RADON PROGENY AS AN EXPERIMENTAL TOOL FOR DOSIMETRY OF NANOAEROSOLS

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Abstract

The study of aerosol exposure and dosimetry measurements and related quantitation of health effects are important to the understanding of the consequences of air pollution, and are discussed widely in the scientific literature. During the last 10 years the need to correlate aerosol exposure and biological effects has become especially important due to rapid development of a new, revolutionary industry – nanotechnology. Nanoproduct commerce is predicted to top $1 trillion by 2015. Quantitative assessment of aerosol particle behavior in air and in lung deposition, and dosimetry in different parts of the lung, particularly for nanoaerosols, remains poor despite several decades of study. Direct measurements on humans are still needed in order to validate the hollow cast, animal studies, and lung deposition modeling. We discuss here the use of nanoscale radon decay products as an experimental tool in the study of local deposition and lung dosimetry for nanoaerosols. The issue of the safe use of radon progeny in such measurements is discussed based on a comparison of measured exposure in 3 settings: general population, miners, and in a human experiment conducted at the Paul Scherer Institute (PSI) in Switzerland. One of the properties of radon progeny is that they consist partly of 1 nm radioactive particles called *unattached activity*; having extremely small size and high diffusion coefficients, these particles can be potentially useful as radioactive tracers in the study of nanometer-sized aerosols. We present a theoretical and experimental study of the correlation between the unattached activity and aerosol particle surface area, together with a description of its calibration and method for measurement of the unattached fraction.

Introduction

The health effects from aerosols in air pollution are discussed widely in the scientific literature. During the last 10 years the need to understand the relationships between aerosol exposure and biological effects has beco me specially important due to rapid development of new, revolutionary industry – nanotechnology. Commerce in nanoproducts could top $1 trillion by 2015 (Nanotechnology Now, July 17, 2007).

Understanding of the relationship between aerosol concentration in the breathing air and particle deposition in different portions of the lung remains poor, in spite of several decades of research. Without direct validation through measurement of aerosol deposition and dose, uncertainty in estimates from inhalation models will persist.

According to the Strategic Plan for NIOSH Nanotechnology Research (NIOSH, 2005) there are many gaps in our knowledge of aerosols in the nanometer range, which we need to fill in order to improve risk assessment and dosimetry of nanoaerosols, including:

- Measurement studies of nanoparticles in the workplace.
- Particle surface area as a dose metric.
- Dosimetry and risk assessment.
- Evaluation of pulmonary deposition and translocation of nanomaterials.
- Filter efficiency of typical respirators for nanoscale particles.
- Evaluation respirator performance.
- Development of computer-aided face fit evaluation methods.

One experimental approach that addresses these problems uses safe doses of radioactive tracer particles: after particles are inhaled, their spatial distribution in the lung is determined through two- and possibly three-dimensional spectrometric imaging. In recent

years published literature on the effectiveness of risks associated with using radioactive markers in human imaging has matured to the point where reliable and safe protocols have been devised for their measurement.

As mentioned by Oberdörster (Oberdörster, et al, 2005) it is not clear if there are significant human exposures to airborne-engineered carbon nanotubes or C_{60} fullerene particles. This is of concern, because, for example, at the very low mass concentration of 10 $\mu g/m^3$ of unit density 20 nm particles, the number concentration is greater than 10^6 particles/cm^3. At this concentration, what will is the particle surface dose delivered per cm^2 to different lung tissue? Animal studies using ultrafine and nanometer-sized aerosols showed that such particles induced significant pulmonary inflammatory responses as well as effects in extrapulmonary organs (Oberdörster, 2005).

Yet, without direct measurements of response in humans with accurate dosimetry we cannot make conclusive estimates of the risks. Examples of the safe use of radioisotopes to label aerosol particles for human inhalation studies are presented in the literature. In one study (Philipson et al. 1996) ten healthy males inhaled monodisperse Teflon particles with geometric diameter 3.6 μm labeled with ^{195}Au. Depending on the detector used, they found the clearance half-life averaged 740 and 680 days for the NaI and the Ge detectors, respectively. In a second study (Brown et al, 2000), ultrafine carbon particle aggregates labeled with ^{99}Tc aerosols having diameters ranging from 50 to 150 nm were developed for use in human inhalation studies. In another study (Kim, et al., 2000) the "respiratory dose" of ultrafine particles (40, 60, 80, and 100 nm in diameter) in healthy young adults was measured using a novel serial bolus-delivery method. More recently, a study on the retention of ultrafine 35 and 100 nm particles in human lungs (Svartengen, et al., 2005), mean retention values were observed to be close to 100%, and no evidence of significant

translocation to the circulatory system from the lungs was observed. Authors suggest that contradictory results from earlier studies might be due to unstable radiolabeling.

A number of studies on the exposure of ultrafine and, especially, nanometer aerosols (Donaldson et al. 1998; Oberdörster et al. 2005), have indicated that health effects associated with low-solubility inhaled particles may be more appropriately associated with particle surface area than with mass concentration. Such data on the correlation between number, surface area and mass concentration are needed for exposure investigations.

The use of particle surface area as a dose metric for nanoaerosols is discussed in many reports: NIOSH (2006), Royal Society (2004**),** NIOSH (2005), NIOSH (2006a), Aitken et al. (2004), DEFRA (2007), SCENIHR (2006), Renn and Roco (2006), ASCC (2006).

It has been mentioned that particle surface area might provide the most suitable criterion for assessing inhalation exposure. Currently however, there is a need to develop and expand methods available by which particle surface area can be assessed in the workplace. The main concern is with free nanoaerosols that are more available for absorption and distribution within the body. Investigators found that when lung burdens and clearance rates were expressed as a function of the surface area, there was a much closer correlation with biological responses, ASCC (2006),

The special importance of the surface area of nanoparticles in the study of the risk assessment is discussed in (Maynard, 2007) by comparing the three characteristics: particle number, surface area, and mass concentration.

Another important issue in the safety of people working with nanomaterials is the efficiency of respirators, discussed in many reports: NIOSH (2006b), Aitken (2004), Renn and Roco (2006). It is well known that the determining factor governing the effectiveness of respiratory protective equipment (RPE) is not absolute penetration through the filter, but rather face-seal leakage causing particles to bypass the device. ASCC (2006)

In this paper we discuss a new approach to the measurement of aerosol surface area concentration based on the rate of deposition of the unattached activity of radon progeny on aerosol particles. The correlation, results of calculation, and the assessment of the sensitivity of this method will be presented.

Approach: Safety of radioactive markers in aerosol exposure study.

We may assume that a radioactive marker is safe in an experiment with human subjects if the radiation exposure is negligible relative to the subjects' background exposures. The following three scenarios of exposure to radon and its decay products put this into perspective:

1. A general population with average background radon concentration of 20-80 Bq/m^3; and lifetime exposure duration of 600,000 hours (70 years);
2. Miners, with the permissible concentration 1100 Bq/m^3; and exposure duration of 60,000 hours (30 work-years);
3. The human exposure experiment in Paul Scherer Institute (PSI), Switzerland (Butterweg et al., 2001), of 20,000 Bq/m^3 and duration of exposure 0.5 hours.

A comparison of these three cases shows that radiation exposure in the human experiment was less than 1/1000th the magnitude of the lifetime background exposure. From a radioactive exposure point of view, the PSI experiment was safe.

Nonetheless, such human experiments need radiation and environmental health and safety reviews. Also, the type of radiation, half-life, clearance, and the particle size of the markers should be taken into account. The chemical characteristics and the size distribution of the non-radioactive aerosol under study are also important in assessing the safety of human exposure experiments. The experiment at the PSI, mentioned above, was conducted after a human subjects internal review board (IRB) approval by the "Uberregionale ehtische Kommision fur klinische Forschung der Schweizerischen Akademie der medizinischen Wissenschaften" was granted (Butterweck, et al 2001).

In the above study, seven nose-breathing and eleven mouth-breathing volunteers were exposed for 30 min in a PSI walk-in radon chamber with the unattached and attached ^{218}Po concentration of 3800 and 200 Bq/m^3, respectively. For these measurements, a whole-body counter at the PSI, equipped with two additional 15.4 cm diameter by 5.1 cm thickness detectors, was employed for the measurement of activity located in the head of the volunteers. To reduce the activity deposited on the surface of the volunteer's body, dust protection clothing including head and foot covering were used. No significant deviation between measured activities and predictions by the ICRP Publication 66 Human Respiratory Tract Model (ICRP, 1994) was found. The expected fast particle transport from nasal passages, larynx, and mouth to the GI tract was not found. The explanation may be that a substantial fraction of deposited activity with diameter of 1 nm is bound to lung tissue. The most important aspect of this study is that from a radiation safety point of view it is possible to provide similar human experiments in laboratory conditions, after radiation safety and IRB approval.

Similar studies (Ruzer, et al 2004) were conducted with miners who during their normal work activities were exposed to much lower concentrations of radon, much higher

gamma-background, and simple instrumentation that quantified post-exposure gamma emissions from the chest of the subjects.

Characteristics of Radon progeny

The presence of radon and its decay products in the air is due to the abundance in the earth of unstable heavy metals (radioactive elements at the end of the periodic table). One of them, uranium, undergoes a long series of transformations to yield radium. The chain of radioactive decay continues beyond radium to generate radon, a radioactive noble gas. Due to its inert chemical properties, radon does not bind completely to surficial soils in the earth or stay in water, but enters the atmosphere as a gas.

The elements following radon in the radioactive decay chain - isotopes of polonium, bismuth and lead, atom-sized radionuclides, may attach to aerosol particles to become radioactive aerosols or exist in unattached forms in the air. Eventually, they may be deposited in the lung and cause irradiation of the lung tissue. The specific biological consequences depend upon the dose of radioactive aerosols which in turn depends on physiological characteristics including human breathing rates, especially changes with physical activity as well as the amount of the radium in the soil and radon and its decay products in the air, and atmospheric conditions both in the open air, dwellings and the underground environment.

Figure 1 presents diagrams of the radioactive families yielded by ^{226}Ra. Clearly, the decay products represent a very complicated system consisting of a series of radioactive elements and various types of decay (alpha-, beta-, and gamma). In terms of the radiation safety, the most important radionuclides are alpha-emitters because the alpha particles have the greatest ionization density (Linear Energy Transfer - LET). Given identical absorbed energy, the biological effect of alpha-particles is thought to be 20 times greater

than the corresponding effect of beta-particles and gamma-radiation (that is, the "quality coefficient" for alpha particles is 20). However, due to low particle penetration through human tissue, it is impossible to externally measure the alpha-activity of aerosols deposited in the lung of a living subject. As a result this alpha-radioactivity is typically measured in the air and the absorbed dose to the lungs is then calculated according to the known concentration, breathing rate and coefficient of deposition in the lungs (which is not accurate).

Assessment of particle deposition in lungs.

Ruzer (1964, 1970) presented another, more precise, opportunity for assessment of the alpha-dose to the lung from radon progeny. It was based on the derived correlation between the alpha-dose and gamma-activity of radon progeny measured directly from the lung. This possibility was studied first on animals, then in model experiments, and finally, after certification from the Soviet Ministry of Health, on hundreds of miners in the former Soviet Republics of Tajikistan, Uzbekistan, and Kazakhstan. It was shown for concentrations in the range of maximum permissible in mines, gamma-activity of radon progeny in the lung can be measured directly by means of a simple technique, such as the use of NaI (Tl) crystal detectors with standard lead shielding.

This approach of direct measurement of the natural marker such as radon progeny can also be used for the assessment of deposition of non-radioactive aerosols, particularly nanometer aerosols, in the lung.

The formula for gamma-activity $A\gamma$ is:

$$A\gamma = a\ v\ k\ (q_b + q_c) \qquad (1),$$

where:

a, a proportionality coefficient,

v, the volumetric breathing rate,

k, the lung deposition coefficient,

q_b and q_c, the concentrations of the ^{214}Pb (RaB) and ^{214}Bi (RaC) correspondingly.

Based on (1) these results yield values for the product vk, which has been termed "Filtration Ability of Lungs" (FAL) (Ruzer et al., 2004), where:

$$FAL = vk = A\gamma / a\, q \qquad (2)$$

where:

$q = q_b + q_c$.

FAL is an important breathing parameter reflecting the gross particle removing behavior of the respiratory system. It is a "bridge" between the quantity of aerosols in the air and in the lung for different physical activities.

Measurements were performed without disturbing the working conditions for three occupational groups: drillers, auxiliary drillers and inspection personnel, totaling approximately 100 workers. The average, standard error, and the median values for a total of 297 air samples and 391 lung measurements are shown in Table 1 (Ruzer et al., 1995). From the average (arithmetic mean) and median values for each group, the air concentrations and chest gamma activity are estimated to be distributed log-normally with a geometric standard deviation of 2.0 to 2.5.

The measurements were also carried out in a non-uranium mine in Tajikistan (former USSR) with a special instrument having two probes, (Antipin et al, 1978), one - for lung gamma-activity measurement, and the other - for air alpha-activity measurement (Figure 2).

As we mentioned before, these experiments, conducted in specific underground conditions with a high gamma-background, were provided with simple, portable instrumentation. Therefore it was difficult to study the detailed distribution of activity in the lung. The successful measurements made in this study under rugged mining conditions illustrate the possibilities for using radon progeny as a tracer in the study of aerosol distribution in lung. This method would be particularly suited for use in the nanometer range, under laboratory conditions, where the background is low, and instrumentation is much more sensitive, similar to the studies conducted at PSI. This approach could be used to map aerosol dose to the lung because it can provide graphic information on where these particles of different sizes are deposited in the respiratory system.

Thus, the approach is to use radon progeny as a marker at safe doses in the study of deposition of non-radioactive nanoaerosols in the human body. The proposed radiation dose during a human experiment will be negligible in comparison with the natural background exposure over time. This is consistent with the use of radiological tracers for other medical research. For human experiments we propose using a generator of unattached fraction of radon progeny. This could be a small environmental chamber such as used in the Swiss research (Butterweck, et al 2001), or using a respirator mask exposure apparatus attached to a small chamber. Both radon and monodisperse aerosols of known size and morphology will be injected into the chamber under controlled conditions.

In terms of radioactive safety, when properly handled, the gamma-activity of radium is negligible. Through radioactive decay, radium produces radon (^{222}Rn), which in turn will produce atoms of ^{218}Po. Once it is released into the air, about 10-12 molecules of air constituents naturally diffuse onto and surround the ^{218}Po atom. These clusters are about 1 nm in diameter and have a diffusion coefficient of ~ 0.06 cm^2s^{-1}. They are called

unattached activity of radon progeny. Again through natural diffusion processes, these Rn progeny deposit on particles coexisting in the air ranging in size from nanometers to micrometers.

Controlled experiments where nanometer (or larger) sized aerosols of known diameter are radiolabeled through natural attachment to unattached activity (e.g., becoming "attached activity") can be used to trace aerosol lung or surface deposition behavior. To do this, a size-characterized monodisperse aerosol is inserted into an exposure chamber containing particle-filtered air. Rn progeny are also inserted into the chamber at a controlled or known rate. . By measuring the unattached fraction in the air we can assess the particle surface area of aerosols, see (Ruzer and Apte, 2005, Ruzer, 2008), and for monodisperse aerosols consequently we assess the particle concentration. The ratio between particles attached to the nanoparticle activity and the nanoaerosol particle concentration itself will be known. After the nanometer aerosol (labeled with radon progeny) is inhaled into the lungs, the nanometer particles will be locally deposited according to their size depending on some breathing parameters (volume breathing rate, humidity and temperature).

Until now, experimental data on nanoaerosol deposition in human lungs have not been available. For larger sized aerosols mostly bulk deposition data are available, based on the difference in concentration in exhaled and inhaled air. However, it is well known that biological effects depend on local deposition.

After exposure, the local gamma emission distribution in the lung can be measured using a gamma-spectrometer, with the local activity being proportional to the aerosol deposition (dose). In addition, it may be possible to use SPECT scanning to provide a

more precise spatial resolution of particle deposition and local dosing (Piai, et al., 2004, Kao, et al., 1997).

As with all such radiotracer studies, the protocol must meet the approval of an IRB and radiological screening review. In these experiments, as in other studies, when radiation is used as a tool, for example, in using radiation in the study of Alzheimer disease, we have to compare the risk with benefit. The use of such experiments will enable us to close the gaps in our knowledge. Quantitative assessment of the local deposition of aerosol is at the core of aerosol, and particularly nanoaerosol exposure and risk assessment. So, our goal will be to find the safest possible and most appropriate marker.

Radon progeny are attractive as a marker for several reasons:

1. Radon and its progeny belong to the natural background of radioactivity to which the general population is exposed during their lifetime. Therefore it is easy to assess the additional risks due to its use by the methods proposed.
2. Part of radon progeny, called "unattached activity," are 1 nm sized particles with diffusion coefficient close to 0.06 $cm^2 s^{-1}$ (a size that attaches readily to nanoaerosols), which make it very attractive as a marker for nanoaerosols with a built-in signal.
3. Radon decay products are easy to generate.
4. Radon decay products are short-lived nuclei.

Direct measurement on humans is needed in order to validate the hollow cast, animal studies, and modeling. From our point of view, this kind of study will be strategically important in nanoaerosol dosimetry and risk assessment. And it will partially close one of the many gaps in our understanding of nanoaerosol exposure.

The first step of this study should be human experiments with monodisperse spherical nanoparticles. In the case of non-spherical particles, typically found in aerosol studies, we should use the term "equivalent diameter," i.e. the diameter of a monodisperse aerosol with the same local deposition as the aerosol of interest. Study of polydisperse aerosols adds complexity that can be resolved after the monodisperse aerosol lung deposition characterization across a broad nanometer size range is completed.

Respirator efficiency

Another substantial gap in our assessment of the exposure to nanoparticles is assessment of the true respirator efficiency. Direct measurement of radon progeny presents such an opportunity. It is well recognized that the determining factor in efficiency of respiratory protection equipment (RPE) against particulate challenges is not absolute penetration through the filter but rather face-seal leakage that bypasses the device. Face seal leakage is dependent on many factors including the fit of the mask to the face, duration of wearing, work activity, etc. (Aitken et al. 2004)

Experiments on true respirator efficiency were provided in mines (Ruzer et al, 1995). Using direct measurement**,** the activity of radon progeny in the lung will be possible to assess the true respirator efficiency. Let us denote:

A_0 – the measured activity in the lung without respirator;

A – the measured activity in the lung with respirator.

The true efficiency of the respirator is

(A / A_0) 100%,

and the leakage through the respirator is

$[1 - (A / A_0)]$ 100%.

In the Ruzer et al. study (1995), the true efficiency was found to be from 67 to 95% for aerosol in mines depending upon the individual's training and type of work. In order to assess the true efficiency of respirators for aerosols in the nanometer size range it is necessary to quantify the dose of these particles that reach the respiratory tract.

Radon progeny as a tool in the assessment of particle surface area.

As discussed above, one very important property of radon decay is that after radon decay, the newly formed atom of Po forms clusters that are useful as markers in studies of properties of non-radioactive aerosols. Figure 3 depicts the basic processes of radon decay producing "unattached" and "aerosol attached" activities. According to this figure there should be some correlation between unattached activity and aerosol concentration. In other words, the smaller the aerosol concentration, the bigger will be the unattached activity and vise versa. In quantitative terms, the unattached fraction of radon progeny can be used as a measure of aerosol particle concentration. This is the basis for the approach proposed in (Ruzer, 1964) for measuring very small aerosol concentrations.

Below, we present the details and calibration procedure for unattached fraction measurement. .

Method and calibration procedure.

The method and calibration procedure for measurement of radon progeny unattached fraction is presented in Ruzer and Sextro (1997). The equipment for calibration and measurement of unattached and attached radon progeny consists of:

1. a chamber with regulated concentration of the unattached fraction of radon decay products in the range from 0, to close to 0.95-1.0 (note that a high aerosol concentration, > 10^6 particles/cm^3, creates surface for diffusion of nearly all

unattached fraction, while a very low aerosol concentration will remove almost none of the attached fraction);

2. an alpha-spectrometer;

3. a set of diffusion batteries (diffusion batteries composed of wire screen can be used for collecting aerosol particles in the ultrafine and nanometer range (Ruzer, Sextro, 1997);

4. an air Pump with regulated flow rate; and,

5. high collection efficiency (99.999% for particle sizes < 1000 nm) gravimetric air filters.

The calibration procedure consists of the following measurements:

1. e_1, e_2 - deposition coefficients of the unattached and attached radon progeny in diffusion battery, respectively;

2. e_3, e_4 - detection efficiencies of the unattached and attached radon progeny deposited in diffusion battery, respectively;

3. e - detection efficiencies of the summary (unattached and attached radon progeny) airborne activity on the filter.

The procedure for measurement of the unattached fraction of radon progeny consists of measuring the activity of radon progeny inside the diffusion battery, in the diffusing battery backing filter, and in the open filter.

The unattached fraction of radon progeny, f, can be calculated as a ratio of the unattached (q_u) and sum [($q_u + q_a$), unattached +attached] concentration according to the formula (Ruzer and Sextro, 1997):

$$f = q_u/[(q_u+q_a) = [eN_{db}(1-e_2)-e_2e_4N_{bf}]/N_{of}[e_1e_3(1-e_2)-e_2e_4(1-e_1)], \quad (3)$$

where N_{db}, N_{bf}, and N_{of} - are measured activity in the diffusion battery, backing filter and open filter respectively.

A summary of the results for this approach is presented in Figure 4, which shows the measurement of unattached concentration of ^{218}Po relative to particle surface area concentration in the range of 0.3 to 2.1 μm, made with monodisperse latex aerosols of different sizes and concentrations (Dokukina and Ruzer, 1976). In each case, the measured aerosol concentration was converted to the aerosol surface area concentration. These results suggest that for aerosols in the size range covered by this calibration, 0.3 to 2.1 μm in diameter, the particle surface area concentration is in the corresponding range from 10^{-5} to 0.3 cm^{-1}, and is related to the unattached fraction of ^{218}Po, *f*. The calibration procedure used is for monodisperse spherical particles, from which the surface area can be directly calculated. In practice, for non-spherical and polydisperse aerosols an "equivalent surface area" should be used, which is the surface area of a spherical aerosol having the same diffusion deposition property as the real aerosol. Under actual measurement conditions (e.g. in a building or in a mine), the only measurements necessary to determine the unattached fraction (and to infer the average aerosol surface area) are those described above - a diffusion battery followed by a backing filter and an open face filter operated in parallel. The alpha activity from ^{218}Po on each of these three collectors is then measured and used with appropriate calibration factors to yield the unattached fraction.

It has been shown (Ruzer and Apte, 2005, Ruzer, 2008) that the direct correlation between the unattached fraction of radon progeny ^{218}Po and surface area of aerosols is in the nanometer range of (1 – 100 nm) is presented in the form of:

$$S = (\lambda_A/\beta)\,[(1/f)-1] \qquad (4),$$

where:

λ_A = decay constant of ^{218}Po;

β = $v/4 \sim 4300$ cm s^{-1};

v = root mean square speed of molecules of radon decay products under standard conditions

Results of these calculations, provided according equation (4) are shown in Figure 5 for ^{218}Po.

Calculations were provided for the conditions where:

r = 1, 5, 10, 20, 50, 75, 100, and 500 nm; and,

f = 0.99, 0.98, 0.97, 0.95, 0.92, 0.90, 0.85, 0.80, 0.75, 0.70, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40, 0.30, 0.25, 0.20, 0.15, 0.10, and 0.05.

Results of calculation of the correlation of particle surface area S and unattached fraction *f* presented in Figure 6

Results of the calculation showed that:

1. For a constant unattached fraction, *f,* aerosol particles surface area, practically speaking, (in the range of measurements errors) does not depend on particle size in the nanometer range from 2 nm to 100 nm in diameter.
2. The presented idea for assessment of the surface area will work for polydisperse nanometer sized particles.
3. This method will be not sensitive to very small individual particles, because its contribution to the general surface area is proportional to the square of their diameter.

DISCUSSION AND CONCLUSIONS.

The problem of aerosol deposition and lung dosimetry is very complicated. First, it is still very difficult to measure the particle size distribution of aerosol particles in the breathing zone of humans. But, even if such data were available, the behavior of aerosol particles according to aerosol size spectra in different parts inside the lung is difficult to predict with high accuracy due to humidity, temperature, lung morphology, and other factors. Therefore, direct measurement of lung deposition parameters is still needed in order to validate the results of modeling. We have discussed the potential use of radon progeny as a radioactive marker, which can be used as an experimental tool in measurement of local deposition parameters and dosimetry of nanoaerosols.

The first problem faced in using radioactive markers is that of safety. We discuss three settings of human exposure experiments using radon decay products. It is clear from the comparison, with careful controls, that the risk of such experiments is minimal. The benefits from gaining information on lung deposition and dosimetry will be extremely valuable. Inter-species variability in respiratory system morphology and physiology is so great that similar data will be impossible to obtain in animal experiments.

Review of literature on environmental health in the new rapidly developing nanotechnology industry shows that problem of exposure has not been adequately assessed (Oberdörster, 2005). Worker health and safety is of initial concern as occupational groups are likely to be among the first to be exposed to elevated concentrations of nanomaterials. A gap exists between existing particle measurement methods and those truly appropriate for nanoaerosol exposure assessment. Until now, the primary tools available for measurement of nano-sized aerosols have been Condensation Particle Counters (CPCs), and Differential Mobility Analyzers (DMA). Results of the

particle counting detection efficiency of the Condensation Particle Counter TSI CPC 3762 for different operating parameters have been presented (Banse et al. 2001). This study showed a substantial decrease in the efficiency in the range of particle diameter of 6-10 nm. DMA measurements suffer mainly due to the low probability with which in this range of sizes nanoparticles are charged (NSF, 2003). Even with improved aerosol instrumentation for nano-sized particles, the issues of respiratory tract deposition quantitation cannot be resolved without a direct localized measurement of particle dose.

The experiments at PSI and the measurements on miners serve as a model for experiments that can be performed in laboratory conditions. These experiments can provide accurate data on human breathing characteristics, deposition, lung dosimetry, and the assessment of true efficiency of respirators.

A new instrument on the market, the Nanoparticle Surface Area Monitor (TSI 3550, Nanoparticle Surface Area Monitor, 2005), is used for assessment of deposited surface area (DSA) in the lung. Lung deposition estimates from this instrument are based on correlations developed (Wilson et al., 2004) between the electrical signal and modeled DSA. The instrument is said to be capable of detecting particles with diameters down to 10 nm. Another attempt to solve the problem of surface area assessment, previously presented (Maynard, 2003), is based on simultaneous number and mass concentration measurements.

In addition to scrutinizing risks associated with exposure to radiation in these experiments, risks associated with exposure of nanometer sized particles must also be considered. In the case of PSI experiments, we can calculate the concentration of the 1 nm radon progeny, using data for concentration of the unattached fraction, which was 3800 Bq/m^3.

According to the equation for radioactive decay:

$(dN/dt) = \lambda * N$

where dN/dt is activity in Bq (decay per seconds),

λ is a decay constant, and

N is the number of atoms.

For ^{218}Po, $\lambda_A = 3.788 * 10^{-3}\ s^{-1}$. At a concentration of 3800 Bq/m^3 the number concentration of 1 nm particles will be approximately $10^6\ m^{-3}$, or 1 cm^{-3}, which is an extremely low aerosol concentration. If expressed in mass concentration units, it will be around $10^{-9}\ \mu g/m^3$, again extremely small in comparison with 10 $\mu g/m^3$ as discussed by Oberdöster for carbon nanotubes and C_{60} (Oberdöster et al., 2005). Of course, with these data, only for air concentration, it is not possible to calculate the true dose for target cells in the respiratory system in terms of the density of the number of particles per cm^2, especially because results from modeling (Balásházy, 2000) showed that such particles can form "hot spots" , i.e. extremely high local density of particles.

Clearly, all human experiments with nanometer particles labeled with radioactive markers need careful consideration from the point of view of both radioactive and non-radioactive nanometer aerosols safety. Still, in the balance, the scientific need for information from good human lung dosimetry experiments suggest that the problem should be considered.

From these observations, the following conclusions can be made:

1. Radon decay products (as a radioactive marker) can be used in a controlled manner that provides minimal risk in human studies under laboratory conditions.

2. Particle deposition, lung dosimetry, measurement of the breathing characteristics, and respirator efficiency for nanometer sized particles may be measured by non-invasive techniques under laboratory conditions, in the range of exposures described in this paper.
3. The unattached fraction of radon progeny can be used for quantitative assessment of a very important characteristic of nanometer-sized aerosols, that is, the aerosol particle surface area.

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FIGURE CAPTIONS

Figure 1. ^{226}Ra Family depicting the chain of decay products and particle emissions.
Figure 2. Instrument for Filtration Ability of Lung (FAL) measurement. 1 – NaI detector; 2 – collimators; 3 – lead shield; 4 – air sample.
Figure 3. Basic processes of Rn decay product behavior in air defining "unattached" and "aerosol-attached" activities.
Figure 4. Unattached fraction of ^{218}Po, f vs. aerosol surface area concentrations.

Figure 5. Relationship between particle surface area and particle radius.
Figure 6. Relationship between particle surface area and unattached fraction

TABLES

Table 1. Measured Air Concentration of 214Pb and 214Bi, Gamma Ray Activity in Miners' Lungs and Calculated Filtration Ability of Lungs (FAL) for Different Groups of Miners in a Metal Mine in Tajikistan

Job Category	# of Air Samples	Concentration of $^{214}Pb+^{214}Bi$ (kBq.m^{-3})			Activity in Lungs (kBq)[a]				FAL=vk (m^3.min^{-1})			FAL_{means}/FAL_{std}[b]	
		Average	Std error	Median	# lung measurements	Average	Std error	Median	Average	Std error	Median	Average	Median
Drilling	92	5.92	0.55	3.7	21	2.66	0.22	2.59	0.0079	0.0014	0.0090	1.6	1.8
Auxiliary	76	6.88	0.81	5.2	104	2.63	0.30	1.92	0.0067	0.0015	0..0062	1.3	1.25
Inspection Personnel	129	11.1	1.11	7.4	68	3.26	0.33	2.11	0.0052	0.0011	0.0055	1.4	1.1
Average		8.9	0.9	5.2		2.85	0.26	2.22	0.0066	0.0011	0.0069	1.4	1.4

[a] Actual gamma activities at time of measurement. In calculating FAL a correction was made on Aγ to account for decay between end of shift and time of measurement, in all cases less than 1 h.

[b] FAL means is the value based on measured data, FAL std is the calculated value based on assumed standard breathing rate of 0.020 m^3.min^{-1} and standard fractional lung deposition of 0.25.

FIGURES

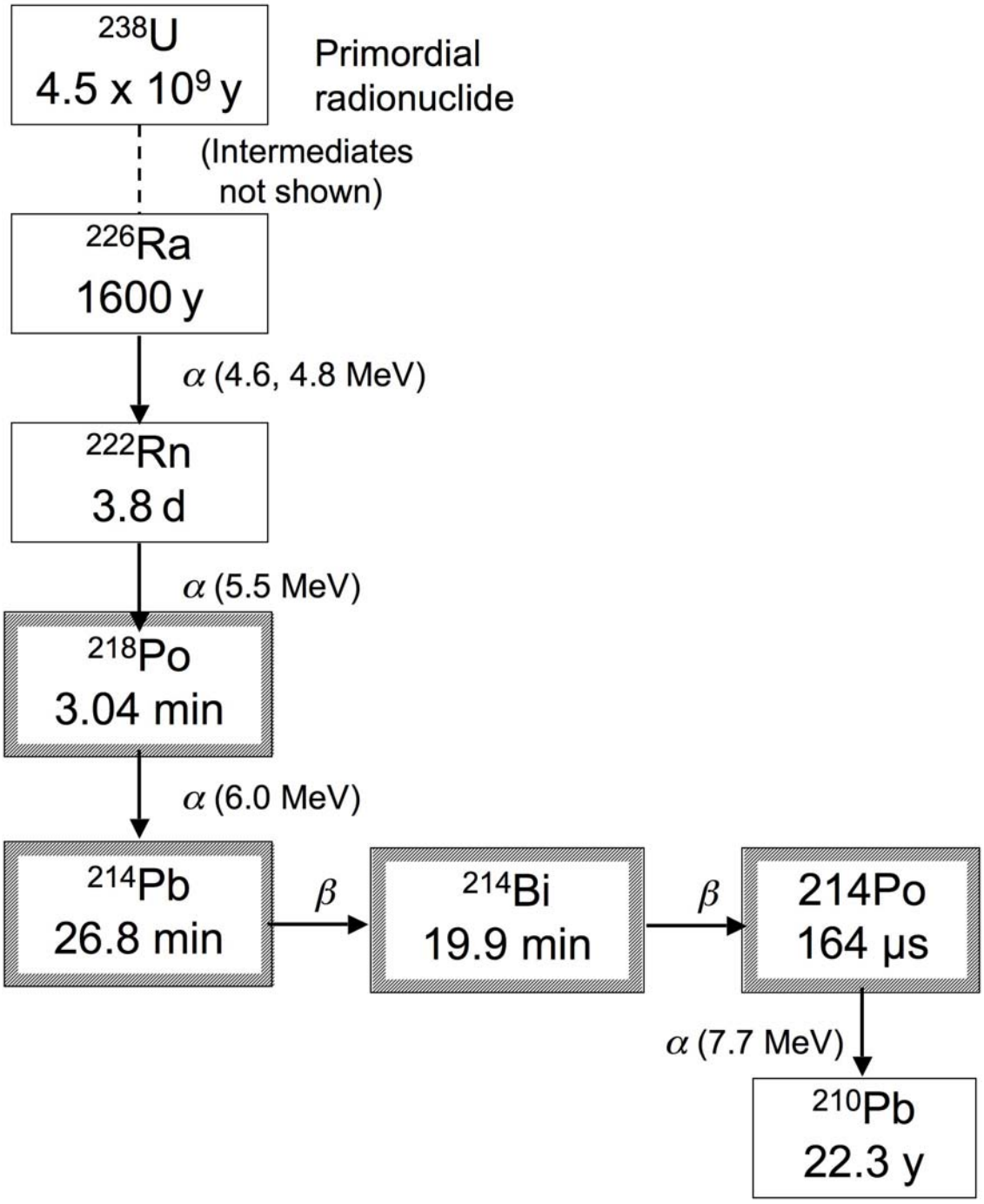


Figure 1. ^{226}Ra Family depicting the chain of decay products and particle emissions.

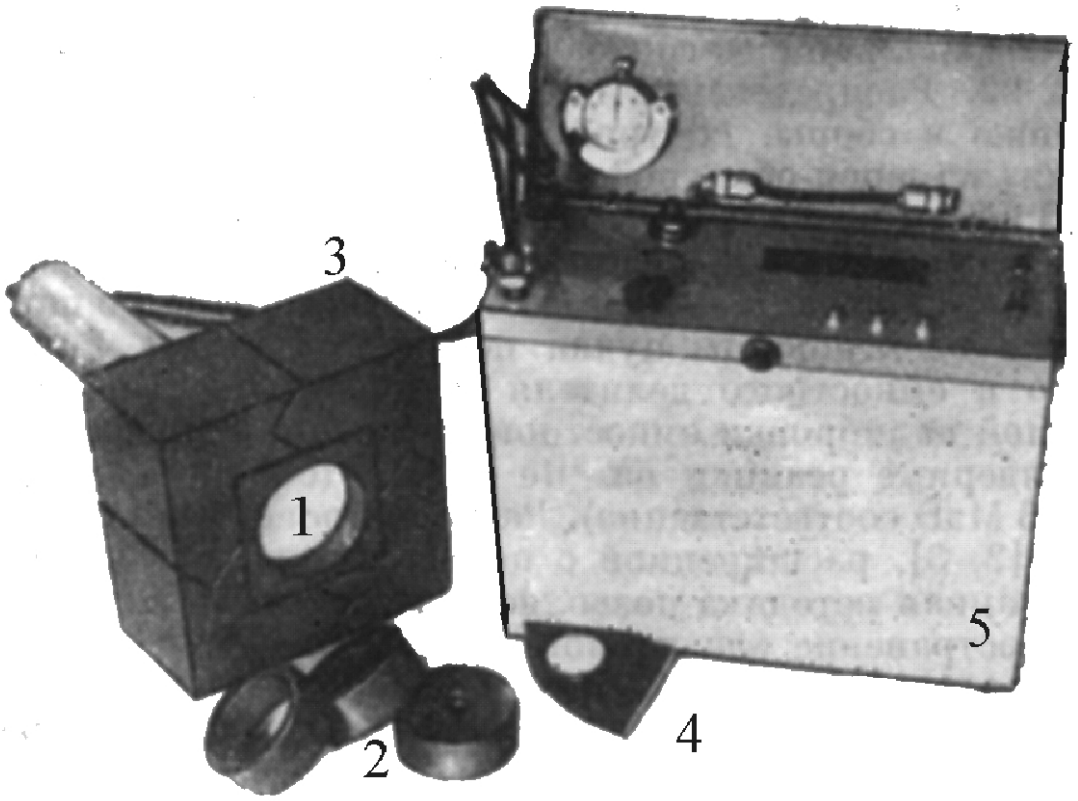
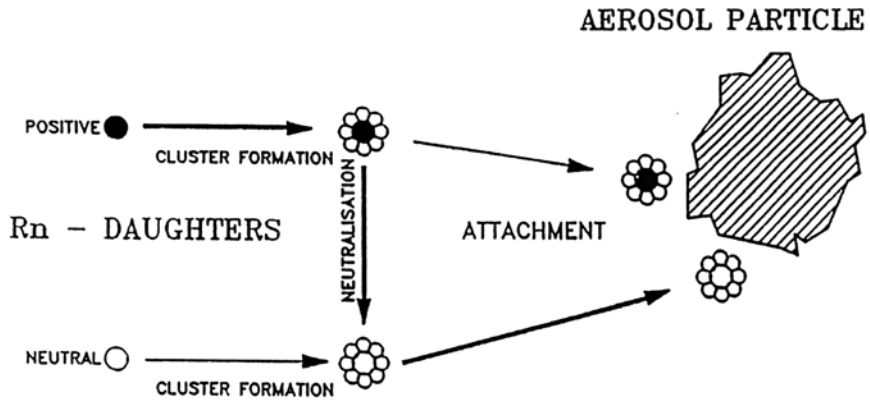


Figure 2. Instrument for Filtration Ability of Lung (FAL) measurement. 1 – NaI detector 2 – collimators; 3 – lead shield; 4 – air sample.



Basic processes of Rn decay product behavior in air defining "unattached" and "aerosol-attached" activities.

Figure 3. Basic processes of Rn decay product behavior in air defining "unattached" and "aerosol-attached" activities.

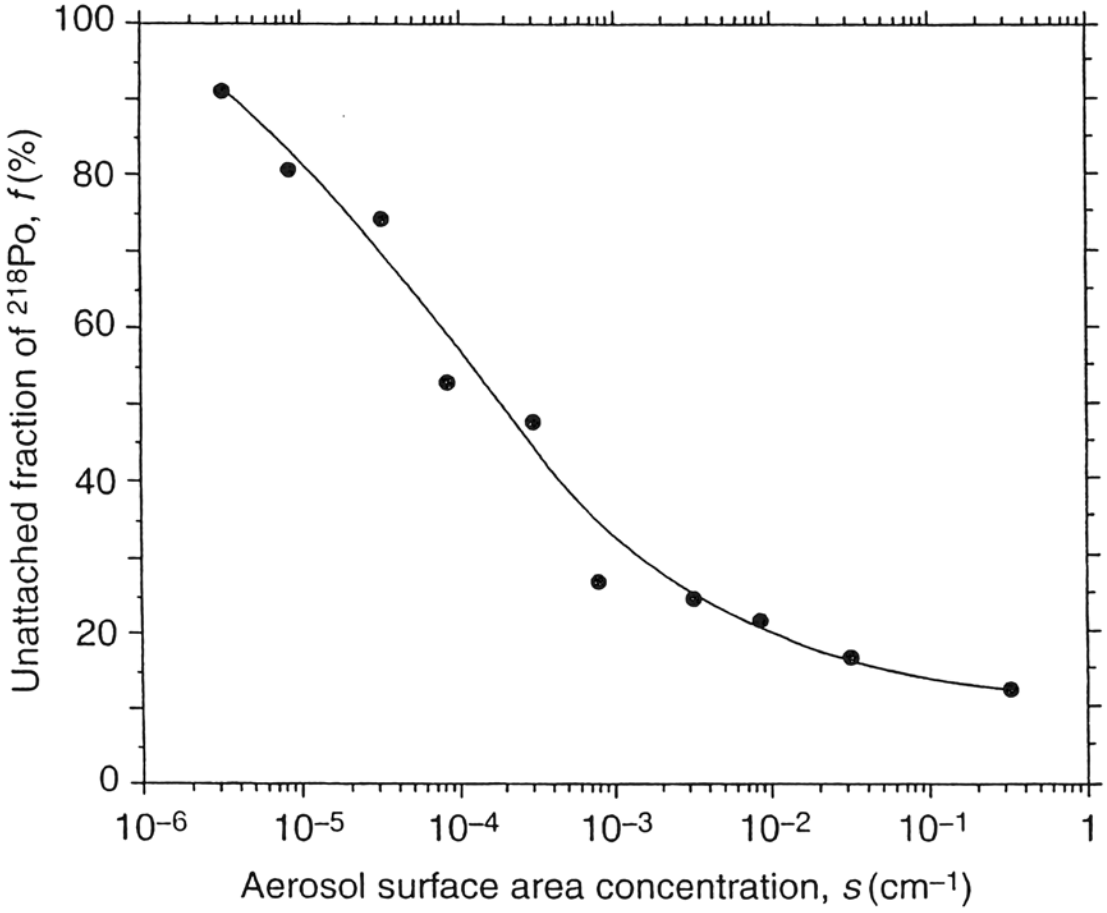


Figure 4. Unattached fraction of ^{218}Po, f vs. aerosol surface area concentrations.

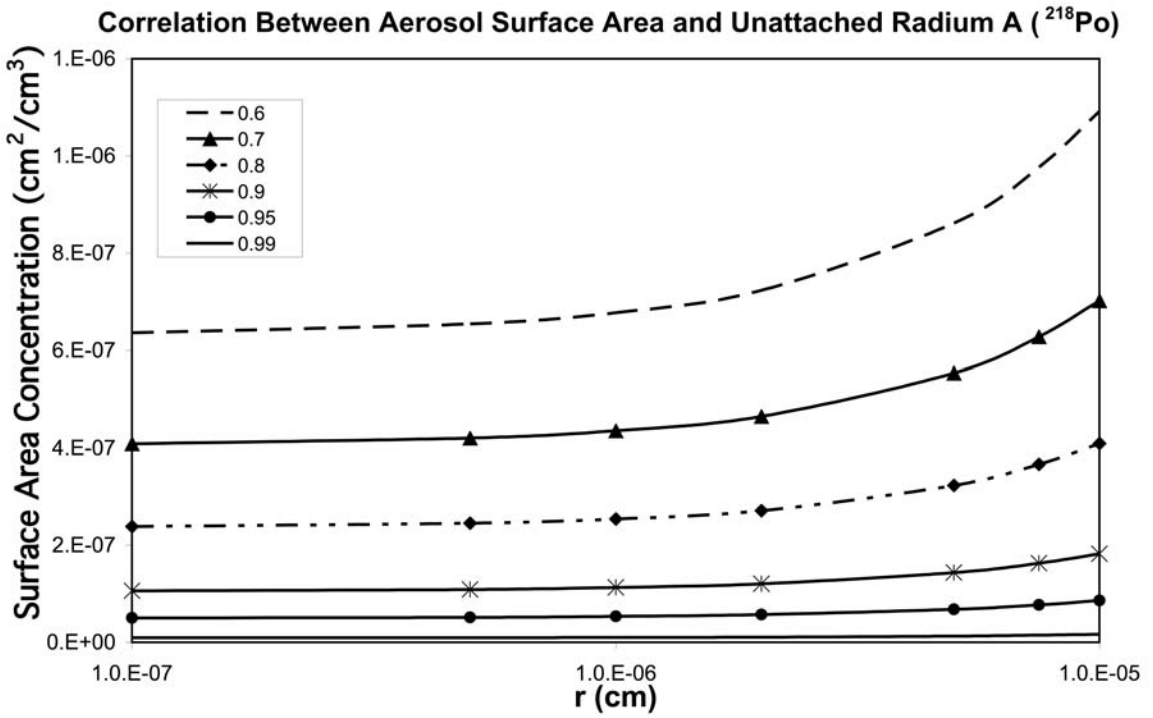


Figure 5. Relationship between particle surface area and particle radius.

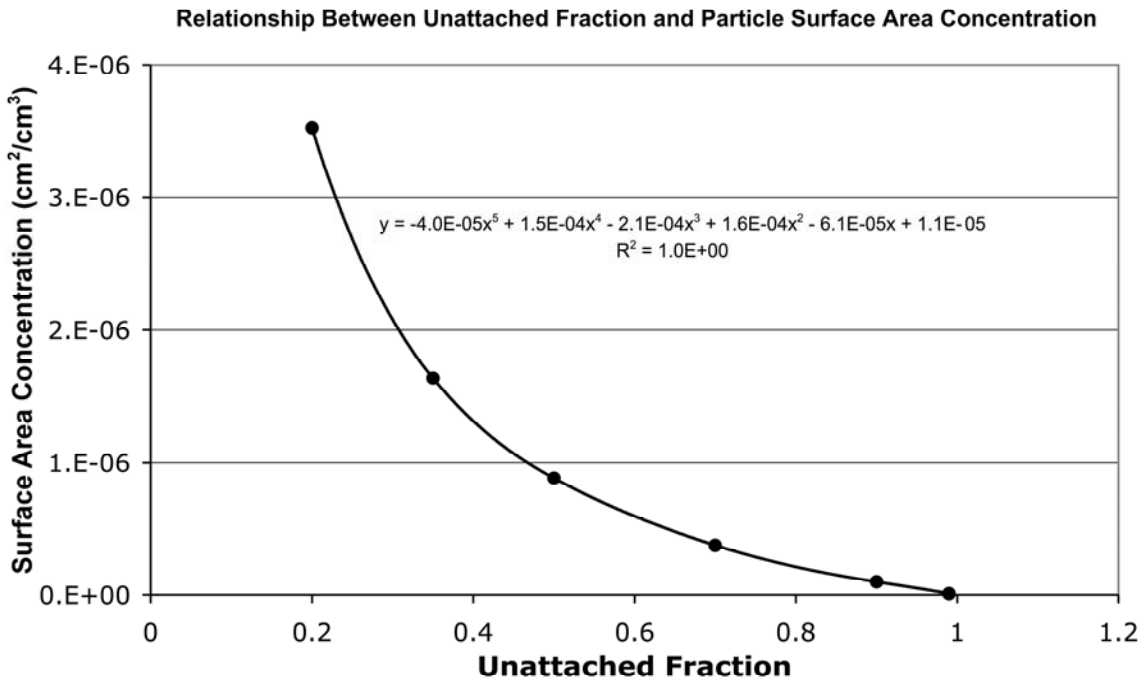


Figure 6. Relationship between particle surface area and unattached fraction