
The nasal air sampler: a device for sampling inhaled aeroallergens

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Objective: The object is to design, develop, and test a personal aerosol sampling device consisting of impaction samplers worn just inside the nostrils, driven by the wearer's respiration. The device provides a novel and unique measure of individual exposure to aeroallergens. It was conceived as an integral part of an allergen diagnostic system, in which collected aerosols are immunostained with monoclonal antibodies or the patient's IgE and associated particles positively identified using techniques of image analysis.

Methods: Each sampler comprises a slot impactor with a detachable impaction plate covered with either a specially developed medical adhesive or a protein-binding membrane. Sampler performance has been validated by rig tests of aerodynamic resistance and collection efficiency of different sized particles at various flow rates. There have also been field trials with human subjects which show that the sampler can be comfortably worn for periods of up to 4 hours. This is sufficient to gather a representative sample of inhaled allergens in most environments.

Results: The sampler collects an increasing proportion of particles in the inhalable range at and above 5 μm . This includes most bioaerosols of interest to allergists. Sampler prototypes have been built by CNC mill and stereolithography. Batches of samplers have been molded in biocompatible materials for field and clinical trials.

Conclusions: The device successfully collects aeroallergens from a patient's own respiration. While developed specifically as a vehicle for the allergen diagnostic system, it can be adapted for studies of other aspects of air quality or for prophylactic use.

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INTRODUCTION

Sampling systems for aerosols and airborne particles involving a variety of freestanding or subject-worn devices have been developed over several decades. Freestanding, or stand alone particle samplers are often deployed in a specific environment to sample air quality and detect carriers of aeroallergens such as pollens and spores and also the presence of pollutants or haz-

ardous materials. They may be intended for indoor or outdoor use, and depend on a variety of particle collection and retention means. The major categories include settling chambers, which depend on the natural settlement of heavy particles in still air, pump driven filtration, electrostatic separators, and a variety of impaction devices. In these, air is drawn in by a pump to an impactor where particles are deposited by their inertia onto an impaction surface. An impactor has a characteristic particle cut-off size for any given flow rate. Particles smaller than this cut-off size remain with the flow and are not collected. An example of the single stage particle sampler is the Burkard spore trap where particles are collected on a tape coated with adhesive.¹ Impaction devices may be arranged in a series of stages of de-

creasing cutoff size, thus segregating the particles removed from the air by size. Examples of the multi-stage cascade sampler are marketed by Andersen Samplers.² A great deal of expertise and data has been accumulated over the years by the users and developers of stand alone samplers and this constitutes much of what we know about aerosols in the atmosphere.

In many applications it is desirable to track the exposure of a single individual to aerosols, and for this subject-worn samplers have been developed. As these require portable pumps and power supplies their design is compromised by the small size and low flow rates necessary to reduce energy requirements and avoid overburdening the wearer. The air intake and collection medium is in a head clipped to the lapel or collar so the particle samples obtained are not necessarily representative of those inhaled by the subject. This is a crucial problem in personal air sampling and determining human exposure. A subject in bed may inhale particles such as dust mite faeces or fungal spores from the pillow or bed that would go undetected by a stand alone sampler placed on a bedside table, or a personal sampler clipped to the pajama lapel.

In order to obtain true personal exposure we have developed personal samplers worn just inside the nose. These use normal human respiratory flow to capture particles by impaction. The aerosols sampled are taken from the air that the subject has inhaled and thus provide a measure of true personal exposure. The samplers are designed to catch inhalable particles larger than a cutoff diameter of about 5 μm , with low enough aerodynamic resistance to avoid any tendency to mouth breathing. In this paper we describe a sam-

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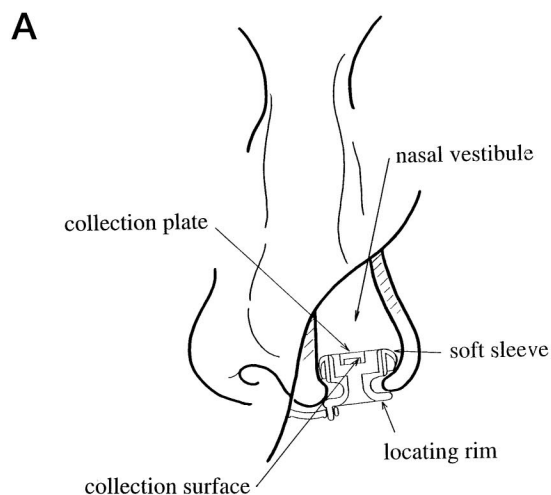


Figure 1. The nasal air sampler (a) cross-sectional diagram (b) as worn by model.

pler that has been refined through laboratory and human testing and whose manufacture has passed through a

number of prototyping steps, including computer numerical controlled (CNC) machining, rapid prototyping by ste-

reolithography, and vacuum molding for the volume runs needed for field and clinical testing. Collection and resistance characteristics are presented, with an outline of testing with human subjects.

DESCRIPTION OF THE NASAL SAMPLER

The nasal sampler is designed to be worn just inside the nares and extends back into the nasal vestibule. A projecting rim at the entry rests against the nares and prevents the sampler from being pushed back into the nose. The small bracket at the front takes a soft silicon strap which connects the two samplers and provides a means of insertion and removal. It further prevents the samplers being pushed too far into the nasal vestibule.

The inhaled flow passes into an accelerating channel and is drawn towards the impaction plate. This constitutes an impaction sampler with an entry slot aspect ratio of about 5:1. The flow splits and leaves by two channels into the nasal airways. The rear of the sampler expands to take advantage of the enlargement of the nostril at the nasal vestibule. Figure 1 shows a cross-sectional diagram of the sampler in the nose, and a subject wearing a pair of samplers. The presently favored collection medium is an acrylic pressure sensitive adhesive tape (Avery Dennison/Adhesives Research) which adheres to the sampler body and is secured by a soft silicon sleeve with a backing bar to secure the tape. The sleeve also prevents air leakage and provides a comfortable and secure fit for the wearer. Figure 2 depicts a disassembled sampler showing the impaction tape on which particles are collected for assay.

The impaction region of the samplers was designed as a slot impactor, from techniques in the open literature.³⁻⁸ It is a single stage impactor, with as low a particle cut-off size as possible at normal inhalation rates within the geometrical confines of the typical nostril. The slot has an aspect ratio considerably smaller than the theoretical ideal. The width of the impac-

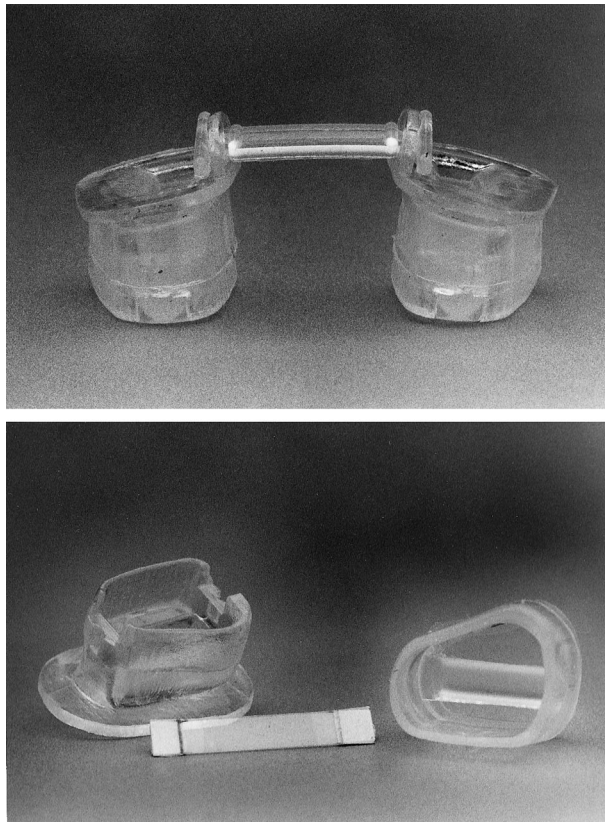


Figure 2. Nasal air sampler. (upper panel) assembled (lower panel) dismantled, showing impactation tape and silicon sleeve.

tion plate is determined by the conflicting demands of sufficient area for particle collection and the need to keep the aerodynamic resistance of the side channels as low as possible, and preferably lower than the impactation slot.

Both inhaled and exhaled flows pass through the same airways. We considered versions with separate airways for these flows, controlled by small flexible valves. This was influenced by the early perception that the collection plate would have to be kept dry to prevent loss of adhesion. Investigation of the samplers when worn by human subjects and in an artificially humidified test rig showed that condensation did not occur. Hence, the complexity of separate airways was not justified.

EXTERIOR MORPHOLOGY

The flow geometry for the sampler impactor must be housed inside an exterior envelope that fits comfortably in a

wide variety of nostril shapes. The present sampler suits the medium to large end of the nasal size range; smaller ones are being developed. The main consideration in designing the sampler exterior is the size and shape of the nasal vestibule. This is the area immediately within the exterior nostrils or nares, continuing up to the interior nares which form the narrow entry to the nasal cavity. The left and right vestibules are divided by a wall of cartilage called the septum or columella, and their outer walls are formed by the flexible ala or "wings" of the nose. The size of the nostril and nasal vestibule varies significantly between individuals according to many factors including age, size and race. Farkas et al.⁹ determined seven different external nostril shapes, which varied significantly in size amongst subjects measured. In order to determine the correct size and shape of the sampler, we re-

quired additional information on the internal geometry of the nasal vestibule, data which was not available in any of the literature studied.

For measuring the internal geometry of the nasal vestibule, computed tomography (CT) scanning, acoustic rhinomanometry, and magnetic resonance imaging were rejected because of the lack of resolution at the level of the nasal vestibule. A number of attempts to cast the nasal cavity and vestibule of cadavers have been reported,^{10,11} and casts of the noses of live subjects were produced by Bachmann and Legler.¹² We made nostril casts of 25 people using a dental impression material (BayerDental Optosil P plus, Bayer, Leverkusen, Germany). The material was mixed and given to the subject to insert into their nostrils as far back as they felt was comfortable, without distorting the nose, and left to set for 3 to 5 minutes. After this time the material can be removed and retain the shape of the nostril interior. Accurate reproductions of the internal geometry of the vestibule were obtained by this method, and combined with direct measurements of the exterior of the nose to determine the design of the sampler housing for medium to large noses, and separately for small to medium sized noses. From these designs prototypes were made and tested in 60 people of varying nose characteristics to determine the suitability of sampler exterior designs.

AIRFLOW RESISTANCE AND SUBJECTIVE PERCEPTIONS

Prototype devices were tested for airflow resistance in a test rig comprising a plenum with a holder for the nasal air samplers in its wall, a mechanical lung reciprocating pump, and flow and pressure transducers. By measuring flow and pressure drop simultaneously, airflow resistance could be calculated.

Studies on natural and artificially increased nasal airway resistance (NAR) show that subjects begin to notice airflow restriction through the nose at a resistance level of 4.5 to 5.0 cmH₂O/L/sec.^{13,14} This occurs at a minimum

total nasal airway cross sectional area of 40 to 45 mm². A pair of the present samplers has an airflow resistance of 5.07 cmH₂O/L/sec at 1.0 cmH₂O pressure drop across the sampler measured with reciprocating flow driven by the mechanical lung. The pressure drop of 1.0 cmH₂O across the sampler occurs at a typical adult inhalation flow of 22 Lpm (liters per minute). The sampler has been designed with a minimum cross sectional area of 49.7 mm² per pair. Resistance of the sampler pair is higher than the nasal airway for any given cross section because of the duct geometry needed to give good impaction. This resistive load places the nasal samplers at the low end of the the 'noticeable change' segment of the curve in Figure 3, and would be equivalent to feeling mildly congested for most wearers. The curves shown correspond to Laine and Warren's measurements^{13,14} in subjects with constricted airways, and our own experiments on subject reactions to standard resistances, nasal plugs with holes of set diameters.

Initial studies have been performed on samplers worn by human subjects. Most adults can tolerate a considerably higher resistance than the present sam-

pler for short periods at rest; however, for reasonable comfort with periods of wear of 30 minutes to 2 hours and moderate exercise levels (housework, vacuuming, and gardening) the present moderate resistance should not be exceeded, while attaining as high a collection efficiency as possible. The present sampler meets these requirements.

EVALUATION OF THE DESIGN

Collection efficiency of the samplers has been established in an airflow rig. Monodisperse polystyrene latex (PSL) microspheres (Bangs Labs, Fishers, IN, USA) of known diameters were aerosolized using a medical nebulizer (Professional Medical Products, Greenwood, SC, USA). Grass pollen (*L. perenne* pollen, defatted, Allergon, Engelholm, Sweden) was aerosolized using a compressed air driven powder blower. Aerosol laden air was drawn in steady flow from a plenum through the nasal air sampler and a downstream membrane filter (Millipore, Bedford, MA, USA) at flow rates spanning the normal human inspiratory flow range. Tests indicate that the samplers, with oil coated impaction surfaces, collect the inhalable range of aerosols down to

about 50% at 5 μm diameter at flow rates associated with normal breathing. The range covers most particles containing allergens of interest. Studies of aeroallergens indicate that >80% of dust mite allergen (Tovey et al¹⁵) and >75% of cockroach allergen (de Blay et al¹⁶) is associated with airborne particles >10 μm in diameter. Over 40% of the major dog allergen is associated with particles >9 μm (Custovic et al¹⁷).

Figure 4 depicts the collection efficiency of a sampler pair for latex particles of 4.2 μm, 5.0 μm, 7.58 μm, and 11.95 μm diameter at a variety of flow rates in the airflow rig. The figure shows that for a typical resting adult inhalation rate of around 25 Lpm, about 50% of 5-μm particles are collected, rising to virtually 100% of 7.58-μm and 12-μm particles. This is defined as a particle cutoff diameter of about 5 μm. When oil covered collection surfaces are replaced with dry pressure sensitive tape there is a falling off of collection efficiency for larger aerosol particles, due to bounce and re-entrainment. Adhesives are being developed to mitigate this effect.

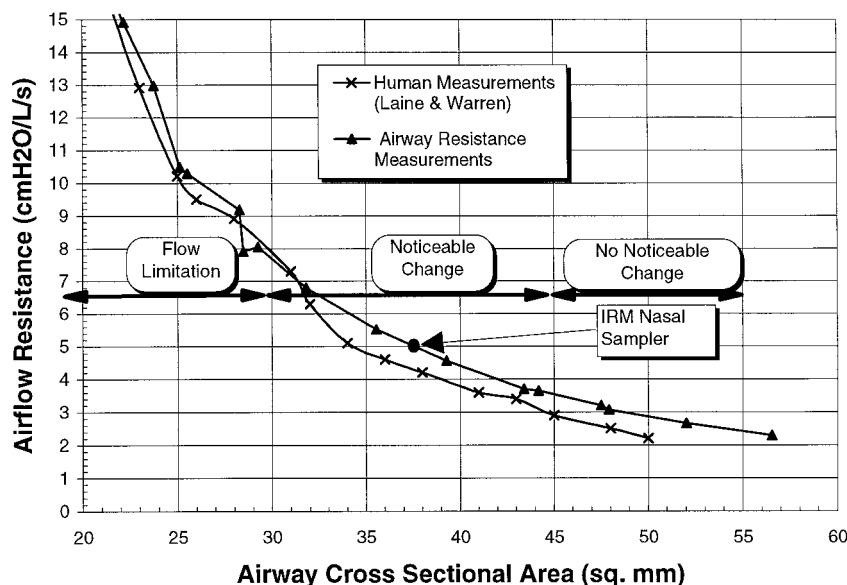


Figure 3. Airflow resistance and nasal airway cross sectional area, with perceptions of nasal airflow, both nostrils together.

SEALING AND SLEEVE DESIGN

The sampler is designed to be worn enclosed in a seal made of a soft, flexible material. The seal sits in contact with the inner surface of the nasal vestibule to prevent air leakage around the sampler, as well as ensuring that the sampler remains secure in the nose. The softness of the seal material means that the lining of the nasal vestibule does not come into contact with the hard plastic of the sampler housing and therefore increases comfort for the wearer. A bar of silicon bridges the sleeve and secures the adhesive collection tape. A number of materials have been considered for the seal, including die-cut slow-release polymer foams, molded silicon rubber, and elastomer gels. Testing is being undertaken to determine the most effective combination of seal design and material.

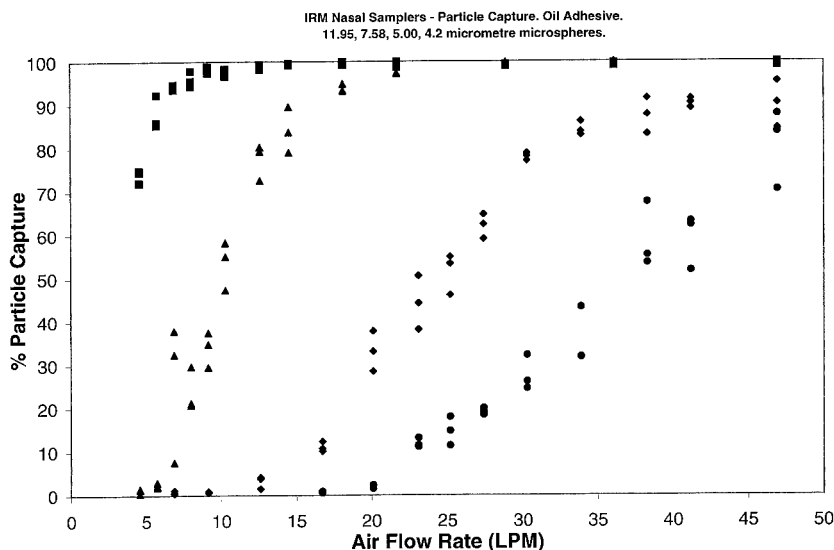


Figure 4. Collection efficiency as a function of flow rate for a number of monodisperse latex PLS particle sizes. ■, 11.95 μm ; ▲, 7.58 μm ; ◆, 5.00 μm ; and ●, 4.2 μm .

HUMAN USE AND APPLICATIONS

The sampler gives a measure of true personal exposure. It shows personal challenge by aeroallergens in environments where the subject experiences allergic symptoms. This is part of an allergen diagnostic system developed at the Institute of Respiratory Medicine that matches the individual's current allergen exposure with the profile of their specific IgE to determine the cause of current allergic symptoms. The nasal sampler could also be used to detect exposure to a wide range of aerosols: wood dust, mineral dusts, and organic particulates among others. It could also be developed as a prophylactic device.

In the present test program the molded version of the sampler has been worn in various environments, including the workplace, various rooms in the home, in gardens and outdoors. Subjects have been at rest, or at moderate levels of exercise such as housework or gardening. The samplers collect amounts of allergens suitable for assay in periods of 10 to 20 minutes, far shorter than the comfort limit of several hours. Samplers have already been employed in research, for detecting and analysing the distribu-

tion of inhaled cat allergen Fel d1 (O'Meara et al¹⁸) and dust mite allergen Der p1 (Poulos et al,¹⁹ DeLucca et al²⁰). An overview of the related allergen diagnostic system can be found in Tovey et al.²¹

DISCUSSIONS

Safety

- The samplers have been successfully tested with air flow rates of 300 L/min and above, with no failures. This is double the maximum human nasal inspiratory rate.
- We are aware that possible flooding with mucus or sneezing may cause safety concerns, but such problems have not occurred in extensive trials and are not likely to be serious.

Materials and Manufacturing

Initial prototyping was done in materials suited to the manufacturing processes, such as perspex and erta polysulphone for CNC machining. Both have excellent finish and precision. Greater geometrical detail and precision is offered by rapid prototyping in stereolithography, a method of 3D modeling using a computer-controlled focused laser beam to set a photopolymer. The resulting solid is excellent in strength and finish for purely mechan-

ical rig testing, but is considered inadvisable for human contact because of possible outgassing of the volatile constituents of the original photopolymer. For human use in field and clinical trials we chose vacuum molding in polyurethane, with molded silicon rubber sleeves. This is considered safe in the nostril. A translucent version of the material was chosen for the prototypes, but it is available in any color.

Future Directions

In newer models the outside envelope of the sampler will make better use of the internal nostril geometry, with due regard to the great variety of human nose shape. Design will be influenced by the needs of high volume molding techniques in medically acceptable materials, and the need to develop efficient handling techniques for the collection medium. Attention will be paid to the range of acceptable colours.

A number of variations on the silicon rubber sleeve are also being considered. These include die-cut and molded foams.

CONCLUSIONS

We have successfully developed and prototyped a nasal sampling device that allows measurement of personal exposure to aeroallergens in the environment and can be comfortably worn for periods of up to four hours with little discomfort. Rig tests give a collection cutoff at 5.0 μm at a mean flow-rate of 25 Lpm using monodisperse latex particles. This allows the collection of most particulate bioaerosols of interest to allergists. Resistance is 5.02 cmH₂O/L/sec at a pressure drop of 1 cmH₂O. Seals or sleeves in molded silicon rubber or die-cut foams provide excellent comfort and security for wearers and help to locate the sampler in the nose. Computer numerical controlled milling and stereolithography have been successful vehicles for prototyping and molding samplers needed for field and clinical trials. The sampler can be manufactured in quantity in a disposable form at reasonable cost. The device is designed to serve as a vehicle for an allergen diagnostic

system, but can be used for airborne particulate studies or could be developed for prophylactic purposes.

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