A Novel Instrument for Measuring Surface Area of Exhaust Particles Deposited in Different Regions of the Lung

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Many different measurements have been made of engine exhaust particulate. Mass measurements are the basis for current standards. Other measurements include particle number as well as size distribution, using a variety of techniques, and a number of instruments that give different diameter weightings and other measurements related to the particles in exhaust.

Many health effects experts have suggested that a good measure of particle health effects would be one related to the surface area of the particles that deposit in the lung. This would be a different measurement than what would be obtained from direct SMPS number concentration converted to total particle surface area.

Using SMPS data of ambient measurements taken over a number of months at the EPA St. Louis Supersite and applying ICRP deposition curves results in deposited number distributions. These number distributions were transformed into a surface area distributions and total deposited surface area values were determined. These deposed surface area values were regressed against the electrometer current values from two collocated TSI model 3070A (EAD) Electrical Aerosol Detectors. The correlations were sufficiently good that the EAD can be considered a useful indicator of particle surface area deposited in the lung.

To improve the correlation of these results modifications were made that resulted in a new instrument called the Nanoparticle Surface Area Monitor (NSAM) model 3550. This new instrument is still being characterized but early indications are that its two settings provide improved correlation to lung deposition for both tracheobronchial deposition and alveolar deposition.

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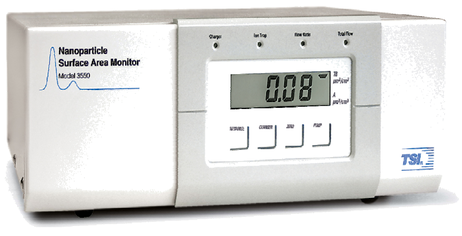

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Presented at the 9th ETH Conference on Combustion Generated Nanoparticles

15-17 August 2005, Eidgenössische Technische Hochschule (ETH) Zürich

ABSTRACT

Health effects associated with engine exhaust particles are not clearly understood but mounting evidence that ultrafine (UF) particles are harmful is generating interest in new instrumentation for improved characterization of such particles in emissions. Current regulations are based on particle mass, and there is interest in a count standard. However, a growing number of experts contend that the surface area, rather than mass, should be measured because nanoparticles have far more surface area for the same amount of mass of larger particles, which increases the chance they may react with the body (Oberdöster, 1996; Donaldson et al., 1998). As a result, the need has arisen to assess exposure to exhaust particles based on the measurement of particle surface area.

The Electrical Aerosol Detector (EAD, TSI model 3070A) is based on using a corona jet charger to provide diffusion charging of particles, followed by detection of the aerosol via electrometer. Wilson et al. (2004) reported that the EAD signal is highly correlated (R2 ranging from 0.82 to 0.87) to the calculated amount of deposited surface area (DSA) in the lung; the absolute relationship between the EAD signal and the DSA being a function of breathing rate and tidal volume as determined by the level of exertion.

Recently, a Nanoparticle Surface Area Monitor (NSAM, TSI model 3550) has been developed. NSAM works on the same principle as EAD but features an improved design that brings the instrument response even closer to the surface area dose. User selectable instrument settings allow response to correlate well with DSA of particles in targeted regions of the lung eg. Alveolar (A) and Tracheobronchial (TB). The instrument response could also be adjusted to specific research application such as measurements corresponding to specific breathing patterns like resting and nose breathing, light exercise and mouth breathing etc. can be obtained. This technique provides a simple and fast solution for measuring the surface area dose.

BACKGROUND

- To date, there has been rapidly increasing epidemiological evidence linking exposure to ambient ultrafine or nanoparticles (diameter < 100nm) and adverse health effects including mortality (Pekkanen et al., 1997; Oberdörster et al., 1995).
- With the commercialization of nanotechnology, worker exposure to homogeneous nano-scale materials is also an emerging issue of concern.
- The nucleation and accumulation modes of engine emissions are major sources of ambient nanoparticles.
- Leading experts believe lung deposition through means of inhalation to be the most efficient way for airborne particles to enter body and potentially cause long-term, adverse health effects.
- Fractional deposition of inhaled particles in the human respiratory tract is a function of particle size (Figure 2).
  - Unlike large particles, smaller nano-sized particles deposit efficiently in the innermost regions of the lung where gas-exchange takes place. For example, alveolar deposition is > 50% for particles ~20 nm in diameter.

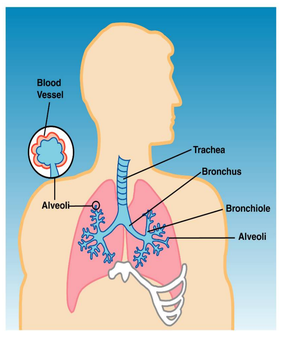


Figure 1
Schematic diagram of human respiratory tract regions

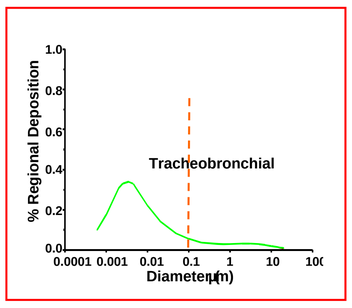
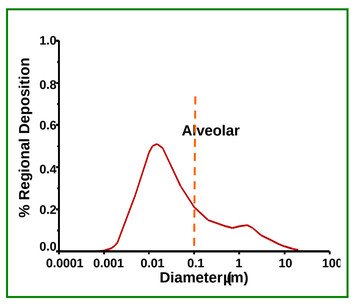


Figure 2
Fractional deposition of inhaled particles in the human respiratory tract

Source: ICRP Model, 1994
Nose Breathing



- Fate of nanoparticles after their deposition may be different from that of larger particles. Toxicological studies indicate that nanoparticles, unlike larger particles are capable of penetrating the cellular membrane, where they create an inflammatory response by means of generating oxidative stress and causing damage to mitochondria. They may even enter the blood circulation which may result in their translocation to extrapulmonary tissue (Oberdörster, 2001; Nemmar et al., 2002).

IMPORTANCE OF SURFACE AREA MEASUREMENT

Traditional Measures of Particles

- Traditional ambient particulate matter (PM) regulations as well as workplace exposure limits are based on particle mass.
- Mass based gravimetric methods that are used to measure larger particles may not be effective for measuring nanoparticles. Nanoparticles have very little mass compared to same number of larger particles. This translates into much longer sampling time required to collect a quantifiable mass.

It takes a billion 10 nm diameter particles to equal the mass of one 10 µm particle!

Number Based Measurements

- Number based measurements effectively quantify the amount of nanoparticles in the environment.
- It is possible to measure the number and size distribution of nanoparticles using Condensation Particle Counters (CPCs) and Scanning Mobility Particle Sizer™ (SMPS™) spectrometers, respectively.
- These measurements are helpful in determining specific sources emitting nanoparticles in the ambient and in workplace environments, and in determining the effectiveness of engineered controls implemented.

Surface Area Measurement

- Surface area is the measurement metric that relates well with particle induced adverse health effects.
- Surface area plays an important role in toxicity of nanoparticles.
- In chronic rat inhalation studies (Oberdörster, 2001):
  - The lung tumor response was found to be highly correlated with retained particle surface area.
  - Inflammatory response induced by different particle types was also found to be best correlated with surface area of particles retained in the alveolar space.
- There is an emerging need to assess ambient concentrations as well as worker exposure to nanoparticles based on the measurement of surface area.

PREVIOUS WORK DONE WITH THE ELECTRICAL AEROSOL DETECTOR

- Atmospheric aerosol was sampled using a nano-SMPS, an SMPS and an EAD at the St. Louis Supersite which is located in East St. Louis and is operated by Washington University in St. Louis. The data collected was analyzed by Wilson et al. (2004).
- The ICRP Dosimetry Model was used to estimate deposition fractions for the tracheobronchial region (TB) and alveolar (A) regions of the lung for the particle size range covered by the SMPS measurements.
- The number distributions were transformed into surface distributions by multiplying the number of particles in each size interval by the formula for surface area (πD^2), using the mean diameter of the size bin.
- The deposited surface area, calculated for each five minute average of the distribution, was regressed against the EAD signal. Results for the four combinations of breathing parameters and deposited region are shown in Figure 3 and 4. It was found that the coefficient of determinations for A and TB are 0.82 and 0.87 for resting and nose breathing and are 0.87 and 0.87 for jogging and mouth breathing, respectively. This indicates that EAD signals are highly correlated with the deposited surface areas.
- Based on the results, Wilson et al. (2004) concluded that the EAD signal provides a useful indicator of particle surface area deposited in the lung.

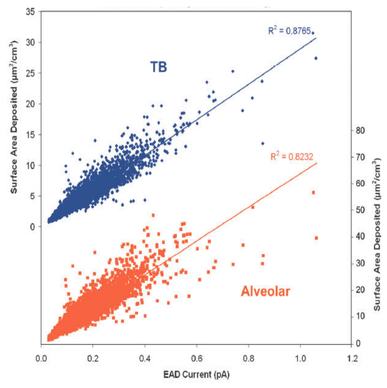


Figure 3
Surface area deposited in the regions of the lung per cm³ of air inhaled versus EAD signal (resting and nose breathing)

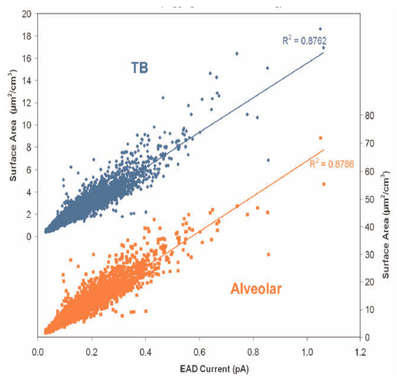


Figure 4
Surface area deposited in the regions of the lung per cm³ of air inhaled versus EAD signal (jogging and mouth breathing)

NANOPARTICLE SURFACE AREA MONITOR

- NSAM features an improved design over the EAD that brings the measurement response even closer to the surface area dose corresponding to specific regions of the lung.
- Measures surface area (µm²/cm³) of inhaled particles deposited in different regions of the lung
  - Tracheobronchial (TB)
  - Alveolar (A)
- Provides a simple, fast solution for measuring surface area dose and assessing workplace exposure to nanoparticles.

NANOPARTICLE SURFACE AREA MONITOR (cont.)

FEATURES

- User selectable measurement response – Tracheobronchial (TB) or Alveolar (A).
- Fast Response Time (1 sec).
  - Detects short periods of high intensity exposures.
  - Correlates surface-area dosing with changing breathing patterns.
- Comprehensive software.
  - View and log data as running average, 8-hour Time Weighted Average (TWA) and cumulative exposure.

APPLICATIONS

- Toxicity studies of engineered-nanoparticles.
- Exposure studies of combustion aerosols, second hand smoke, diesel exhaust, etc.
- Occupational exposure assessment.
  - Function of concentration, toxicity and time.
- Ambient monitoring near sources.
- For use in community epidemiologic studies.

PRINCIPLE OF OPERATION

- Combines a counter-flow corona-jet charger and a highly sensitive aerosol electrometer (Figure 5).
- Ions are generated by a positive corona charger and carried into the mixing chamber by HEPA filtered air.
- Aerosol mixes with the ions and is charged by diffusion.
- A weak electric field is used to precipitate out the remaining ions and appropriate amount of particles prior to charged particle collection.
- The separation of the particles from direct interaction with the corona needle and/or the strong field near it reduces particle losses and makes the charging process more efficient and reproducible.
- Charged particles are collected on a filter connected to an electrometer. The net electrometer current is proportional to the surface area of particles deposited in human lung.

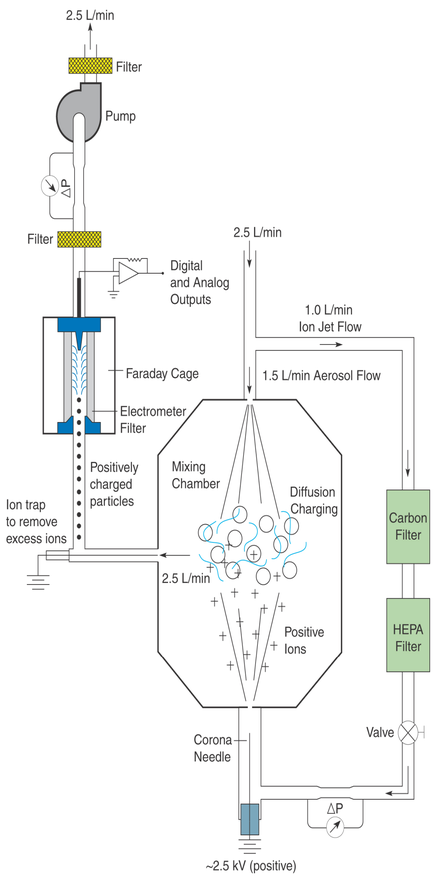


Figure 5 Schematic of the NSAM

SUMMARY AND FUTURE WORK

- EAD signal in previous studies was found a useful indicator of particle surface area deposited in the lung.
- The Nanoparticle Surface Area Monitor (NSAM) is a new instrument based on EAD principle with an improved design that brings the measurement even closer to surface area dose.
- Characterization of NSAM is ongoing. In future we plan to accomplish following work:
  - Test NSAM response for different particle materials.
  - Test NSAM response for spherical as well as agglomerated particles.

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