z1CS was labeled as “non-nano.” Products Z2HS and Z4HS contained zinc pyrithione and were not explicitly labeled as containing nanoparticles; however, other studies suggested that such products are likely to create nanosized particles once sprayed (Nazarenko et al., 2011). Product Z6HS containing Zn gluconate is a dietary supplement that is supposed to be sprayed into the mouth, but the user could inhale the created airborne particles as well. Moreover, Zn gluconate is an active ingredient in Zicam-branded products (marketed as a homeopathic product to alleviate cold symptoms). The US Food and Drug administration issued an advisory for several such products due to possible anosmia - loss of smell (Lim et al., 2009). Thus this product was also included in the study. As of this writing, all products except S3CS, are available for purchase.

2.2. Analysis of metal content in liquid state

Little is known about metals concentrations in nanotechnology-based consumer sprays; thus, all products in liquid form and without any alteration prior their analysis were analyzed by using inductively coupled plasma mass spectrometry (ICP-MS) (iCAP Q ICPMS, ThermoFisher Inc., Waltham, MA). Here, ~0.01 g of each sample was digested in 10 ml concentrated nitric acid in a microwave digestion system. The digest was then kept at 210 °C for 30 min, followed by dilution to ~50 g. The detection limit of the method for Zn was ~1.36 ppm and ~3.65 ppb for Ag. Since Zn-based products were labeled as containing not pure Zn, but Zn compounds, the mass of these compounds was determined by taking into account the difference in molecular weight between pure Zn and a particular Zn compound. Here we made an assumption that all zinc in the product is present as the advertised zinc compound (e.g., zinc pyrithione).

2.3. Measurement of released particles when using sprays

All products were tested by spraying them into a specially designed 124 L glove box described in Supplemental Materials (Fig. S1 and text). The use of the glove box allowed simulating an untreated aerosol that would be present near a consumer’s breathing zone. A similar setup was used in other studies (Lorenz et al., 2011). The size distribution and concentration of the released particles were measured using a Scanning Mobility Particle Sizer 3986 (SMPS) and an Aerodynamic Particle Sizer 3321 (APS) (both by TSI, Inc., Shoreview, MN). The two instruments measured a combined size range of 14–20,000 nm. Operational details of the devices are provided in Supplemental Materials.

At the beginning of each test, the glove box was uncovered and placed inside an operating Class II Type A2 biological safety cabinet (NuAire Inc. Plymouth, MN, USA) with ULPA (ultra-low particulate air) filter. Once the background concentration of particles the box was ~3 particles/cm³, a spray bottle was positioned inside the box, and its lid was closed. Each product was aerosolized manually using built-in valves. At the beginning of each experimental repeat, each product was sprayed five times in approximately 5 s to achieve a steady airborne particle concentration. Then the aerosol measurements were started, and the spray was activated approximately every three seconds to maintain constant aerosol concentration inside the chamber. Each repeat lasted at least 3.5 min, time needed by the SMPS to complete a full scan. Experiments were performed at room temperature and the relative humidity inside the box at the start of the experiments was ~50%. After each repeat, the box was opened, and its walls were wiped with alcohol. A minimum of three spray measurement repeats was completed for each product. Each product was sprayed using a supplied sprayer. Products S2HO and S4HO, which were suggested to be ingested orally as liquid by the manufacturers, did not have sprayers, so they were tested by using a Mon Image Mist Spray 60 ml travel spray bottle (Paris Presents, Inc., Gurnee, IL, USA).

2.4. Determination of aerosol size distribution by mass and overall aerosol mass concentration

Measurements with the SMPS and APS produced particle size distributions by number. These data were converted into particle size distributions by mass determining the density of the spray liquids and assuming that the measured particles (droplets) were spherical. These data were expressed as ΔM/logDp, where ΔM is the calculated aerosol mass concentration in an instrument’s size bin; logDp is the difference between the logarithms of the upper and lower sizes of a size bin. By adding mass concentrations ΔM across all channels, we also determined the overall aerosol mass concentration. Since the APS measures the aerodynamic diameter and the SMPS measures the electrical mobility diameter, the latter was converted into aerodynamic diameter as described elsewhere (Hinds, 1999). The density of each product was determined by weighing 1 ml of the product using a calibrated balance (model AB54-S, Mettler Toledo Inc., Columbus, OH).

We also estimated the concentrations of Ag and Zn that could be released into the air when the products are used. Here, the total aerosol mass determined as described above was multiplied by the respective concentrations of Ag and Zn determined by ICP-MS. It was assumed that the fraction of each metal in the airborne sprays did not depend on droplet size.

2.5. Analysis of airborne and liquid-borne particle properties using transmission electron microscopy (TEM) and Energy Dispersive X-ray spectroscopy (EDS)

Two Ag and two Zn products were selected to verify the presence of nanoparticles and/or their agglomerates in the airborne state using transmission electron microscopy (TEM). The chemical composition of particles captured on TEM grids was determined using Energy Dispersive X-ray Spectroscopy (EDS). The latter step allowed a comparison of chemical composition with that determined by ICP-MS. To compare properties of liquid-borne and airborne spray liquids, the spray liquid of the same products was
deposited on TEM grids and the presence of nanoparticles and agglomerates as well their chemical composition was analyzed by TEM and EDS.

Airborne particles were collected on TEM grids by an electrostatic precipitator (ESP). The ESP and experimental setup are described in Supplemental Materials and accompanying Fig. S2. The samples were collected for 1 h so that a sufficient amount of material would be collected. Therefore, the selected products were aerosolized using a commercial nebulizer (Collison nebulizer, Mesa Labs Inc., Butler, NJ) instead of hand-spraying them. We realize that this approach leads to the desiccation of the droplets, most likely making them smaller than sized observed during measurements in the glove box. Desiccation could even affect agglomeration of particles within the droplets. However, the need to remove the liquid content of those particles was dictated by the TEM procedure. At the same time, desiccation should not have changed the metals content in the samples.

For liquid-borne particle analysis, aliquots of solution were drop cast onto a holey carbon copper grid using a pipette. Excess solution was blotted from the grid, and the grid was dried before putting it in the microscope.

Both airborne and liquid-borne samples were analyzed using a Jeol JEM 2100F microscope equipped with a Schottky FEG and operated at 200 kV in both transmission (TEM) and scanning electron microscopy (STEM) modes. Chemical analysis was done in situ in the electron microscope by EDS using an Oxford Instruments XMax silicon drift EDS detector with the 80 mm2 chip. To obtain a fair representation of the chemical composition of the deposited sample (liquid or airborne state), the TEM beam was expanded as far as possible without giving a signal saturated by the copper grid on which the sample was placed (15–20 μm diameter) and EDS spectra were acquired from the region illuminated by the beam. This gave an EDS spectrum from a relatively large region of the sample which was representative of the sample as a whole. Using EDS, any present elemental species are detected within the detection limit of the system (∼0.1 wt%). EDS spectra were quantified using Aztec (Oxford Instruments). The C signal was removed from the quantification procedure due to the signal primarily being from the amorphous matrix surrounding the nanoparticles and the carbon film on which the sample was sitting. Due to cost constraints, one liquid-borne and one airborne sample was analyzed from each selected product.

3. Results

3.1. Size distribution of the produced aerosol

The size (aerodynamic diameter) distributions by mass of Ag-based and Zn-based sprays are presented in Fig. 1a and b, respectively. Both figures also present 3rd order linear regressions (solid red line) and 95% prediction intervals (red dashed line). The density of the products is provided in Tables S1 and S2.

As per Fig. 1a, all sprayed Ag products produced particles ranging from 14.1 nm to 20.0 μm (the smallest and largest measured sizes, respectively). The mass concentration is presented as AM/ΔLogDp, averaged over all Ag products, it ranged six orders of magnitude from approximately 10−3 μg/m3 for smallest measured particles to almost 104 μg/m3 for ~3 μm particles. In the SMPS measurement size range (14–700 nm), the airborne mass concentration increased with increasing particle size for most products. Two products stood out within this range, especially within the nanosized range of 14–100 nm. First, product S3CS (shoe deodorant) showed a clear peak at 26 nm with the mass concentration of 4.9 μg/m3. Second, product S2H0 (dietary supplement with silver) had the overall highest particle mass concentration for particles smaller than 400 nm and a peak concentration of 136 μg/m3 at 136 nm. For particles larger than 720 nm, there was a greater variability among the products, with some of them showing increasing mass concentration as a function of particles size, while some showed plateauing and some showed decreasing mass concentration as a function of particle size. The highest mass concentration in this size range was registered for product S3CS (shoe deodorant) with the mass concentration of approximately 5.5 × 104 μg/m3 at 4 μm.

The average mass concentration for Zn products ranged from 10−2 μg/m3 to almost 104 μg/m3 (Fig. 1b). The product Z4CS showed the highest overall airborne mass concentration with a peak of 2.3 × 103 μg/m3 at 685 nm and approximately 5.0 × 104 μg/m3 at 20 μm Z1CS, which was advertised as “non-nano,” showed the lowest concentration in the nanosized region. Although Z1CS had the lowest nano-sized particle concentration among the investigated products, its spray still produced particles in the nano-size range. This finding was consistent with an earlier observation that the use of sprays that are not advertised as nanotechnology-based may still result in the release of nano-sized particles and that they may potentially be inhaled (Nazarenko et al., 2011).

As could be seen in Fig. 1, the measurements by the SMPS and APS over the overlaps size particles was always agreed, mostly due to different detection methods used by the instruments, and their different sensitivity in the overlapping region. A more detailed discussion of this topic is provided elsewhere (Nazarenko et al., 2011).

Averaged size distribution parameters by mass and number are presented in Table S3. Here it was assumed that all particles were spherical. The average number-based median, mean, geometric mean and mode sizes for Ag-based products were larger than those for Zn-based products. On the other hand, all particle mass-based parameters of Zn-based products were substantially greater than those for silver products. These data indicate that the Ag sprays produce more of the smaller particles, while Zn-based sprays produce higher quantities of larger, especially super-micron (>1 μm) sized particles, resulting in a mass distribution dominated by larger particles. The difference is likely due to different particle sizes in the respective product types.

The number concentrations of particles (particles/cm3) released from Ag-based and Zn-based products are shown in Tables S4 and S5, respectively. In addition to the total number concentrations (14 nm–20 μm as per equipment capability), we also list the concentrations of particles <100 nm in aerodynamic diameter, concentrations of particles 100 nm–25 μm, and 2.5 μm–10 μm. As could be seen from both tables, the number concentrations in all sizes fractions varied approximately three orders of magnitude depending on a product. Concentrations of particles <100 nm for Ag-based products ranged from 1.4 × 104 particles/cm3 (S5CS, a skin spray) to 1.1 × 105 particles/cm2 (S3CS, a shoe deodorizer), while for Zn-based products the minimum and maximum number concentrations were 1.7 × 102 (Z1CS, a sunscreen) and 2.0 × 104 (Z4HS, a skin protectant) particles/cm3, respectively. A similar number concentration range has been observed for particles 100 nm–2.5 μm. As could be expected the lowest number concentration was observed for particles 2.5–10 μm in aerodynamic diameter. Here, the concentrations for Ag-based products varied from 7.8 × 102 particles/cm3 (S9HS, a sprayable dietary supplement) to 5.6 × 105 particles/cm3 (S3CS, a shoe deodorizer). For Zn-based products, the minimum and maximum concentrations in this size range were 1.9 × 102 to 3.4 × 105 particles/cm3 (Z4HS, a skin protectant) and Z2CS (a sunscreen), respectively. The total number concentrations for both product groups varied from 9.1 × 107 (Z1CS, a sunscreen) to 1.2 × 109 (S3CS, a show deodorizer) particles/cm3. Thus, if Tables S4 and S5 and Fig. 1 are regarded together, it is clear...
that the particle number concentration is dominated by nanoscale and nanosized particles, while their mass distribution is dominated by supermicron and coarse particles.

3.2. Presence of metals in the spray products (spray liquid)

The extent of information about the product composition provided by the manufacturers (Table S1) varied from product to product, and in most cases was only semi-quantitative, especially regarding the presence of metals. Therefore, all investigated products were analyzed for the presence of metals using ICP-MS, and the results are presented in Table 1 for Ag products and Table 2 for Zn products.

Ag (Ag 107) was detected in all Ag-based sprays (Table 1). The concentrations ranged from ~1 μg/ml (ppm) to ~20 μg/ml (ppm). The highest concentrations of Ag were detected in products S4HO (~20.2 ppm) and S7HS (~15.9 ppm), respectively. The lowest concentrations were observed for products S3CS (~1.2 ppm) and S13OS (~1.2 ppm) for each. Interestingly enough, the product S3CS had a very pronounced peak in the nano size range as shown in Fig. 1. In all Ag products, other detected metals included ~2 ppm of strontium (Sr 88), barium (Ba 138), and lead (Pb 208). Concentrations of lithium (Li 7), vanadium (V 51) and manganese (Mn 55) were below 0.1 ppm in all products. Only one Ag product (S3CS) was found to contain zinc (Zn 66): at the concentration of ~90 ppm.

Zn was detected in all products labeled as containing Zn compounds, with concentrations ranging from 13.2 ppm (Z1CS) to ~98,000 ppm (Z1CS) (Table 2). Interestingly, all Zn products also contained Ag (Ag 107) at approximately 1 ppm. The presence of lithium, strontium, barium, lead, vanadium, manganese, iron, nickel and copper at concentrations ranging from ~0.05 ppm to ~6 ppm was detected in all Zn sprays. Table 2 also presents the concentration of Zn-compounds in Zn-based products. Both Z1CS and Z3CS were labeled as sunscreens with ZnO; however, their concentrations of ZnO were dramatically different: ~121,000 ppm for Z1CS, and ~9 ppm for Z3CS.

Fig. 1. Total aerosol size distributions by mass of (a) silver-based products and (b) zinc-based products aerosolized with built-in sprayers. The solid line represents 3rd order linear regression, while a dashed line represents a 95% prediction interval. The data are averages of three repeats.

<table>
<thead>
<tr>
<th>Element/Product</th>
<th>Z1CS</th>
<th>Z2HS</th>
<th>Z3CS</th>
<th>Z4CS</th>
<th>Z6HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag107</td>
<td>8.45</td>
<td>0.08</td>
<td>1.20</td>
<td>20.21</td>
<td>2.03</td>
</tr>
<tr>
<td>Ba138</td>
<td>1.34</td>
<td>1.52</td>
<td>1.76</td>
<td>1.37</td>
<td>1.24</td>
</tr>
<tr>
<td>Cr53</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
</tr>
<tr>
<td>Cu63</td>
<td>0.58</td>
<td>0.26</td>
<td>0.86</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>Fe56</td>
<td>1.82</td>
<td>0.22</td>
<td>3.08</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
</tr>
<tr>
<td>Li7</td>
<td>0.35</td>
<td>0.33</td>
<td>0.46</td>
<td>0.31</td>
<td>0.30</td>
</tr>
<tr>
<td>Mg24</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>0.22</td>
<td>&lt;LOD</td>
<td>1.07</td>
</tr>
<tr>
<td>Mn55</td>
<td>0.07</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Ni60</td>
<td>0.00</td>
<td>0.08</td>
<td>0.10</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Pb208</td>
<td>1.19</td>
<td>1.19</td>
<td>1.51</td>
<td>1.19</td>
<td>1.14</td>
</tr>
<tr>
<td>Sr88</td>
<td>1.29</td>
<td>1.29</td>
<td>2.06</td>
<td>1.35</td>
<td>1.23</td>
</tr>
<tr>
<td>V51</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Zn66</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
<td>89.97</td>
<td>&lt;LOD</td>
<td>&lt;LOD</td>
</tr>
</tbody>
</table>

3.3. Mass concentration of airborne sprays and airborne Ag and Zn compounds

Fig. 2 presents the overall aerosol mass concentration produced by each spray inside the glove box, as well as the concentration of airborne Ag and Zn for the corresponding products. These two concentrations were estimated by multiplying the respective total aerosol mass concentration by their Ag and Zn concentrations determined by ICP-MS, and it was assumed that the metals concentration is independent of particle size. The overall airborne particle mass concentration for Ag sprays ranged from 26.1 ng/m³ (S9HS) to ~28,000 ng/m³ (S3CS). The mass concentration of airborne Ag released from Ag sprays ranged from 0.2 ng/m³ (S9HS) to 40.4 ng/m³ (S3CS). The overall airborne particle mass concentration from Zn sprays ranged from 4600 µg/m³ (Z2HS) to ~18,000 µg/m³ (Z4HS). The concentration of airborne Zn released from zinc sprays ranged from 91 ng/m³ (Z2HS) to ~600,000 ng/m³ (Z1CS). The horizontal lines in Fig. 2 present the median mass concentrations of airborne Ag and Zn that a consumer would be exposed to when using these products. We chose median concentrations as representative of these two data sets because airborne mass concentrations of both Ag and Zn did not satisfy normality requirements as per Shapiro-Wilk test (p < 0.05). The concentrations of particular Zn compounds could be obtained by multiplying the concentration of airborne Zn by the conversion factors presented in Table 2.

3.4. Nanoparticle presence and composition in airborne and liquid states

The data presented in Figs. 1–2 and Tables 1 and 2 indicate that when the sprays are used, they release particles ranging in size from 14 nm to 20 μm and that those particles are likely to contain various metals, including Ag and Zn compounds. Thus, according to our simulation, if the sprays are applied near a consumer’s breathing zone, the consumer would be exposed to those particles and metals via inhalation. At the same time, it is unknown if the

for Z1CS compared to ~16 ppm for Z3CS. The calculated concentration of zinc pyrithione in Z2HS and Z4HS were approximately the same: ~2000 ppm. The concentration of zinc gluconate in Z6HS was ~35,600 ppm.

While various metals were detected in all sprays, the highest concentrations of Ag and Zn were found in products labeled as Skin protectant, Z3CS: Sunscreen, Z4CS: Skin protectant, Z6HS: Ingestible dietary supplement.
borne particles are more heterogeneous and consist of large morphology between liquid-borne and airborne particles. Liquid-nano-sized particles (pronounced at the edges. However, one does see the presence of single effects from the spray. These drying effects seem to be most pro-
liquid-borne state exhibit clusters of about 500 nm comprised of based product (S13OS) look different (Fig. 4). Images from the shaped particles are also present. In contrast, images of another Ag-
majority of the observed particles seem to be spheroids, but some rod-
formed from product matrix. As the droplets travel from emission point to the breathing zone, their size changes due to diffusion, sedimentation, evaporation, and coagulation (Losert et al., 2014). Therefore it was important to verify the presence of nanoparticles and to investigate their composition in the airborne state once the carrier liquid evaporated. This was done for two silver products (S3CS and S13OS) and two zinc products (Z2HS and Z4HS). S3CS exhibited a pronounced peak in the nanoparticle size range (Fig. 1) and produced not only the highest overall airborne mass concentration but potential also could have the highest airborne silver concentration (Fig. 2). S13OS had a relatively high concentration of nano-sized particles (Fig. 1), second highest overall aerosol concentration and one of the highest anticipated concentrations of silver in the airborne state (Fig. 2). Z4HS has the highest mass concentration of particles in almost every measured size bin while Z2HS had relatively high concentration of nanosized particles.

The representative TEM micrographs of these products from liquid and airborne states are shown in Figs. 3–6, respectively. As could be seen from Fig. 3 (product S3CS), there was a clear presence of individual nano-sized particles as well as nano-sized particle agglomerates in both the airborne state and liquid state. The majority of the observed particles seem to be spheroids, but some rod-shaped particles are also present. In contrast, images of another Ag-based product (S13OS) look different (Fig. 4). Images from the liquid-borne state exhibit clusters of about 500 nm comprised of small nano-sized particles. These were likely caused by drying effects from the spray. These drying effects seem to be most pronounced at the edges. However, one does see the presence of single nano-sized particles (<5 nm in size) in the airborne state as well.

Samples from Z2HS (Fig. 5) show distinct differences in morphology between liquid-borne and airborne particles. Liquid-borne particles are more heterogeneous and consist of large crystalline particles and their agglomerates, and “needles.” Particles in the airborne state include smaller nano-sized particles and shorter “needles.” The morphology of particles from Z4HS (Fig. 6) is somewhat similar to that of Z2HS: the liquid sample shows greater variation in particle morphology and presence of larger particles and their agglomerates. The presence of nano-sized particles within the agglomerates could also be observed. Particles from the airborne state seem to be more uniform, and nano-sized particles are abundant. For both Z2HS and Z4HS, the difference in particle morphology between airborne and liquid-borne particles is likely caused by the aerosolization process: larger agglomerates were broken-up.

Summary of EDS analysis of liquid state particles and airborne particles deposited on TEM grids is presented in Table 3, while a sample EDS map is presented in Fig. S3. One can see that there is no data for S13OS in Table 3: there was a high amount of hydrocarbon component in the product which caused a buildup of contaminants and prevented us from performing EDX. As per Table 3, the principal elements for all samples were Zn and S (if one excludes oxygen). High concentration of Zn in liquid samples of investigated products is consistent with ICP-MS results (Tables 1 and 2). Table 3 also suggests that Zn content was transferred from the liquid state into the airborne state. All liquid state samples except S3CS contained S. Surprisingly, silver was observed only in airborne samples of Z2HS and liquid state samples of Z4HS. An airborne sample of S3CS contained a trace of Ag which was insufficient to quantify. Admittedly, as per Table 2, Ag concentrations in spray liquid were already low. Thus, it is likely that proportionally low amounts of silver from this product were transferred into the airborne state. It is also possible that particles containing silver were not efficiently collected onto the TEM grids due to the high electrical conductivity of such particles. Elevated levels of oxygen suggest that observed metals were in the form of oxides.

![Fig. 2. Total airborne mass concentrations and concentrations of silver and zinc released from silver and zinc products, respectively.](chart.png)
4. Discussion

4.1. Observed aerosol size distribution

The experiments were designed to simulate the use of spray products and production of untreated aerosol that would be

present in a consumer’s breathing zone and available for inhalation. In most cases, the size of the released aerosol particles ranged from nanosized (<100 nm) to greater than 10 \( \mu \)m. Similar observations were made in other studies. Quadros and Marr (2011) showed that the size of total emitted aerosols spanned from the nanoscale up to 10 \( \mu \)m. However, their observed particle number concentration

Fig. 3. Transmission electron microscope (TEM) micrographs of silver product S3CS: (a) and (b) from the liquid state; (c) and (d) from the airborne state.

Fig. 4. Transmission electron microscope (TEM) micrographs of silver product S13OS: (a) and (b) from the liquid state; (c) and (d) from the airborne state.
showed a pronounced concentration decrease for particles approximately 100 nm in size. Such local minima were not observed for any of our investigated products or in other studies (Hagendorfer et al., 2009; Lorenz et al., 2011). Both the study by Quadros and Marr (2011) and this study clearly show the release of coarse particles, which constitute the highest aerosol mass available for inhalation. However, the release of coarse particles was not reported by the other two studies mentioned here since they investigated only airborne particles smaller than 500 nm.

Zn products that were not labeled as containing nanoparticles produced nano-sized aerosol nonetheless. At least some of these particles seem like engineered particles that were introduced into
spray products were within or below concentration ranges investigated here is being addressed in a separate study. The spraying mechanism seems to play a major role in the observed particle size distribution and concentration and needs to be examined separately. While Hagendorfer et al. (2009) and Lorenz et al. (2011) suggested that only propellant gas sprays can release nanoparticles, Losert et al. (2015) show that both propellant and gas sprays can release nanoparticles. The observed variation in particle size and concentration is likely due to differences in product ingredients in product Z6HS at much higher than advertised concentration. On the other hand, Ag concentrations in S8HS and S9HS were higher than advertised by factors 1.2 and 4.3, respectively. Relatively low Ag concentration in S3CS was the likely reason why Ag was not detected in this product by EDS (Table 3). On the other hand, Ag concentrations in S9HS and S7HS were lower than advertised by factors 8.3 and 1.3, respectively. Ag concentrations in S3CS and S7HS were lower than advertised by factors 8.3 and 1.3, respectively.

We show that the concentration of the released particles can differ substantially depending on a product. The mass concentrations of airborne particles <1 μm in diameter spanned about three orders of magnitude, while the mass concentrations of particles ~10 μm in size ranged as much as four orders of magnitude. Differences in the released particle concentration among products were also observed in other studies (Hagendorfer et al., 2009; Lorenz et al., 2011; Quadros and Marr, 2011). Since multiple products were investigated in this study, one can now use prediction intervals, as shown in Fig. 1, to anticipate size distributions and concentration ranges of typical consumer sprays when they are used close to the breathing zone. The observed variation in particle size and concentration is likely due to differences in product composition, volatility of the carrier fluid, and the sprayer mechanism and design. Hagendorfer et al. (2009) compared pump spray with a gas spray dispensers when using water-based nano-Ag solution and observed no measurable particle release when the pump spray was used, while a significant release was observed with the gas spray. Nazarenko et al. (2011) showed that the use of different sprayer mechanisms could result in different released particle concentrations which would lead to varying levels of exposure. The effect of sprayer mechanism on the total particle release from the products investigated here is being addressed in a separate study.

### 4.2. Differences in produced aerosol size and mass concentration among products

Most of the Ag concentrations detected in the liquid state of the spray products were within or below concentration ranges indicated on the product labels. For example, Ag concentrations in S3CS and S7HS were lower than advertised by factors 8.3 and 1.3, respectively. Relatively low Ag concentration in S3CS was the likely reason why Ag was not detected in this product by EDS (Table 3). On the other hand, Ag concentrations in S9HS and S7HS were higher than advertised by factors 1.2 and 4.3, respectively. It is worth noting that one of the Ag sprays (S3CS) contained Zn at a concentration of 90 ppm. We did not investigate further whether it was pure Zn or a Zn compound. The relatively high fraction of Zn in this product was confirmed via EDS where a droplet of S3CS was added to a TEM grid.

For products advertised as having Zn, our observed median concentration was ~510 ppm and similar to the concentration of 470 mg/kg (ppm) in a shoe impregnator measured by Lorenz et al. (2011). For the most part, the advertised Zn compound concentrations were in reasonable agreement with our detected concentrations. The concentration of ZnO in Z1CS and the concentration of pyrithione Zn in Z4CS was lower than advertised by a factor of 1.6 and 1.3, respectively. On the other hand, the concentration of Zn gluconate in Z6HS was advertised as 0.0975 mg/ml (97.5 ppm), while we found the concentration to be ~35,640 ppm: higher by a factor 362.5. Given that Zn gluconate containing products, such as Zicam, have been associated with elevated risk of anosmia (i.e., loss of smell) (Lim et al., 2009), health implications of having this ingredient in product Z6HS at much higher than advertised concentrations warrant further investigation.

As per Tables 1 and 2, a variety of metals was observed in spray suspensions of the products. The presence of a diverse group of metals as also observed in other study investigating consumer sprays (Losert et al., 2015).

Overall, Ag concentrations in Ag–based products ranged from 1.2 ppm to 20 ppm and were similar to those observed in other studies. Ag concentrations in liquid products investigated by Quadros and Marr (2011) ranged from 12.5 to 27.5 ppm, and Ag concentration in the three products investigated by Lorenz et al. was ND (not detected), 6.8 and 9.1 mg/kg (ppm). Thus, based on these three studies it seems that typical concentrations of Ag found in consumer sprays range from approximately 1 ppm to approximately 30 ppm. This observed Ag concentration range in several studies justifies the calculation of prediction intervals (Fig. 1a) and their use when modeling population exposure to Ag from the consumer sprays.

### Table 3

<table>
<thead>
<tr>
<th>Element/Product</th>
<th>S3CS (air)</th>
<th>S3CS (liquid)</th>
<th>Z2HS (air)</th>
<th>Z2HS (liquid)</th>
<th>Z4HS (air)</th>
<th>Z4HS (liquid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.8</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Mg</td>
<td>3.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Cl</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Mn</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>1.3</td>
<td>1.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Co</td>
<td>0.6</td>
<td>1.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Zn</td>
<td>6.3</td>
<td>1.8</td>
<td>3.7</td>
<td>0.5</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td>O</td>
<td>1.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>2.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Si</td>
<td>1.2</td>
<td>18.3</td>
<td>52.4</td>
<td>28.2</td>
<td>53.6</td>
<td>28.2</td>
</tr>
<tr>
<td>Cl</td>
<td>5.0</td>
<td>0.1</td>
<td>0.1</td>
<td>1.7</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>S</td>
<td>6.8</td>
<td>9.1</td>
<td>53.6</td>
<td>53.6</td>
<td>53.6</td>
<td>53.6</td>
</tr>
<tr>
<td>Ca</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>1.7</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Zn</td>
<td>0.5</td>
<td>6.5</td>
<td>6.4</td>
<td>6.4</td>
<td>6.4</td>
<td>6.4</td>
</tr>
</tbody>
</table>

* A small amount of Ag detected in some spectra but not sufficient to quantify.
4.4. Concentration of metals in spray aerosol

Based on the total released aerosol mass (Fig. 2) and concentrations of metals in the spray liquid, especially concentrations of Ag and Zn (Tables 1 and 2), we estimated the total airborne mass concentration of Ag and Zn (Fig. 2). Here we made an assumption that the metals fraction in airborne particles does not depend on metal size distribution in the liquid state or on the airborne droplet size. Quadros and Marr (2011) concluded that the size of Ag-containing aerosols emitted by the four products investigated by them was largely independent of the Ag size distributions in the liquid state. The same authors attempted to estimate the Ag content as a function of aerosol size but concluded that due to the different methodology used to measure and sample aerosols, such an estimate was rather uncertain. The presence of Zn and Ag in the airborne state of investigated products was also confirmed by TEM-EDX. However, this test indicated only the relative abundance of each element and not its actual airborne concentration. Losert et al. (2015) investigated the composition of released particles six consumer sprays. These workers detected silver in liquid and aerosol only in one of the two sprays labeled as having silver nanoparticles.

4.5. Implications for potential exposure to particles and metals due to the use of consumer sprays

As can be seen in Fig. 1, all products released particles ranging from nanosized (<100 nm) to greater than 1 μm and, in most cases, greater than 10 μm with total aerosol mass concentration reaching as high as tens of mg/m³. The released particles included individual nanoparticles and their agglomerates (Figs. 3–6). In addition, the aerosol produced by the products contained Ag, Zn compounds, and various metals (Fig. 2 and Tables 1–3). Thus, if these products are used in the vicinity of a consumer’s breathing zone, the consumer would be exposed via inhalation to engineered nanoparticles and their agglomerates, including those containing various species of metals.

The total inhaled aerosol mass, as well as the mass of inhaled Ag or Zn compounds, will depend on an intended product application type (e.g., surface, skin, throat, etc.), the actual application type, application duration, inhalation rate, mixing conditions and the distance of the inhalation point from the sprayer. Since the products were tested by spraying them in a glove box to simulate near-field breathing conditions, inhalation exposures for such scenario could be estimated using concentrations and size distributions presented in Fig. 1. In fact, this data has already contributed to our modeling of population exposures to Ag nanoparticles in consumer products (Royle et al., 2014), which will help produce a comprehensive source-to-dose-to-effect framework for characterizing risks due to exposure to manufactured nanoparticles.

The observed total airborne mass distributions (Fig. 1) are dominated by coarse and even supercoarse (>10 μm) (Lioy et al., 2006) particles, especially for Zn-based products. Based on spray deposition modeling work by Nazarenko et al. (2014), who investigated inhalation and deposition of sprays released from their native sprayers, the data from this study suggest that majority of the inhaled particle mass, including mass of metals present in spray liquid, is likely to deposit in the head airways and only a relatively small mass fraction will deposit in tracheobronchial and alveolar regions. Based on the observed size distribution parameters (Table S3), mass deposition in the head airways will be especially pronounced for Zn-based products. Based on Figs. 5 and 6, one can infer that larger particles are likely to consist of nanoparticle agglomerates as well as aggregates composed of nanoparticles and particles from product matrix, while particles penetrating into the deeper lung (bronchoalveolar spaces) would consist of individual nanoparticles as well as small particle agglomerates. Future studies should address whether the inhaled agglomerates will stay loosely bound, as was observed for TWC dust (Lioy et al., 2002) or will disintegrate into smaller particles that are then able to penetrate deeper into the lungs.

We also note that inhalation exposures would occur to not only Ag and Zn compounds — which were advertised on respective product labels — but also other metals including lithium, strontium, barium, lead, manganese and others. These findings suggest that investigation of risks and health effects associated with the use of consumer sprays, including those that are nanotechnology-based, should consider the size and mass characteristics of inhaled and deposited particles, and their chemical composition. Given that the presence of various metals was not described on product labels, changes in manufacturer-supplied information, including standardization of product labeling, should be evaluated and applied to consumer products for fuller disclosure.

Acknowledgement

The study was supported by a joint program of the U.S. Environmental Protection Agency (STAR grant 83469302) and the U.K. Natural Environment Research Council (grant NE/H012893), and the NIEHS-funded Center for Environmental Exposures and Disease (P30ES05022). AEP acknowledges additional support from an ERC starting grant (# 257182). AEP and MPR acknowledge a grant from NERC (# NE/N006402/1).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.02.016.

References


