Acute and subacute pulmonary toxicity and mortality in mice after intratracheal instillation of ZnO nanoparticles in three laboratories

Jacobsen, Nicklas Raun; Stoeger, Tobias; van den Brule, Sybille; Saber, Anne Thoustrup; Beyerle, Andrea; Vietti, Giulia; Mortensen, Alicja; Szarek, Józef; Budtz, Hans Christian; Kermanizadeh, Ali; Banerjee, Atrayee; Ercal, Nuran; Vogel, Ulla Birgitte; Wallin, Håkan; Møller, Peter

Published in:
Food and Chemical Toxicology

Link to article, DOI: 10.1016/j.fct.2015.08.008

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Jacobsen, N. R., Stoeger, T., van den Brule, S., Saber, A. T., Beyerle, A., Vietti, G., ... Møller, P. (2015). Acute and subacute pulmonary toxicity and mortality in mice after intratracheal instillation of ZnO nanoparticles in three laboratories. Food and Chemical Toxicology, 85, 84-95. DOI: 10.1016/j.fct.2015.08.008
Acute and subacute pulmonary toxicity and mortality in mice after intratracheal instillation of ZnO nanoparticles in three laboratories

Nicklas Raun Jacobsen a,*, Tobias Stoeger b, Sybille van den Brule c, Anne Thoustrup Saber a, Andrea Beyerle b, Giulia Vietti c, Alicja Mortensen d, Józef Szarek e, Hans Christian Budtz a, Ali Kermanizadeh f, Atrayee Banerjee g, Nuran Ercal g, Ulla Vogel a, h, Håkan Wallin a, h, Peter Møller f

a National Research Centre for the Working Environment, Lersø Parkalle 105, DK, 2100 Copenhagen Ø, Denmark
b Institute of Lung Biology and Disease, Comprehensive Pulmonary Medicine Center Helmholtz Zentrum München, German Research Center for Environmental Health, Munich, Germany
c Louvain Centre for Toxicology and Applied Pharmacology, Université catholique de Louvain, Avenue E. Mounier 52 — Bte 8152.12, 1200 Brussels, Belgium
d National Food Institute, Technical University of Denmark, Søborg, Denmark
e Faculty of Veterinary Medicine, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland
f Department of Chemistry, Missouri University of Science and Technology, Rolla, MO, USA
g Institute of Lung Biology and Disease, Comprehensive Pulmonology Center Helmholtz Zentrum München, German Research Center for Environmental Health, Munich, Germany
h Department of Micro- and Nanotechnology, Technical University of Denmark, DK, 2800 Lyngby, Denmark

A R T I C L E   I N F O

Article history:
Received 2 June 2015
Received in revised form 28 July 2015
Accepted 4 August 2015
Available online 7 August 2015

Keywords:
Cytotoxicity
DNA damage
Fibrosis
Inflammation
Mortality
Oxidative stress

A B S T R A C T

Inhalation is the main pathway of ZnO exposure in the occupational environment but only few studies have addressed toxic effects after pulmonary exposure to ZnO nanoparticles (NP). Here we present results from three studies of pulmonary exposure and toxicity of ZnO NP in mice. The studies were prematurely terminated because interim results unexpectedly showed severe pulmonary toxicity. High bolus doses of ZnO NP (25 up to 100 µg; >1.4 mg/kg) were clearly associated with a dose dependent mortality in the mice. Lower doses (≥6 µg; ≥0.3 mg/kg) elicited acute toxicity in terms of reduced weight gain, desquamation of epithelial cells with concomitantly increased barrier permeability of the alveolar/blood as well as DNA damage. Oxidative stress was shown via a strong increase in lipid peroxidation and reduced glutathione in the pulmonary tissue. Two months post-exposure revealed no obvious toxicity for 12.5 and 25 µg on a range of parameters. However, mice that survived a high dose (50 mg; 2.7 mg/kg) had an increased pulmonary collagen accumulation (fibrosis) at a similar level as a high bolus dose of crystalline silica. The recovery from these toxicological effects appeared dose-dependent. The results indicate that alveolar deposition of ZnO NP may cause significant adverse health effects.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Zinc oxide (ZnO) nanoparticles (NP) are extensively used in consumer products. Worldwide production is estimated at 0.1–1.2 million tons per year (Das et al., 2011; Kumar and Dhawan, 2013). ZnO and/or ZnO NP are used in numerous products like cosmetics, sunscreens, plastics, rubber, ceramics, cement, glass, paints, lubricants, electronic sensor and solar cells. Furthermore, ZnO are added to fertilizers and animal food as a source for the micronutrient (Zn) essential for hundreds of enzymes (Baxter and Aydil, 2005; Pan et al., 2001; Pinnell et al., 2000; Ma et al., 2013).

In vitro studies have shown that ZnO is cytotoxic at relatively low concentrations as compared to other types of engineered nanomaterials such as titanium dioxide, carbon nanotubes (Danielsen et al., 2014; Kermanizadeh et al., 2012, 2013a; Karlsson et al., 2014). Similar findings on cytotoxicity have been observed in broncho-alveolar lavage cells after pulmonary exposure to ZnO NP, which has been attributed to the dissolution of Zn ions (Cho et al., 2011; Kao et al., 2012). It has been shown that nanosized (50–70 nm) and fine (<1000 nm) ZnO particles elicited pulmonary inflammation and cytotoxicity in rats after inhalation and intratracheal exposure (Sayes et al., 2007; Warheit et al., 2009). Another
2.1. Study #1

Larger dose range.

The present communication is to expand information on toxicological studies on ZnO NP in mice. The investigations were conducted in different laboratories, using different ZnO nanomaterials and different mouse strains exposed via a fairly similar pulmonary exposure technique (instillation or aspiration). These studies were prematurely terminated because the highest exposures were unexpectedly associated with severe toxicity or death. The purpose of the present communication is to expand information on toxicological data of ZnO nanomaterials up to acute and sub-acute effects of a larger dose range.

2. Material and methods

2.1. Study #1

2.1.1. Mice and caging conditions

Female wild-type C57BL/6JomTac (C57) mice aged 5–6 weeks were obtained from Taconic (Ry, Denmark). The mice were randomly divided into housing groups of 10 in polycarbonate cages (425 mm × 266 mm × 150 mm) with pinewood sawdust bedding and enrichment in form of sticks of aspen wood and rodent tunnels (Brogaarden, Denmark). The cages were stored in rooms with a 12 h light period from 6 a.m. to 6 p.m., and the temperature and relative humidity in the animal room were 21 ± 2 °C and 50 ± 5%, respectively. The cages were sanitized on two occasions every week. All mice were given free access to tap water and standard diet (Altromin no. 1324, Altromin International, Lage, Germany). The mice were kept under conventional animal facilities and were allowed to acclimatize for 2–3 weeks before they entered the experimental protocol (Saber et al., 2012a). All mice were 8 weeks old at the time of the study, and the average weight at the day of instillation was 18 ± 1.4 g. All animal procedures followed the guidelines for the care and handling of laboratory animals according to the EC Directive 86/609/EEC and the Danish law. The Animal Experiment Inspectorate under the Danish Ministry of Justice approved the study (2012-15-2934-00223).

2.1.1.1. Nanoparticles, characterization and preparation of suspensions. The ZnO NP powder (CAS-No: 1314-13-2) (ZincoxTM 10, IBU-tec advanced materials AG, Weimar, Germany) was produced by pulsed arc discharge technique. According to the manufacturer, the Brunauer Emmett Teller (BET) surface area was 60 ± 5 m²/g, the spherical particles had an average size of 12 ± 3 nm and a hexagonal crystallographic phase. The purity was above 99% determined by energy dispersive x-ray analysis. Characterization of the instillation suspension by dynamic light scattering (DLS) Zetasizer nano ZS (Malvern Inc., UK) was performed as previously described (Jacobsen et al., 2009). However, the refractive (RI) and absorption indices (RS) was set at 2.020 ± 0.400, respectively, the values for ZnO NP. At concentrations between 0.04 and 0.36 mg/ml the ZnO NP was present in a very similar narrow and clear peak with an agglomerated number size between 59 and 68 nm. Reliable data with a low polydispersity index (PDI) (between 0.21 and 0.29) was obtained for the 3 low concentrations of ZnO NP. However, the high dose used in the pilot experiment (3.24 mg/ml; 162 µg/animal) yielded unreproducible, unreliable results likely caused by strong agglomeration, sedimentation with decreasing count rates (Zeta average size of 1–3 μm, PDI: 0.33–0.6).

The ZnO NP was suspended in 2% sibbling mouse serum in MilliQ water. The suspensions were sonicated as described in Poulsen et al. (2015a) using a Branson Sonifier S-450D (Branson Ultrasonics Corp., Danbury, CT, USA) equipped with a disruptor horn (model number 101-147-037 (Jackson et al., 2011a)). Total sonication time was 16 min at an amplitude of 10%. Samples were continuously cooled on ice during the sonication procedure. For the pilot experiment a suspension of 3.24 mg/ml (162 µg/animal) was prepared. Each instillation was 50 µl suspension followed by 150 µl air. For the following study the high dose stock suspension was prepared at 0.36 mg/ml (18 µg/animal). This suspension was diluted 1:3 for the medium dose (0.12 mg/ml; 6 µg/animal) and further 1:3 for the low dose (0.04 mg/ml; 2 µg/animal). Each of these dilutions, were sonicated for 2 min. Vehicle control solutions were prepared by sonicating 2% sibbling mouse serum in MilliQ water according to the full protocol.

2.1.1.2. Experimental design and exposure. Two mice were exposed in a pilot study to 162 µg ZnO NP/animal. However, on the second day these became visibly ill (immobile, pilo erection, hunched posture) and the pilot experiment was terminated following approximately 30 h. This was followed by the main study were groups of mice were given 0, 2, 6 or 18 µg ZnO NP or 162 µg carbon black PrinTex 90 by a single intratracheal instillation. PrinTex 90 is a highly inflammatory particle that has been extensively examined and used as a benchmark particle (Jacobsen et al., 2007, 2008, 2011; Jackson et al., 2012; Bourdon et al., 2012; Hogsberg et al., 2013; Vestergaard et al., 2010; Kjøvska et al., 2015a). Each exposed group consisted of six mice (N = 6) and each control group of twelve mice (N = 12) and was planned to be killed after 1d and 3d. Additionally eight unexposed mice were included in the study. A total of 80 mice were used in this study. An originally planned later time point for termination was omitted due to high toxicity. The instillation technique was performed as previously been described (Kjøvska et al., 2015b). Briefly, mice were anesthetized by inhalation of 4% isoflurane, before being placed back down on a 50° sloped instillation board. The tongue was gently pushed aside. Using an external cold light source (KL1500LED; Schott, Lynbyh, Denmark), the trachea could be visualized and intubated using a 24 gauge BD Insyte catheter (Becton Dickinson, Denmark) with a shortened needle. The correct location of each intubation catheter was tested using a highly sensitive pressure transducer (pneumotachometer) developed at the National Research Centre for the Working Environment in collaboration with John Frederiksen (FFE/P, Copenhagen, Denmark). A 50 µl suspension was instilled followed by 200 µl air with a 250 µl SGE glass syringe (250F-LT-GT, MicroLab, Aarhus, Denmark). Control animals received vehicle instillations. All animals were gently downwards shaken three times to ensure that no liquids were blocking the upper respiratory airways. After instillation, the mice were weighed and transferred to the home cage until termination.
2.1.1.3. Blood, broncho-alveolar lavage fluid, cells and preparation of tissues. Mice were weighed at the day of instillation and again on the day of dissection. The mice were anesthetized using Hypnorm® (fentanyl citrate 0.315 mg/mL and fluanisone 10 mg/mL from Janissen Pharma) and Dormicum® (Midazolam 5 mg/mL from Roche). Both anesthetics were mixed with equal volumes of sterile water. A volume of 0.15 mL/25 g body weight was injected intramuscularly (half the dose per leg).

Preparation of broncho-alveolar lavage fluid (BALF) was performed as previously described (Poulsen et al., 2015b). Briefly, exsanguination was caused by withdrawal of blood from a heart puncture. BALF and cells were obtained by infusing the lungs twice with 1 mL sterile saline water per 25 g body weight. Each flush consisted of 3 slow up and downwards movements. The second flush was also performed with fresh saline water. The BALF was stored on ice until centrifuged (400 g, 4 °C, 10 min). The supernatant was divided in strips, snap-frozen in liquid-nitrogen and stored at −80 °C before quantification of protein concentration (Pierce BCA, Bie-−Berntsen, Denmark) according to the manufacturer’s description. The BALF cells were re-suspended in 100 μL medium (HAMF12 with 10% fetal bovine serum). The cell suspension (40 μL) was mixed with 160 μL medium containing 10% DMSO and stored at −70 °C for comet assay analysis which was performed as previously described (Saber et al., 2012b). For differential count 50 μL cell suspension was collected on a microscope slide by centrifugation at 55 g, 4 min in a Cytofuge 2 (StatSpin, Bie and Berntsen, Rødovre, Denmark). The slides were fixed with 96% ETOH and stained with May-Grünwald-Giemsa stain. The cellular composition of BALF cells was determined by scoring 200 cells. The total number of cells was determined by using the NucleoCounter (Chromometec, Allered, Denmark) live/dead assay according to the manufacturer’s instructions.

Tissue samples of liver and lung were taken from two mice in each of the three ZnO NP groups (2, 6 and 18 μg) as well as vehicle controls. The samples were fixed in neutral buffered formaldehyde (4%), trimmed, paraffin-embedded and sections of 4–6 μm were made and stained with hematoxylin and eosin for the histological examination.

2.2. Study #2

2.2.1. Mice and caging conditions

Eight to twelve weeks old, female BALB/CAnNcrl mice were obtained from Charles River Laboratories (Sulzfeld, Germany). The animals were kept in isolated ventilated cages (IVC-Racks; BioZone, Margate, UK), supplied with filtered air and a 12-hr light/12-hr dark cycle. Specific pathogen-free hygienic status was approved and certified according to the Federation of European Laboratory Animal Science Associations guidelines (Nicklas et al., 2002). Standard diet (Altromin no. 1314, Altromin International, Lage, Germany) and water were available ad libitum. Animals were 10–12 weeks of age with body weights between 19.6 and 23.1 g at the beginning of the study. Animal experiments were carried out according to the German law of protection of animal life and were approved by an external review committee for laboratory animal care. The approval number for the specified studies was Az55 2-1-54-2531-115-05.

2.2.1.1. Nanoparticles, preparation and characterization of suspensions. ZnO NP was obtained from Alfa Aesar (ID 43141, A Johnson Matthey Company, Karlruhe, Germany) with a nominal average diameter of 70 nm. According to manufacturer the primary particle size is: 24–71 nm; BET surface area: 15–45 m²/g, agglomerated. The authors have previously determined the BET size to 13 m²/g (Lenz et al., 2013). Crystalline silica (Min-U-Sil 5, a-quartz) was obtained from U.S. Silica Company, Berkerly Springs, WV, USA, with a median diameter of 1.7 μm declared on the datasheet from the manufacturer.

ZnO NP (5 and 15 μg in 50 μl suspension) and crystalline silica (35 μg in 50ul suspension) was prepared in sterile, pyrogen-free distilled water. Stock solutions (10 mg/mL) were sonicated using a SonoPlus HD70 (Bachofer, Berlin, Germany) at a moderate energy of 20 W for 15 min prior to dilution. Each suspension was sonicated for 10 min directly before use. According to our previous experience, the instillation of 50 μL distilled water did not cause any measurable stress effects such as the expression of heat shock protein hsp70/hsp1a (Stoeger et al., 2006). Unexposed control animals were included as well as and sham exposed animals receiving 50 μL pure distilled water.

2.2.1.2. Experimental design and exposure. Controls and two dose groups (5 and 15 μg/animal) were planned to be killed 24 h, 3 days, or 7 days post-exposure. Each group consisted of 8 mice (N = 8). However, the experiment was terminated early for reasons of animal welfare (acute significant weight loss) thus only 24 h post-exposure were completed. A total of 40 mice were used for this study.

Before instillation mice were anesthetized by intraperitoneal injection of a mixture of xylazine (41 mg/kg body weight) and ketamine (188.3 mg/kg body weight). The animals were then fixed in a supine position on a 60° incline board by holding their upper incisor teeth. The tongue was gently extended using coated tweezers, and the mice were intubated through the mouth and trachea using a bulb headed cannula inserted 10 mm into the trachea; a suspension containing 5 or 15 μg particles, respectively, in 50 μL pyrogene-free distilled water was instilled, followed by 100 μL air.

2.2.1.3. Blood, broncho-alveolar lavage fluid and cells. Mice were weighed at the day of instillation and again on the day of dissection. They were anesthetized with an overdose of ketamine/xylazin (1%/0.1%). Exsanguination was caused by retro-orbital collection of 500–700 μl of blood. The blood was collected in EDTA-coated tubes and continuously rotated/moved prior to measurement by the ADVIA 120 Hematology System (Siemens Healthcare Diagnostics, Deerfield, USA).

The lungs of the mice were lavaged 10 times with 1 mL of fresh phosphate-buffered saline (PBS; 37 °C), supplemented with complete protease inhibitor cocktail (Roche Diagnostics, Mannheim, Germany). BALF of each animal were pooled. Cytocentrifuged slides were prepared by centrifugation (100 g, 5 min). BALF cells were prepared for cell differentiation with May-Grünwald-Giemsa staining. Two slides were prepared per animal and 2x 200 cells scored on each slide.

Total protein and lactate dehydrogenase (LDH) as well as secretion of 10 cytokines/chemokines were measured in cell-free BALF. BALF was centrifuged at 1200 g, 15 min at 4 °C. Total concentration of protein was determined using the Bradford method and LDH concentration was determined by using Cytotoxicity Detection Kit (Roche Applied Diagnostics, Germany). Levels of total IgM were measured by ELISA using complementary capture and detection antibody pairs as previously described (Beyerle et al., 2011a). Cytokine release: Ten cytokines/chemokines were detected simultaneously in the BALF using Luminex technology (Linco Research, St. Charles, MO). In this study, the secretions of the following cytokines/chemokines were investigated: Interleukin (IL)-1α, IL-6, IL-10, tumor necrosis factor (TNF)-α, granulocyte colony-stimulating factor (G-CSF), chemokine (C-X-C motif) ligand (CXCL)-1, CXCL-2, CXCL-5, CXCL-10, interferon (INFγ). The assay was performed as described previously (Beyerle et al., 2011b). Monocyte chemotactic protein (MCP)-1 also called chemokine (C–C motif) ligand (CCL)2 was quantified in the BALF using mouse CCL-2/JE
2.2.4. Oxidative stress parameters in lung tissue. Glutathione (GSH), malondialdehyde (MDA) levels and catalase activity in the lung tissue were determined by HPLC, as previously described (Banerjee et al., 2009).

3. Study #3

3.1. Mice and caging conditions

Eight week-old C57BL/6N female mice were obtained from Taconic Europe (Ry, Denmark). The animals were kept and housed in positive-pressure air-conditioned units (25 °C, 50% relative humidity) on a 12:12-h light/dark cycle. All mice were given free access to tap water and standard diet. The protocol of this study was approved by the local ethical committee for animal research. The laboratory approval number is LA1230312 and the approval for the speciﬁed studies was 2010/UCL/MD/034.

3.1.1. Nanoparticles and preparation. The NM-111 (BASF Z-Cote; Zincite ZnO NP functionalized with triethoxycaprylsilane, 130 nm) was received from the European Commission Joint Research Centre repository (JRC, Ispra, Italy). Nanomaterials were sub-sampled and preserved under argon in the dark at room temperature until use. The details on raw material characteristics have been thoroughly examined previously within the same project (Kermanizadeh et al., 2013b). X-ray diﬀraction (XRD) size: 58–93 nm. BET surface area: 18 m2/g. Via transmission electron microscopy (TEM) the size morphology was shown to be diverse; about 90% of particles with an aspect ratio of 1 were in the 20–200 nm size range and about 90% of particles with an aspect ratio between 2 and 8.5 were in the 10–450 nm size range.

With the following exceptions the preparation of the suspensions was identical as in study #1. The vehicle was composed of 0.5% EtOH (96%), 2% C57BL/6 mouse serum in MilliQ water. The stock suspension was prepared at 2 mg/mL and it was sonicated on ice (Virsonic 300 ultrasonic cell disrupter, Virtis, Gardiner, USA) for 16 min at an amplitude of 15%. The stock suspension was serially diluted in the same dispersion media and sonicated for 15 min in a water bath. Min-U-Sil was directly dispersed with the dispersion medium (no sonication).

3.1.2. Experimental design and exposure. Mice received a single pulmonary exposure dose of 12.5, 25, 50 and 100 μg ZnO NP/mouse or vehicle/negative control (N = 5). The positive control group consisted of 8 mice and was exposed to crystalline silica (2.5 mg Min-U-Sil/mouse; U.S. Silica Company, Berkeley Springs, USA), known to induce an inﬂammatory and ﬁbrotic response. The vehicle control animals were exposed to 0.5% EtOH (96%), 2% C57BL/6 mouse serum in MilliQ water. The original experimental plan was for the sacriﬁce of mice 2 months post-exposure.

The particles were administered in the lungs by pharyngeal aspiration after 4% isoflurane for 30 s. NP suspensions at a ﬁxed instillation volume of 50 μl were deposited at the entrance of the trachea utilizing a pipette. At the ﬁrst breath, the liquid was aerosolized and aspirated into the lungs of the mice.

3.1.3. Broncho-alveolar lavage ﬂuid, cells and preparation of tissue. Mice were sacriﬁced 2 months after instillation with an overdose of sodium pentobarbital (15 mg/mouse intraperitoneally). Lungs were lavaged by the cannulation of the trachea and ﬂushing lobes with 1 ml NaCl 0.9%. The lavage ﬂuid was centrifuged (200 g, 10 min, 4 °C) and the cell-free supernatant was used for the measurement of LDH activity, protein content and quantiﬁcation of selected cytokines. The measurement of LDH activity was performed using a Synchron LX Unicell DXC-800 (Beckman Coulter, Brea, USA) in the presence of 11 mM of NAD+, and 50 mM lactate. The total protein concentration was quantiﬁed spectrophotometrically at 600 nm after complexation with molybdate pyrogallol red. Finally, enzyme-linked immunosorbent assays (ELISA) were performed according to manufacturer’s instructions (R&D Systems, Minneapolis, USA): TNFα, IL-1α, IL-1β, IL-6, IL-13, active transforming growth factor (TGF)–β1 and osteopontin (OPN) also called secreted phosphoprotein 1 (SPP-1).

The cell pellets were resuspended in NaCl 0.9%. BALF total cell number for each animal was determined in Turch (1% crystal violet (Merck, Darmstadt, Germany), 3% acetic acid). Cells were also pelleted onto glass slides by cytocentrifugation for diﬀerentiation by light microscopy after Diﬀ-Quick staining (200 cells counted, Dade Behring AG, Düdingen, Switzerland).

Total pulmonary collagen was determined via OH-proline, an amino acid relatively speciﬁc for, and a major component of collagen. Following lavage, lungs were perfused with NaCl 0.9% excised and placed in 3 ml ice-cold PBS. They were then homogenized on ice with a Ultra-Turrax T25 homogenizer (Janke & Kunkel, Brussels, Belgium) and stored at –80 °C. Part of the lung homogenate was hydrolyzed in HCl 6N at 108 °C during 24 h and OH-proline was quantiﬁed by high-performance liquid chromatography (Biondi et al., 1997).

**Table 1**

<table>
<thead>
<tr>
<th>Instillation</th>
<th>Weight</th>
<th>Termination</th>
<th>Weight</th>
<th>Δ Weight</th>
<th># Of mice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Day 0</td>
<td>17.2 ± 0.3</td>
<td>Day 1</td>
<td>ND</td>
<td>12</td>
</tr>
<tr>
<td>ZnO 2 μg</td>
<td>Day 0</td>
<td>17.8 ± 0.5</td>
<td>Day 1</td>
<td>ND</td>
<td>6</td>
</tr>
<tr>
<td>ZnO 6 μg</td>
<td>18.3 ± 0.5</td>
<td>ND</td>
<td>ND</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>ZnO 18 μg</td>
<td>17.8 ± 0.8</td>
<td>ND</td>
<td>ND</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>P90 162 μg</td>
<td>17.6 ± 0.2</td>
<td>ND</td>
<td>ND</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>Day 0</td>
<td>18.5 ± 0.8</td>
<td>Day 2</td>
<td>19.2 ± 0.9</td>
<td>0.7 g</td>
</tr>
<tr>
<td>ZnO 2 μg</td>
<td>Day 0</td>
<td>17.2 ± 0.0</td>
<td>Day 2</td>
<td>17.3 ± 0.0</td>
<td>0.2 g</td>
</tr>
<tr>
<td>ZnO 6 μg</td>
<td>19.0 ± 0.5</td>
<td>17.0 ± 0.0</td>
<td>2.0 g*</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>ZnO 18 μg</td>
<td>18.2 ± 0.7</td>
<td>15.6 ± 0.7</td>
<td>2.6 g*</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>Day 0</td>
<td>18.3 ± 0.7</td>
<td>Day 3</td>
<td>19.0 ± 0.5</td>
<td>0.3 g</td>
</tr>
<tr>
<td>ZnO 6 μg</td>
<td>17.3 ± 0.7</td>
<td>17.5 ± 0.7</td>
<td>0.2 g</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>ZnO 18 μg</td>
<td>18.3 ± 0.7</td>
<td>16.1 ± 0.7</td>
<td>2.2 g*</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>P90 162 μg</td>
<td>18.1 ± 0.4</td>
<td>18.4 ± 0.4</td>
<td>0.3 g</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Average weight of all 72 mice at the day of instillation 18 ± 1.3 g.

Results are given as mean ± SEM. P90; Printex 90 carbon black. ND: Not determined. Asterisks refer to statistical signiﬁcance *p < 0.05 when comparing to the relevant vehicle control.
Red blood cells (RBC) were scored on a 4 tier scale (0; non to very few RCB, 1; high levels of RBC, 2; very high levels of RBC). Proteins are determined (terminated due to animal suffering). Asterisks refer to statistical significance *p < 0.05 and ***p < 0.001 when comparing to the relevant vehicle control. All samples were scored randomized.

### Table 3

Red blood cells and concentration of protein in broncho-alveolar lavage fluid and DNA damage by the comet assay in the lavaged cells.

<table>
<thead>
<tr>
<th>Dose (µg)</th>
<th>RBC</th>
<th>Protein</th>
<th>Comet assay</th>
<th># Animals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>2</td>
<td>0.5</td>
<td>312 ± 21</td>
<td>12</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>0.8</td>
<td>522 ± 58</td>
<td>6</td>
</tr>
<tr>
<td>ZnO 6</td>
<td>1.0</td>
<td>0.9</td>
<td>659 ± 76</td>
<td>6</td>
</tr>
<tr>
<td>18</td>
<td>1.2</td>
<td>1.4</td>
<td>626 ± 91</td>
<td>6</td>
</tr>
<tr>
<td>P90 162</td>
<td>0.6</td>
<td>ND</td>
<td>301 ± 34</td>
<td>10</td>
</tr>
<tr>
<td>3 day</td>
<td>2</td>
<td>0.3</td>
<td>574 ± 158</td>
<td>4</td>
</tr>
<tr>
<td>ZnO 6</td>
<td>6</td>
<td>2.1***</td>
<td>4591 ± 1083***</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P90 162</td>
<td>0.2</td>
<td>ND</td>
<td>126 ± 1.5</td>
<td>6</td>
</tr>
<tr>
<td>Unexposed</td>
<td>0.1</td>
<td>235 ± 20</td>
<td>8.1 ± 1.0</td>
<td>8</td>
</tr>
</tbody>
</table>

Results are given as mean or mean ± SEM. P90; Printex 90 carbon black. Not determined (terminated due to animal suffering). Asterisks refer to statistical significance *p < 0.05 and ***p < 0.001 when comparing to the relevant vehicle control. All data are presented as µg/ml. Comet assay scored randomized.

### 2.3.1.4. Statistical analysis for all 3 studies.

All data are presented as mean values ± standard error of the mean (SEM). Differences were evaluated by using one-way analysis of variance followed by Sidak’s test. Blood parameters (study 2) were analyzed by general linear model (GLM) followed by Sidak’s test. Certain endpoints within study 2; macrophages, lymphocytes, neutrophils, CXCL-1, IL-6, CXCL-10 CXCL-5, G-CSF, MDA, Protein and LDH, and within study 3; total BAL cells, macrophages, lymphocytes and neutrophils displayed inhomogeneity of variance (p < 0.05, Bartlett’s test). The statistical significance was confirmed using Kruskal–Wallis non-parametric test, whereas we have reported P-values of Sidak’s tests for consistency in the manuscript. The mortality data was analyzed by χ². All statistical analysis was performed using STATA 13 (STATACORP LP, College station TX, USA) except for blood parameters which were analyzed using MiniTab 17 (Minitab Inc., State College, PA, USA).

### 3. Results

#### 3.1. Study #1

The pilot study (2 mice, 162 µg ZnO NP) was terminated after about 30 h as the mice showed complete immobility and breathing difficulty. At autopsy it was shown that their lungs were filled with blood.

#### 3.1.1. Body weight of mice

The weight of all mice was recorded immediately before the exposure and again at the termination day 2 and 3 (but not day 1).
The body weight significantly decreased by 14% at 2 days post-exposure in the group of mice that received 18 mg ZnO NP (Table 1). A decrease in body weight was also observed for mice exposed to 6 mg. Their weight significantly decreased by 11 and 12% at day 2 and 3 post-exposure, respectively. A marginal increase (between 0.9 and 3.8%) in body weight was observed for vehicle, 2 mg ZnO NP and Printex 90 exposed mice.

3.1.2. BALF: cellular composition, proteins and comet assay

The number and composition of cells in the lung lumen was assessed by NucleoCounter and microscopy (Table 2). One day post-exposure the results show a reduction in macrophages and an increase in neutrophils. However, three days post-exposure total cell numbers increased 2–5-fold for 2 and 6 μg exposures, respectively. This was mainly driven by a doubling of macrophages and a very
large increase in neutrophils (30 to 511-fold for 2 and 6 μg exposures, respectively). In addition to these large increases in macrophages and neutrophils, 6 μg exposed mice also showed an increase in lymphocytes (3-fold w/o, 12-fold with a high outlier) (Table 2). As these mice also displayed very high numbers of red blood cells in the BALF, these results indicate alveolar-capillary barrier damage indicative of pulmonary injury were oedema (perivascular, sub-epithelial, interstitial and/or of alveolar walls) in animals from mid and high ZnO NP dose groups, lymphoid cell infiltration of the interstitial tissue or in alveolar interstitium or lamina, and hypertrophy of single epithelial cells or proliferation of epithelial cells of bronchioles were recorded occasionally (Table 4).

In the livers from ZnO NP exposed animals the most noteworthy changes were an increased presence of binucleate hepatocytes and enlargement of single hepatocyte. Both these lesions are considered as indicative of a regenerative activity of liver tissue after exposure to a toxicant (Kostka et al., 2000). Mice exposed to 2 and 18 μg ZnO NP had necrosis of single hepatocytes. The number of recorded pathomorphological changes was similar in animals exposed to ZnO NP; however the changes appeared more severe in the animals exposed to 18 μg ZnO NP. Exemplified images of lung and livers from all exposure groups are shown in Fig. 1.

3.2. Study #2

3.2.1. Weight of mice
The experiment was stopped 24 h after exposure due to signs of distress and acute toxicity (reduced body weight, reduced mobility and pilo erection) in the 15 μg ZnO NP group. Body weight was determined on day of application and on day of dissection. Body weight loss was calculated as the difference between the day of dissection and the day of instillation. At 24 h the 15 μg ZnO NP group had an 11% reduced body weight (p < 0.001), whereas all other groups showed a marginal weight reduction of 4–5% (Table 5). This is a clear sign of acute poisoning in the high dose ZnO NP group.

3.2.2. Blood parameters
Systemic effects were determined via a hematological analysis of 45 parameters. The GLM ANOVA showed significant difference for 32 of the 45 blood parameters. The 32 parameters were tested post hoc and the high dose zinc group showed significant differences from the controls recorded record pathomorphological changes was similar in animals exposed to ZnO NP, however the changes appeared more severe in the animals from mid and high ZnO NP dose groups, lymphoid cell infiltration of the interstitial tissue or in alveolar interstitium or lamina, and hypertrophy of single epithelial cells or proliferation of epithelial cells of bronchioles were recorded occasionally (Table 4).

In the livers from ZnO NP exposed animals the most noteworthy changes were an increased presence of binucleate hepatocytes and enlargement of single hepatocyte. Both these lesions are considered as indicative of a regenerative activity of liver tissue after exposure to a toxicant (Kostka et al., 2000). Mice exposed to 2 and 18 μg ZnO NP had necrosis of single hepatocytes. The number of recorded pathomorphological changes was similar in animals exposed to ZnO NP; however the changes appeared more severe in the animals exposed to 18 μg ZnO NP. Exemplified images of lung and livers from all exposure groups are shown in Fig. 1.

3.2. Study #2

3.2.1. Weight of mice
The experiment was stopped 24 h after exposure due to signs of distress and acute toxicity (reduced body weight, reduced mobility and pilo erection) in the 15 μg ZnO NP group. Body weight was determined on day of application and on day of dissection. Body weight loss was calculated as the difference between the day of dissection and the day of instillation. At 24 h the 15 μg ZnO NP group had an 11% reduced body weight (p < 0.001), whereas all other groups showed a marginal weight reduction of 4–5% (Table 5). This is a clear sign of acute poisoning in the high dose ZnO NP group.

3.2.2. Blood parameters
Systemic effects were determined via a hematological analysis of 45 parameters. The GLM ANOVA showed significant difference for 32 of the 45 blood parameters. The 32 parameters were tested post hoc and the high dose zinc group showed significant differences from the controls recorded results.

3.1.3. Lung and liver histology by light microscopy
As mice exposed to 18 μg ZnO NP manifested severe clinical signs of toxicity (recumbency, immobility, pilo erection) 2 days post-exposure, it was decided to terminate this group (off schedule) and to perform a histopathological examination of lungs and liver from two mice in each of the groups 0, 2, and 6 μg ZnO NP/mouse. The rest of the mice were terminated as scheduled three days after exposure. Histological results are summarized in Table 4. As the animals were not eviscerated, congestion was observed in all samples from lungs and livers.

An excessive desquamation of epithelial cells of bronchioles as compared to the controls was recorded in all but one ZnO NP exposed animals; the severity of the lesion varied between the treated animals without a clear dose response. Other changes indicative of pulmonary injury were oedema (perivascular, sub-epithelial, interstitial and/or of alveolar walls) in animals from mid and high ZnO NP dose groups, lymphoid cell infiltration of the interstitial tissue or in alveolar interstitium or lamina, and hypertrophy of single epithelial cells or proliferation of epithelial cells of bronchioles were recorded occasionally (Table 4).

In the livers from ZnO NP exposed animals the most noteworthy changes were an increased presence of binucleate hepatocytes and enlargement of single hepatocyte. Both these lesions are considered as indicative of a regenerative activity of liver tissue after exposure to a toxicant (Kostka et al., 2000). Mice exposed to 2 and 18 μg ZnO NP had necrosis of single hepatocytes. The number of recorded pathomorphological changes was similar in animals exposed to ZnO NP; however the changes appeared more severe in the animals exposed to 18 μg ZnO NP. Exemplified images of lung and livers from all exposure groups are shown in Fig. 1.

3.2. Study #2

3.2.1. Weight of mice
The experiment was stopped 24 h after exposure due to signs of distress and acute toxicity (reduced body weight, reduced mobility and pilo erection) in the 15 μg ZnO NP group. Body weight was determined on day of application and on day of dissection. Body weight loss was calculated as the difference between the day of dissection and the day of instillation. At 24 h the 15 μg ZnO NP group had an 11% reduced body weight (p < 0.001), whereas all other groups showed a marginal weight reduction of 4–5% (Table 5). This is a clear sign of acute poisoning in the high dose ZnO NP group.

3.2.2. Blood parameters
Systemic effects were determined via a hematological analysis of 45 parameters. The GLM ANOVA showed significant difference for 32 of the 45 blood parameters. The 32 parameters were tested post hoc and the high dose zinc group showed significant differences from the controls recorded results.

3.1.2. Blood parameters

3.1.1. Body weight and selected blood parameters.

3.1.2. Blood parameters

3.1.1. Body weight and selected blood parameters.

3.1.2. Blood parameters

3.1.1. Body weight and selected blood parameters.

3.1.2. Blood parameters

3.1.1. Body weight and selected blood parameters.

3.1.2. Blood parameters

3.1.1. Body weight and selected blood parameters.
Table 8
Cytokines assessed in broncho-alveolar lavage fluid.

<table>
<thead>
<tr>
<th>1 Day Dose (µg)</th>
<th>IL-6</th>
<th>CXCL-1</th>
<th>CXCL-10</th>
<th>CCL-2</th>
<th>G-CSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO 0</td>
<td>2.8±0.0</td>
<td>27.3±14.4</td>
<td>8.9±4.7</td>
<td>5.6±0.9</td>
<td>6.6±1.1</td>
</tr>
<tr>
<td>5</td>
<td>4.7±3.3</td>
<td>25.3±9.6</td>
<td>6.2±0.0</td>
<td>10.5±2.0</td>
<td>9.0±7.1</td>
</tr>
<tr>
<td>15</td>
<td>1356.1±990.6**</td>
<td>349.9±183.8***</td>
<td>108.3±34.1***</td>
<td>37.3±2.1***</td>
<td>1933.4±3742.3***</td>
</tr>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt; 35</td>
<td>1.8±1.0</td>
<td>175.9±32.7</td>
<td>11.9±8.8</td>
<td>11.1±1.5</td>
<td>47.3±8.3</td>
</tr>
<tr>
<td>Unexposed</td>
<td>2.8±0.0</td>
<td>148.3±2.5</td>
<td>5.5±1.6</td>
<td>9.2±1.5</td>
<td>3.5±0.9</td>
</tr>
</tbody>
</table>

Table 9
Oxidative stress parameters determined in lung tissue.

<table>
<thead>
<tr>
<th>1 Day Dose (µg)</th>
<th>GSH (mM)</th>
<th>MDA (mM)</th>
<th>Catalase (nmol/mg protein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO 0</td>
<td>16.6±0.7</td>
<td>16.7±0.3</td>
<td>13.9±0.5</td>
</tr>
<tr>
<td>5</td>
<td>16.1±0.6</td>
<td>17.5±1.0</td>
<td>17.6±0.4***</td>
</tr>
<tr>
<td>15</td>
<td>12.4±0.5***</td>
<td>30.4±0.9***</td>
<td>13.2±0.5</td>
</tr>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt; 35</td>
<td>14.0±0.4*</td>
<td>18.4±0.8*</td>
<td>14.5±0.2</td>
</tr>
<tr>
<td>Unexposed</td>
<td>15.8±0.4</td>
<td>14.4±0.4</td>
<td>14.4±0.2</td>
</tr>
</tbody>
</table>

Table 10
Cellular distribution in broncho-alveolar lavage fluid.

<table>
<thead>
<tr>
<th>2 Months Dose (µg)</th>
<th>Total #</th>
<th>Macrophages</th>
<th>Lymphocytes</th>
<th>Neutrophils</th>
<th>Eosinophils</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO 0</td>
<td>48,300±14,181</td>
<td>34,235±6089</td>
<td>7376±3804</td>
<td>163±94</td>
<td>6526±4457</td>
</tr>
<tr>
<td>12.5</td>
<td>49,400±13,917</td>
<td>48,710±13,828</td>
<td>499±185</td>
<td>190±101</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>75,833±16,220</td>
<td>72,857±17,459</td>
<td>2975±1291</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>44,750±9750</td>
<td>43,582±9282</td>
<td>1031±331</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt; 0</td>
<td>26,571±2438</td>
<td>22,148±2217</td>
<td>2450±635</td>
<td>182±71</td>
<td>1790±671</td>
</tr>
<tr>
<td>2500</td>
<td>80,062±14,228*</td>
<td>54,237±10,878</td>
<td>14,934±3384*</td>
<td>9865±1874***</td>
<td>1221±497</td>
</tr>
</tbody>
</table>

Mortality (%) of ZnO NM-111

Fig. 2. Mortality curve for mice exposed to nanosized ZnO (N = 5).

Results are given as mean ± SEM. SiO<sub>2</sub> is crystalline silica Min-U-Sil 5. All cytokines (pg/ml). Asterisks refer to statistical significance *p < 0.05, **p < 0.01 and ***p < 0.001 when comparing to the vehicle control (N = 8).

A strong increase in neutrophils and a reduction in white blood cells and lymphocytes was observed for the 15 µg ZnO NP group as compared to vehicle control. Increased number of blood neutrophils is a clear sign for an acute systemic inflammatory response to the pulmonary injury caused by ZnO. The increase in neutrophils might be on the expense of lymphocytes which present the majority of white blood cells in mice (Table 5). This combined with a possible retention of activated leukocytes in the injured capillary bed of the lungs cause a temporal lymphopenia.

Acute inflammation is often accompanied by increased platelet production, resulting in increased platelet counts and enhanced blood coagulability. The presence of immature, large platelets and clumps of activated platelets are the hematological signs observed during the acute phase of systemic inflammation. Platelet count (p < 0.05), large platelets (p < 0.01) and clumps count (p < 0.05; not shown) were all significant elevated in the 15 µg ZnO NP group indicating thrombocytosis/thrombocythemia (Table 5). No other group showed any statistically significant altered platelet status, although the low dose ZnO NP showed a marginal increase in large platelets.

Increased production of red blood cells (polycythemia) and raised hematocrit (Table 5) may be assumed as further systemic signs to pulmonary injury, as the body compensates insufficient oxygen absorption by producing more red blood cells.

3.2.3. BALF: cellular composition, LDH, protein, immunoglobulin M and cytokines

Cellular composition was determined by microscopy. A very strong pulmonary influx (9-fold) of neutrophils was observed in the 15 µg group 24 h post-exposure, accompanied by a reduction of macrophages to about half. There was no increase in neutrophils and only a marginal reduction in macrophages was observed for the 15 µg group (Table 6).

ZnO NP (15 µg) caused significant toxicity to lung. This was parameter, respectively. Selected parameters are shown in Table 5.
illustrated by a strong increase in LDH (28-fold, p < 0.001) caused by cell and tissue damage. Additionally, increased epithelial-endothelial permeability and cell leakage was shown by elevated concentration of BALF proteins (3-fold; p < 0.001). There was a 36-fold (p < 0.001) increase in Immunoglobulin M (IgM) in BALF 24 h post-exposure in the high dose group. IgM is the largest antibody in the bloodstream and the first antibody to appear in response to initial antigen exposure. IgM accumulation in BALF may indicate an injury to the alveolar barrier allowing the leakage of large serum proteins into the alveolar space (IgM is 970 kDa). Only minor differences were observed for the low dose group (5 μg) (Table 7).

Overall, treatment with 15 μg of ZnO NP caused a dramatic increase in expression of pro-inflammatory cytokine IL-6 (484-fold) as well as chemotactic cytokines such as CXCL-1 (KC) and CCL-2 (MCP-1) involved in the recruitment of neutrophils and monocytes/macrophages, respectively, to the site of inflammation. The latter two increased by 13- and 7-fold, respectively. Additionally, G-CSF and CXCL-10 which also may be involved in maintaining pulmonary inflammation, enhancing granulocyte survival and attraction of monocytes/macrophages and T cells were significantly elevated 293- and 12-fold, respectively. Elevated levels of CCL-2 and CXCL-10 have been associated with pulmonary fibrosis, although CCL-2 is a known fibrocyte chemoattractant (Murray et al., 2008), exogenous CXCL-10 inhibited fibrogenesis (Jiang et al., 2010). CCL-2 may promote fibrogenesis whereas CXCL-10 may act antifibrogenic. Finally, no significant changes in expression of TNFα, IL-1β and the anti-inflammatory cytokine IL-10, CXCL-5 and IFNγ were observed for any of the groups (Table 8).

3.2.4. Oxidative stress in lung tissue

Oxidative stress markers assessed in lung tissue, reflected depletion of the antioxidant glutathione (GSH), levels of the lipid peroxidation product malondialdehyde (MDA), and activity of the antioxidant enzyme catalase. For the high dose ZnO NP (15 μg) a significant decrease in GSH accompanied by a significant increase in MDA levels was observed, while catalase activity was unaltered. The 5 μg group showed the opposite with no change in GSH and MDA but with a significant increase in catalase activity (Table 9).

3.3. Study #3

3.3.1. Mortality

Mice were exposed once to NM-111 ZnO NP by oro-pharyngeal aspiration. Animal mortality was observed for some doses. All 5 mice in the 100 μg/mouse group and 3 mice in the 50 μg/mouse group died within 5 days post-exposure. Two mice in the 25 μg/mouse group died within 13 days post-exposure. None of the mice in the 12.5 μg/mouse, negative control or positive control (crystalline silica) groups died prior to scheduled termination (Fig. 2). There was a strong association between ZnO NP dose and mortality (p < 0.01; χ² = 15).

3.3.2. BALF: cellular composition, LDH, proteins and cytokines

Only animals that survived 2 months post-exposure were included in these analyses. This weakens the statistical power. The number and composition of cells in the BALF was not significantly changed for any of the ZnO NP exposure groups 2 months post-exposure (Table 10). There was a small increase of macrophages, although CCL-2 is a known inflammatory cytokine IL-10, CXCL-10 have been associated with pulmonary fibrosis, whereas CCL-2 may promote fibrogenesis whereas CXCL-10 may act antifibrogenic. Finally, no significant changes in expression of TNFα, IL-1β and the anti-inflammatory cytokine IL-10, CXCL-5 and IFNγ were observed for any of the groups (Table 8).

3.3.3. Pulmonary fibrosis

A potential fibrotic response was assessed via the hydroxyproline content, a marker for collagen accumulation. ZnO NP induced a marginal (low doses) and significant (50 μg) induction of collagen. However, although significant for high dose group, it should be noted that 3 mice died shortly after intratracheal instillation in this group. Thus only 2 mice are represented in the 50 μg group 2 months post-exposure. The fold increase in hydroxyproline was similar for 50 μg ZnO NP and 2500 μg SiO2 (1.4 and 1.5-fold, respectively) (Table 11).

4. Discussion

NP are mobile, easily inhaled and can deposit in the pulmonary alveoli at a much higher frequency than larger bulk sized particles. Although literature on hazards related to inhalation of nanosized...
ZN0 is available, information on lung toxicity is still limited and the doses used are primarily low. Here we present results from three experiments that each investigate the acute or sub-acute pulmonary toxicity of nanosized ZN0. The pulmonary toxicity is characterized by oxidative stress, inflammation, genotoxicity and cell death. Doses used in the present publication spanned from 2 to 100 μg/mouse (162 μg in the pilot study).

The most pronounced effect observed following the ZN0 NP exposure was the clear association between exposure dose and mortality (Study 3). A mortality rate of 40% was observed at a bolus dose of 25 μg (~1.4 mg/kg mouse body weight) and increasing to 100% at a dose of 100 μg. Mortality caused by pulmonary exposure to ZN0 particles has to the best of our knowledge not been previously reported in the literature. The currently available reports on ZN0 toxicity in animal models have used sub-lethal doses, too short post-exposure time, or moribund/dead animals have not been included in the biochemical and histopathological examinations. However, LD50 for ZN0 NP was calculated to be 0.3 mg/kg in intravenously exposed ICR mice (Fujihara et al., 2015). Also mortality has been reported following high periteneal exposure (80 mg/kg body weight) of ZN0 < 200 nm in rats (Landsiedel et al., 2010) and a high oral NP exposure in mice (333 mg/kg body weight) (Esmaeillo et al., 2013). The highest pulmonary exposure dose found in the literature is 50 mg instilled in guinea pigs (222 mg/kg guinea pig body weight). Although, these particles were very large (≈5000 nm) leading to a slow dissolution of ZN0(NI), species specific differences in the toxic response cannot be excluded (Gupta et al., 1986). Also no mortality or reduced body weight was observed when ZN0 NP was instilled at a dose of 10 mg/rat (37 mg/kg body weight) (Chuang et al., 2014) or when ZN0 NP was given as multiple instillations of 17.5 mg/kg rat every second day for five weeks (Liu et al., 2013). In our study mice exposed to 6 and 18 μg (study 1 and 15 μg (study 2) showed a significant decrease in body weight of more than 10%. It should be noted that a clear difference in toxicity towards ZN0 fumes has been observed in a test of 11 different inbred mouse strains (Wesseler Kamper et al., 2001) making interspecies differences very likely. It is especially noteworthy that C57BL/6j (C57BL/6j and C57BL/6N was used in study 1 and 3, respectively) was amongst the lowest responders with regards to inflammation (PMNs) (10-fold) and protein concentration (1.1-fold) in BALF following a single inhalation exposure vs air exposed controls. BALB/c mice (similar to study 2) were more sensitive than C57BL/6j in terms of these parameters. These results indicate that even stronger responses might have been observed in our studies if high responder strains had been used, e.g. C3H/HeOuJ and CBA/J mice which showed a 555 and 420-fold increase in PMNs and a 3 and 2.4-fold increase in protein concentration vs air exposed controls (Wesseler Kamper et al., 2001).

We hypothesize that leakage of fluids to the lung is the direct or at least partial cause for the observed mortality. In the pilot study, within study 1, two mice were exposed to 162 μg ZN0 NP. These mice were killed off schedule after about 30 h. Their lungs were completely filled with blood. Although at much lower levels, mice exposed to 6 μg (study 1) showed epithelial damage, desquamation and a concomitantly increased barrier permeability of the alveolar/blood (2–3 days post-exposure). This was especially evident by the large increase in red blood cells and protein in BALF. Results from study 2 support these findings. Mice exposed to 15 μg showed a strong increase in LDH, protein and IgM in BALF 1d post-exposure. Similar results are generally observed in the literature (Ho et al., 2011; Chuang et al., 2014) and are indicative of strong pulmonary toxicity with cell death and injury to the alveolar barrier allowing fluids to enter the pulmonary space. Indeed, the detailed and dramatic cell death of alveolar epithelial cells, and therefore barrier destruction has been studied in vitro (LA4-alveolar epithelial cells).

Toxicity was observed starting at very low concentrations (≥3 μg/ml ZN0 NP) and was not observed with e.g. ≤500 μg crystalline silica (Min-U-Sil 5) (Beyerle et al., 2010). However, as mentioned above mice have died from ZN0 exposure via other routes; e.g. an LD50 of 0.3 mg ZN0 NP/kg body weight indicates other toxic mechanisms not related to leakage of fluid into the pulmonary space.

Available data show that it is dissolution of ZN0(NI) ions from the particles that is the major determinant for ZN0-mediated toxicity and cell death (Landsiedel et al., 2014). Accordingly, NP are more toxic than larger counterparts as the dissolution rate increases with decreasing particle size (Meulenkamp, 1998). Additionally, ZN0 purity is important as e.g. dissolution is reduced by doping ZN0 NP with iron (Xia et al., 2011). Uptake in acidic endosomes and later lysosomes accelerate dissolution leading to lysosomal damage, mitochondrial disturbance, production of ROS and cytokines (Nel et al., 2009). Similar effects have been observed in human cell lines (Kao et al., 2012). In Cho and co-workers detailed work the authors hypothesized that a rapid dissolution of ZN0 NP inside endosomes/lysosomes is the primary cause for severe lung injury caused by ZN0 NP (Cho et al., 2011). It is worth mentioning that the mortality was observed in study 3 using the largest particle of the 3 studies (10 μm vs 12 and 70 nm in study 1 and 2, respectively). Mortality was not observed in study 1 and 2 as the exposure times were short term. However, this indicates that even stronger responses (higher mortality) might have been observed in study 3 if even smaller NP were used.

Mice surviving the initial exposure of ZN0 NP up to 25 μg (~1.35 mg/kg mouse body weight) appeared to have no effects assessed on a number of markers of pulmonary inflammation and barrier integrity 2 months post-exposure. However a dose of 50 μg (~2.7 mg/kg mouse body weight) caused increased collagen accumulation in the lungs. Fibrosis was identified at a time point when all inflammatory end-points were similar to control levels indicating a resolved inflammation. Additionally, the levels of collagen were similar after exposure to 50 μg ZN0 NP and 2500 μg crystalline silica. Cho and co-workers have previously shown that aspiration of 310 μg ZN0 NP (~1.4 mg/kg rat body weight) caused “severe fibrosis and airway epithelial injury” and that the mechanism likely involved ZN0(NI) ions. Instillation of ZN0(NI) ions (92.5 μg) caused both fibrosis and mortality (Cho et al., 2011).

In general ZN0 NP caused a very strong inflammatory response with neutrophils increasing between 4- and 7-fold in study 1 (2, 6 and 18 μg) and between 1.4 and 9-fold in study 2 (5 and 15 μg) 1d post-exposure. End-points determined in study 1 and 2 (18 μg and 15 μg, 24 h post-exposure) were similar in fold-inductions with a marginal tendency to stronger results in study 2 neutrophils, lymphocytes and protein. Since study 1 incorporated a smaller particle (12 nm vs 70 nm) and slightly larger dose (18 μg vs 15 μg) the differences might be caused by the more responsive BALB/c mice used in study 2. Inflammation is not in itself problematic if it is resolved quickly. However, if not resolved inflammation may lead to oxidative stress; an imbalance between production of reactive oxygen/nitrogen species and antioxidant defense systems. Both inflammation and oxidative stress are important mechanisms implicated in particle-induced health effects such as cancer and systemic effects (Moller et al., 2010, 2014, 2015). Whilst oxidative stress markers are frequently assessed in vitro with ZN0 they are very seldom assessed in animal studies. Markers of oxidative stress were determined in our study 2, where 15 μg of ZN0 NP caused a significant increase of lipid oxidation and decrease of the antioxidant glutathione. The antioxidant enzyme catalase was increased at the low dose but not in the high dose group. It is possible that low doses of ZN0 induce the antioxidant response via the Nrf2 pathway and thus the expression of catalase, whereas larger doses of ZN0 NP...
may deplete it. We also found that the local milieu affects genome integrity. DNA damage was observed in the BALF cells 1 d post-exposure. However, this effect was not present 3d post-exposure. Previously short term in vitro exposures have shown that ZnO NP are a potent inducer of strand breaks and oxidatively damaged DNA determined by comet assay (Gerloff et al., 2009).

Pulmonary exposure to ZnO also caused systemic effects. Several blood parameters indicative of acute systemic inflammation was altered in the 15 µg ZnO NP group. Histology of the liver showed an increased regenerative activity by the presence of binucleated hepatocytes and enlargement of single hepatocyte. In both study 1 and 2 systemic effects were stronger in animals receiving the high dose (18 and 15 µg, respectively).

In summary, a bolus pulmonary exposure of 6 µg ZnO NP (0.3 mg/kg mouse body weight) manifested severe signs of toxicity in terms of reduced body weight, large acute pulmonary inflammation and excessive desquamation of epithelial cells with concomitant leakage of the alveolar barrier. Additionally, histology revealed increased proliferation and hypertrophy of bronchiolar epithelial cells as well as lymphoid cell infiltration and oedema. Increased number of binucleated cells and hypertrophy was evident in the liver indicating systemic effects of a pulmonary bolus dose of 6 µg ZnO NP. Higher doses of 15 and 18 µg ZnO NP yielded stronger effects and animal suffering which led to the termination of experiments (study 1 and 2). Even higher bolus doses of ZnO NP were clearly associated with a dose dependent mortality (≥25 up to 100 µg) and with collagen accumulation indicative of pulmonary fibrosis (50 µg).

Conflicts of interest

The authors report no competing interests.

Acknowledgment

The authors indebted and thanks Michael Gulbrandsen, Anne-Karin Asp, Elzbieta Christiansen, Lourdes M. Pedersen (National Research Centre for the Working Environment), Kathrin Kappes (Helmholtz Zentrum München), Sarah Grundt Simonsen (National Food Institute, Technical University of Denmark) and Aleksander Penkowski (University of Warmia and Mazury in Olsztyn) for their excellent technical assistance. The project was supported by Danish Centre for Nanosafety, grant# 20110092173–3 from the Danish Working Environment Research Foundation, the E.C. FP7 ENPRA (n°228789) grant, the E.C. FP7 Nanosustain (n°247989) and the E.C. FP7 NanoValid (n°263147).

Transparency document

Transparency document related to this article can be found online at http://dx.doi.org/10.1016/j.jfct.2015.08.008.

References


cytotoxicity, pro-inflammatory cytokines and functional markers. Nano-
toxicology 7, 301–313.
Lenz, A.G., Karg, E., Brendel, E., Hinze-Heyn, H., Maiar, K.L., Eickelberg, O., Stoeger, T., Schmidt, O., 2013. Inflammatory and oxidative stress responses of an alveolar epithelial cell line to airborne zinc oxide nanoparticles at the air–liquid inter-
Nicklasi, W., Baneux, P., Boot, R., Decelle, T., Deeny, A.A., Fumanelli, M., Ilgen-
-scale 6, 7052–7061.
Sayes, C.M., Reed, K.L., Warheit, D.B., 2007. Assessing toxicity of fine and nano-