Sniffers: Fluid-Dynamic Sampling for Olfactory Trace Detection in Nature and Homeland Security—The 2004 Freeman Scholar Lecture

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Vertebrates aim their noses at regions of interest and sniff in order to acquire olfactory trace signals that carry information on food, reproduction, kinship, danger, etc. Invertebrates likewise position antennae in the surrounding fluid to acquire such signals. Some of the fluid dynamics of these natural sensing processes has been examined piecemeal, but the overall topic of sniffing is not well investigated or understood. It is, however, important for several human purposes, especially sampling schemes for sensors to detect chemical and biological traces in the environment. After establishing some background, a general appraisal is given of nature's accomplishments in the fluid dynamics of sniffing. Opportunities are found for innovation through biomimicry. Since few artificial ("electronic") noses can currently sniff in the natural sense, ways are considered to help them sniff effectively. Security issues such as explosive trace detection, landmine detection, chemical and biological sniffing, and people sampling are examined. Other sniffing applications including medical diagnosis and leak detection are also considered. Several research opportunities are identified in order to advance this topic of biofluid dynamics. Though written from a fluid dynamics perspective, this review is intended for a broad audience. [DOI: 10.1115/1.1891146]

1 Introduction

Sniffing for chemical traces is as old as nature itself. It dominates the lives of most animal species, relegating touch, hearing, and sometimes even vision to lower status. Animals depend on olfaction for food, reproduction, kin recognition, and danger alert [1]. The first three of these require little sniffing in humans, but recognizing danger is still very important to us in the 21st century.

The study of olfaction is a well-established scientific discipline, but hardly a stagnant one. Zwaardemaker's book on vertebrate olfaction [2] already listed over 200 references in 1895, but at this writing, researchers R. Axel and L. B. Buck have just been awarded the Nobel Prize in Medicine for their research on odorant receptor genetics. Some of the many recent surveys of the field are given in Refs. 1 and 3–6. These authors discuss olfaction from the perspectives of neuroscience, psychology, zoology, chemistry, anatomy, and communication. Few, however, have included the perspective of fluid dynamics.

But fluid dynamics is central to olfaction, and it is therefore surprising that sniffing flows have not attracted much attention to date. Biofluid dynamics has been mainly concerned with the larger themes of blood flow, respiration, and external locomotion flows [7,8], and has left the fluid dynamics of sniffing mostly unexplored.

Hence the time is right to investigate this topic, especially in that—until recently—no technology could begin to emulate the animal nose. Now, however, we have artificial or "electronic" noses [9,10] with substantial and growing capabilities. They need samplers—*sniffers*—of comparable aptitude.

The closely related issue of chemical trace sampling has likewise received little attention. S. F. Hallowell, head of the U.S. Department of Homeland Security's Transportation Security Lab, said "Chemists have been so fixed on detector development [that] that's exactly what we got: very well-developed detectors that have no front ends. We're going to have to reach out to other disciplines to develop novel sampling systems" [11]. Fluid dynamics is the principal discipline that must fulfill this need.

1.1 Scope. This is an unusual Freeman Lecture: Rather than a detailed review of a current fluids topic, it attempts to bring together several diverse fields—some outside the traditional fluids realm—in order to introduce a novel biofluid dynamics topic. Rather than the culmination of a career, it is an attempt to strike out in a new direction.

Of course, not all chemical sensing methods require fluid-dynamic sniffing *per se*. An early distinction is made here between trace and bulk detection, for example. The latter involves non-olfactory methods to sense significant quantities of a target material such as a concealed explosive or other contraband. Also, direct-contact methods like swabbing can acquire trace samples without an overt fluid-dynamic step.

A similar distinction is made between standoff and point detection [12]. Standoff detection requires physical separation between the sensor and the site of interest. In this paper, except for air-scenting and chemical plume tracing, sniffers are considered to be point-detection devices.

The well-developed fields—some broader than others—that bear on the present topic include:

1. Biofluid dynamics [7,8].
2. Animal olfaction, neurophysiology, and evolution.
3. Artificial olfaction, often called the "electronic nose."
4. Airborne particle sampling of the sort used to determine air quality [13]. (In [14] more than 1000 such instruments manufactured by 240 companies were identified.)
5. Inhalation toxicology, where laboratory animals are used to

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assess human responses to inhaled pollutants [15,16].

6. Ventilation, especially inlets and hoods for industrial capture and local exhaust of fumes [17–20].
7. Electronics cooling, where high convective heat transfer occurs in confined spaces [21,22].
8. Aerobiology [23–25], "the science of the aerial transport of microorganisms…together with their transfer to the air, their deposition, and the ensuing consequences…" C. S. Cox [23].
9. Analytical chemistry, the science of identifying and quantifying compounds using laboratory instruments, e.g., [26].

1.2 Goals. Lighthill, in the introduction to his *Mathematical Biofluiddynamics* [7], wrote "The value of seeing any biofluiddynamic problem…against the background of a systematic comparative survey of the biological function in question in many different groups of animals, can hardly be overestimated." Such a survey of sniffers is the principal aim of this paper. It is intended for a broad audience, including zoologists, biologists, environmentalists, anatomists, and physiologists as well as the fluids community. It also aims to encourage the fluids community to consider olfaction and the olfaction community to include fluid dynamics. The role of sniffers is examined in nature, instruments, and applications, the state-of-the-art is summarized, and future developments are projected. It is, in other words, a fluids engineer's view of olfaction.

2 Fluid Dynamics of Sniffing and Sampling

A brief overview of some pertinent fluid dynamics is given here as a resource for nonfluids-oriented readers. This is no substitute for a basic fluid mechanics course, but it does include some history and a collection of pertinent—if little-known—fluids issues. The breadth of the topic and that of the anticipated audience precludes mathematical rigor in favor of an approach based on physical reasoning, phenomenology, similarity, and scaling.

2.1 Flow Visualization. As elegantly stated by Kline [27] and Roshko [28], solutions of the equations of fluid motion have limited value without some accompanying phenomenological insight, usually gained from flow visualization [29]. This marriage of fluids, optics, and artistry serves research for purposes of discovery, exploration, illustration, qualitative insight, and nowadays quantitative measurement. Modern flow visualization includes a computational element and benefits from both computer and laser technology.

The visualization of olfactory flows apparently began with Paulsen [30], who placed litmus paper inside the nasal cavity of a human cadaver head and caused the head to "inhale" ammonia. This early surface-flow visualization method revealed elements of the internal airflow pattern. In the same era, Zwaardemaker [2] observed the flow of breath from the human nostril by way of moisture condensation on a cold mirror. This method is still useful in modern times, [31] and Fig. 1(*a*).

More modern attempts to visualize the airflow in the human nasal cavity used transparent plastic models ranging in scale from 1:1 [32] to 20:1 [33]. Computational fluid dynamics (CFD) simulations, e.g., [16,34], agreed with experiment in that only a fraction of the inspired airflow reaches the olfactory region.

Brueggemann and Jeckstadt also reached that conclusion in 1938 [35] following chemical tracer and dust deposition studies in the nasal cavity of a dog. Dawes [36] used cigarette smoke to visualize the airflow through a thin slice of a dog's nose between clear plastic plates. Such particle visualization is also important in external airflow studies of chemical plume tracing [37,38] and ventilation exhaust effectiveness [39].

Underwater, Teichmann used dye to study the water flow through the olfactory lamellae of an eel [40]. Similar visualizations of both the antennule flows of crustaceans and the chemical plumes they detect are shown in [41–43]. Invoking fluid-dynamic similarity, human [44,45] and lab-rat nasal flow patterns were examined in water models with dye injection.

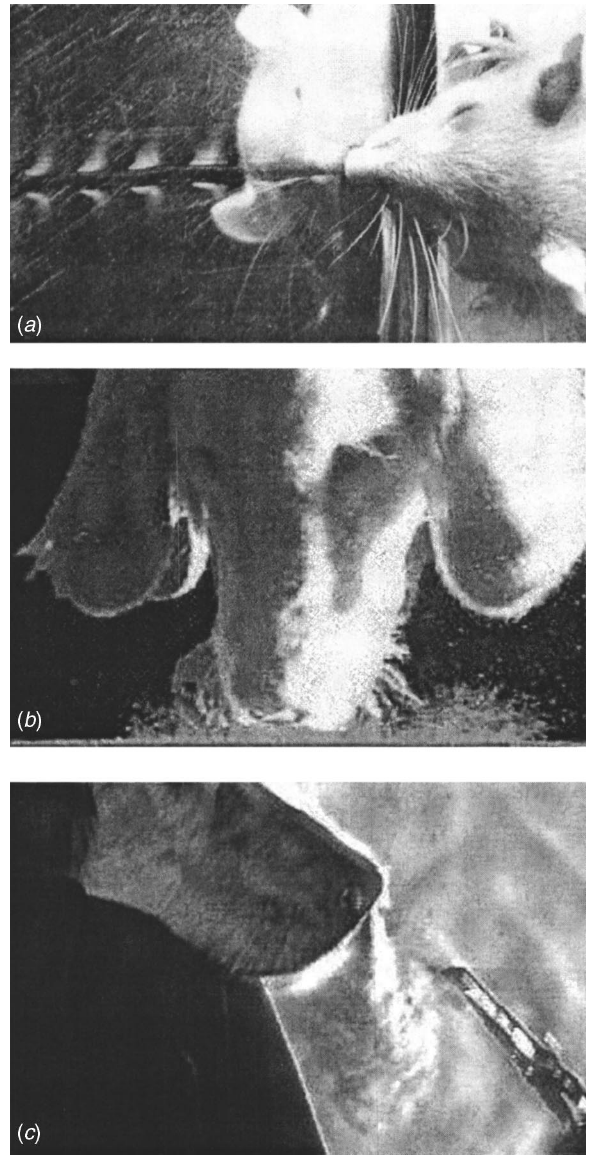

Fig. 1 Examples of olfactory flow visualization in nature. (*a*) condensed moisture traces of a rat sniffing on a Zwaardemaker mirror, a form of surface flow visualization, courtesy F. Bojsen-Møller, and (*b*) tracer particles disturbed by a dog sniffing a horizontal surface, and (*c*) schlieren image of the exhalation from a dog's nose [47]

In contrast, the optical flow visualization methods (schlieren, shadowgraph, and interferometry [29,46]) were used only once for olfactory research, [47] and Fig. 1(*c*). This requires special optics but has the advantage of imaging air currents without tracer particles. A National Research Council study recommends Schlieren imaging for the detection of explosive vapor plumes [48].

In summary, there is a wealth of resources on flow visualization [29] that can be used in future olfactory research. Visualization should always be done first; it defines the flow phenomena and sets the stage for more quantitative and detailed measurements. It teaches you the physics of the flow.

2.2 Definitions and Assumptions. Sniffing is sampling the surrounding fluid by olfaction, and a sniffer is the apparatus—whether natural or artificial—that sniffs. A sniffer has an external

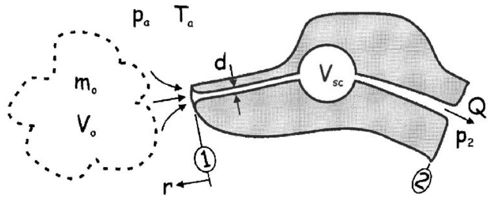

Fig. 2 Diagram of a basic sniffing process (the actual interior of a dog's nose is much more complicated than this)

naris, or nostril, and a nasal cavity containing olfactory sensors in vertebrates and in artificial noses (though the latter do not also breathe.) Invertebrates have their olfactory sensors outside their bodies, but we consider them to be sniffers as well. Sometimes the sensor is stationary with respect to a moving fluid, other times the sniffer transports fluid through a stationary sensor apparatus. Either way, mass transfer by fluid flow is required for olfaction.

Olfaction is the sensory detection of an odor or scent, some chemical signal in the environment. The sources of such chemicals need not be present for olfaction to occur. Moreover, only *trace* amounts, not bulk amounts, are required. A trace is a very small chemical signal—sometimes only a few molecules. W. J. McGann has defined trace detection as "the process of sample collection, detection, and identification of targeted substances not measurable by any other means." For present purposes we draw no distinction between trace detection thus defined and olfaction.

Incompressible single-phase fluid flow is assumed throughout this paper. Solid particles, when present, represent a negligible mass fraction. Weak odorant concentrations are passive scalars that do not change the gas properties. Reactions between sensors and odorants do not alter the energy level of the flow. Three-dimensional (3D) unsteady flow occurs in the most general sense, although lower dimensionality and quasisteady flow are assumed in many practical examples. The flow may be laminar, transitional, or turbulent, depending upon a Reynolds number that ranges broadly over the phenomena of interest. Viscosity is ignored in external flows away from surfaces. For internal flows a lumped friction loss is assumed for simplicity. All body forces are neglected. Readers unfamiliar with these assumptions should consult a basic fluid mechanics text, e.g., [49,50].

The equations to be solved, then, are the Navier-Stokes equations of continuum fluid motion, generally by numerical computation and experimental analog. Often, though, the external flows of sniffers lend themselves to simpler solutions like potential-flow approximations, where fluid rotation is neglected. Software is available to do these simple solutions, e.g., [51], and some examples are shown later. The underlying theory is covered in fluids texts and does not bear repeating here. However, potential-flow theory is inadequate for the flow inside an animal's nose or an artificial nose, where friction is important. Several complete Navier-Stokes solutions of such nasal flows in rats, monkeys, and people were done by Subramaniam et al. [16], Kimbell et al. [52,53], Kepler et al. [54], and Kimbell and Subramaniam [55].

2.3 Modeling and Scaling. A simple modeling exercise can help to introduce the key parameters of sniffing. Consider the rudimentary sniffer sampling the atmosphere in Fig. 2. (Much of this paper concerns ingenious ways of sample acquisition by sniffing, the simplest of which is shown in this figure.) A certain mass m_o of odorant is dispersed in the air within an odor cloud of volume V_o, yielding an average odorant mass concentration $C_o = m_o/V_o$. A sampler, or nose, approaches the vapor cloud closely enough that much of the cloud lies within the "reach" of the nose, i.e., the maximum distance over which it can induce a significant airflow. By inhaling a volume V_i through the nostril at ① over time interval Δt—"sniffing"—the nose transfers odorant from V_o to its internal sensor chamber, which has a volume V_{sc}, at a flow rate $Q = V_i/\Delta t$.

The sniff is caused by a reduction in pressure p_2 compared to ambient pressure $p_1 = p_a$. The pressure differential $\Delta p = p_1 - p_2$ induces the desired airflow. Conservation of mass between stations ① and ② requires that $U_1/U_2 = A_1/A_2$, where U is the airspeed and A is the duct cross-sectional area. The steady-flow energy equation between stations ① and ②, ignoring any heat transfer, is

$$\frac{p_1}{\rho} + \frac{U_1^2}{2} = \frac{p_2}{\rho} + \frac{U_2^2}{2} + g(h_f + \Sigma h_m) \qquad (1)$$

where g is gravitational acceleration and ρ is the gas density. This familiar relation reveals that wall-friction losses gh_f and "minor" losses $g\Sigma h_m$ occur at the expense of the fluid kinetic energy inside the nose, and are balanced by the pressure differential according to

$$\Delta p = p_1 - p_2 = \frac{\rho K(U_2^2 - U_1^2)}{2} \qquad (2)$$

where K is a lumped nondimensional loss coefficient expressing the sum of wall friction plus any duct losses caused by sudden expansions, contractions, bends, etc. K is not known *a priori* for a complicated nasal passage, but it can be evaluated from Eq. (2) using basic pressure and velocity data from experiments or computations.

This textbook material stresses to artificial nose designers the importance of minimizing the minor losses. Each of these wastes a portion of the velocity head $1/2\rho U^2$, and such flow energy loss must be made up by the lung or blower or pump that drives the sniffing process (see Sec. 5.3.2). Narrow flow constrictions are also lossy [45]. Inside an animal, too many minor losses overload the lungs and impede olfaction, if not respiration itself [56]. In an artificial nose, after the airstream has been sampled and interrogated, a *diffuser* is needed to recapture the potential energy of the flow before it is discharged to the atmosphere.

Returning to Fig. 2, if no extraneous unscented air is inhaled and $V_{sc} \leq V_o$, then the odorant concentration in the sensor chamber is simply $C_{sc} = C_o$. Of course this is unlikely, for in reality the nose also inhales some extraneous ambient air V_a, thus reducing the concentration of odorant in the sensor chamber by a sampling efficiency factor $\eta_s \sim V_a/V_i$. The sensed odorant concentration, then, is $C_{sc} = \eta_s C_o$. Other inefficiencies can occur, such as signal loss to the walls of the nasal passages. When particles are present in the odorant cloud, they may also be lost during sniffing by settling or impaction [57]. Realistically, then, the odorant concentration C_{sc} in the sensor chamber is often much less than C_o, which itself is usually tenuous in the environment. In other words there is an "impedance mismatch" due to poor sampling efficiency, by analogy with the transfer of electrical energy.

Large impedance mismatches in sniffers are often dealt with by *preconcentration*, in which a fraction m_s of the odorant mass m_o is sampled, usually by being adsorbed or impacted upon a surface during the sniff, and the large original volume of air V_i is discarded. (The additional apparatus and ductwork required to do this are not shown in Fig. 2.) After the capture, artificial noses use a much smaller volume of carrier gas V_p to collect the odorant mass, which is thermally desorbed from the surface, and convey it to the sensor chamber. This process takes time, but yields a preconcentration factor $\eta_p = V_i/V_p$ as large as 1000 or more, greatly ameliorating the impedance mismatch. Natural noses have evolved the ability to sense trace odorants directly via the sensory tissue upon which they collect: a much-faster and more elegant approach.

Having arrived at an odorant concentration C_{sc} in the sensor chamber by sniffing, noses sense the odorant by way of a chemical reaction. In nature, odorant molecules interact directly with receptor cells mediated by a mucous layer, for example. True artificial noses mimic this, while other man-made detector types usually interrogate the captured odorant by spectroscopy. The natural response to odorant concentration is the psychophysical power law (Stevens' law) $R \sim C_{sc}^n$, where n is less than 1 and is dependent upon the particular odorant species [58,59].

Now from a different viewpoint, the total odorant mass m_s sampled during the sniff is given by

$$m_s = \eta_s \cdot Q \cdot C_o \cdot \Delta t \tag{3}$$

This shows that higher sniffing flow rates and longer sniffs increase m_s. But does that mean greater olfactory sensitivity? Stuiver [44] reasoned that a higher flow rate reduces odorant dwell time upon the receptors and thus elicits less olfactory response. Mozell et al. and Hahn, Scherer, and Mozell [58,60] further noted that increasing Q by raising Δp with fixed Δt in olfaction studies also increases V_i and changes several variables at once, causing confusion. The design of the sensor chamber also bears upon this question (discussed in Sec. 5.3).

A longer sniff at the same flow rate, however, clearly does expose the receptors to more odorant mass according to this simple quasisteady-state model (which neglects *adaptation*, the loss of sensor response with time). Dogs can do this in case of weak or inaccessible scents by taking 1/2 Hz "long sniffs" in place of their normal ~5 Hz sniff rate [47,61–63].

Finally, the Reynolds number $\text{Re}_d = Ud/\nu$ governs the nature of this flow, where d is the nasal passage diameter and ν is the kinematic viscosity of the air. Below $\text{Re}_d \sim 2000-3000$, laminar flow is expected in simple ducts, though not necessarily in the complicated nasal passages of *macrosmatic* animals—those with keen olfactory powers. Since ν is roughly constant at about $1.5 \times 10^{-5}\ \text{m}^2/\text{s}$ for air in the near-ambient temperature range, the Reynolds number varies mainly with airflow rate Q and physical scale d. The anterior nasal passages of terrestrial vertebrates range from about 1 mm diameter in the rat [64] to a centimeter or more in the largest animals. Given rat respiratory flow rates in the 100 ml/min–900 ml/min range, a typical Re_d is about 350 and laminar nasal flow is assumed [53], at least initially. In humans, however, the issue is controversial [45].

Underwater, ν is an order of magnitude smaller than in air but the pertinent length scale is also often much reduced. The chemosensory hairs (*aesthetascs*) of crustaceans, for example, operate with $\text{Re}_d \sim 1$, where the interplay of fluid viscosity and inertia is delicately balanced, [65] and Chap. 15 of [66].

2.4 Potential-Flow Inlets. The potential flow approximation, mentioned earlier, naturally describes the flow of ideal fluids into suction orifices like the nostrils of present concern. We can examine external sniffing airflows by simple means, so long as Re is large and both wall friction and flow separation are either avoided or ignored. Ventilation engineering takes major advantage of this as is detailed in several references [17–19,67,68].

In brief summary, potential flow theory reveals that a simple inlet is not directional. Wile E. Coyote's ACME vacuum cleaner may suck in all sorts of objects from a distance, but that only works in the cartoon world. In reality an inlet draws fluid equally from all available directions, so its influence drops rapidly with distance. Consequently, except for the case of airborne scent plumes, sniffing is not a stand-off activity and proximity is essential for a nose to acquire a localized scent.

Potential flow also explains the inefficiency of a simple free-standing pipe as an air inlet: Even when aimed at something, it draws air equally from behind as well as from in front. It further has a high loss coefficient, 0.93, meaning that it wastes 93% of the velocity head $1/2\rho U^2$. A flanged inlet, Fig. 3(*a*) is an improvement: The forward reach is extended by excluding any suction from the rear hemisphere. Still, the sharp-edged inlet orifice has a loss coefficient of 0.49. Whether a nose is powered by lungs or batteries, such an unnecessary pressure loss is a burden.

Nature abhors sharp edges in favor of smooth, bulbous, aerodynamic nostril inlets like the one shown in Fig. 3(*b*). Also called a *bellmouth*, this inlet has a very small loss coefficient. Here is an important design principle for artificial noses: avoid the sharp edge and the step change in area. It is the natural thing to do.

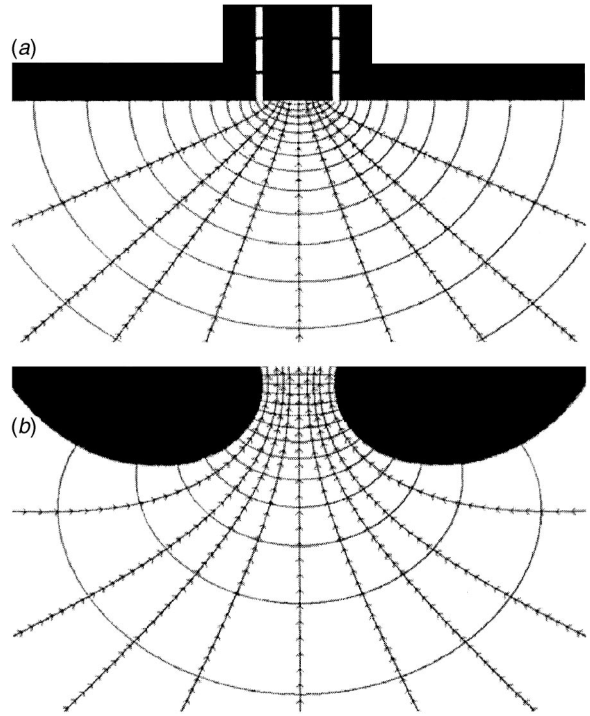

Fig. 3 Streamlines (arrowed) and equipotential lines (solid) for (*a*) a flanged, sharp-edged inlet and (*b*) a bulbous "natural" bellmouth inlet. (These planar 2D potential flow solutions are shown only for illustration purposes)

A definition of the "reach" of an inlet is the size of the region upwind of the inlet from which all of the fluid is ultimately captured [19]. In Fig. 2, in order for the sampling efficiency η_s to approach unity, the reach of the sniffer shown must at least encompass the entire odorant cloud. Industrial local-exhaust ventilation has the same problem: The exhaust hood must reach out to collect fumes from welding, for example, and not let any escape. Given the limited reach of a potential-flow inlet, this is quite a challenge. For the case of Fig. 2, approximated as a simple sink flow, the induced airspeed $u = Q/\pi r^2$ drops linearly with distance r forward of the nostril inlet.

Potential-flow inlets scale up or down geometrically without regard for nondimensional numbers like Re, so the reach of an inlet also grows linearly with its diameter d because $Q = \pi d^2 U_1/4$. This works against the small-diameter tubing used in wand-type leak samplers, e.g., [69]. They have little reach even at the extreme U_1 corresponding to choked flow, and must be physically inserted into an odorant cloud to sample it.

2.5 Turbulent Jets. There is a key distinction between the behavior of potential-flow inlets just described and fluid jets: while inlets are omnidirectional, jets can be vectored. Aim an air jet in a certain direction and it maintains that direction in still air. The "reach" of a jet, then, is many times longer than the reach of an inlet having the same flow rate Q. Jets thus project fluid momentum at a distance.

The turbulent jet literature is vast. Useful surveys of it for present purposes are found in Chap. 4 of [17] and in [70–72]. The recent discovery of synthetic jets is also pertinent [73].

A jet entrains fluid from all directions perpendicular to its axis, which causes it to grow linearly in diameter with increasing distance downstream. The volumetric entrainment rate of turbulent jets is approximately $0.25x/A^{1/2}$, where x is the distance from the nozzle and A is the nozzle cross-sectional area [70].

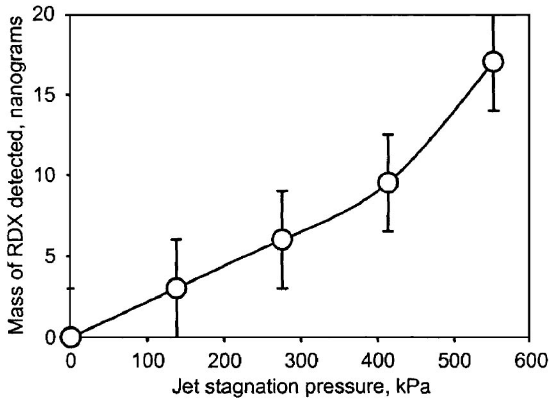

Fig. 4 Portal results of liberated RDX particle mass as a function of impinging-jet stagnation pressure [83]

When a jet impinges upon a solid surface it tends to attach and to exhibit starting impinging jet behavior [74]. Free jets impinge upon surfaces to become wall jets [75].

Even though jets seem at first antithetical to the present goal of sniffing, they can be useful on at least two counts. First there is jet-assisted olfaction, where jets help to focus the suction of a sniffer in the forward direction to improve its reach, Secs. 4.3.1 and 5.2.4. Second is the use of jet momentum to stir up the environment, resuspending settled particles and making them available for olfaction as shown in Fig. 1(*b*).

Phares, Smedley, and Flagan at Caltech have studied the second topic at length [76]. They explored the effects of Re_d, nozzle height, and jet velocity profile on particle removal using both normal [77] and oblique [78] jets, and found that surface particles respond to the shear stress imposed upon them by jet impact [79]. Particle removal depends on particle size and jet duration as well [80]. With these results in hand, they examined previous resuspension theories and proposed a new model. Other recent investigators [81] also studied this topic, and one [82] suggested an analogy with heat transfer enhancement by pulsed jets.

In applied experiments in the Penn State Gas Dynamics Laboratory [83], short-duration air jets from round nozzles impinged upon human subjects whose clothing was contaminated by 10-micron-range trace particles of the explosive cyclotrimethylene-trinitramine (RDX). Dislodged particles were collected (Sec. 6.3.2) and quantified with results shown in Fig. 4. In addition to the shear-stress mechanism described above, inertial detachment of particles also occurs due to jet impact ruffling of the clothing. No matter what the mechanism, though, jet impingement has become the principal means of liberating trace particles from people for analysis and detection in a reasonably nonintrusive manner.

The quasilinear response shown in Fig. 4 is understandable in that the nozzle-to-person distance was fixed in the experiments and the nozzle exit was sonic. Since jet momentum is conserved, an increase in stagnation pressure thus produces a proportional increase in jet momentum, which is thought to be responsible for inertial particle removal from clothing.

2.6 Particles and Stokes Number. Can particles in a flow follow streamlines, as molecules do by definition? This question is answered by considering the nondimensional Stokes number, the ratio of the aerodynamic response time of a particle to the characteristic flow time,

$$Stk = \frac{\rho_p \cdot d_p^2 \cdot U}{18 \cdot \mu_f \cdot L_c} \tag{4}$$

where ρ_p is particle density, d_p is diameter, μ_f is fluid viscosity, and L_c is a characteristic length, such as the size of a flow obstruction. As *Stk* approaches 0, particles have no significant inertia and they faithfully follow streamlines, but for *Stk* greater than about 1, impaction of particles upon obstructions is likely. This is the basis of devices called *impactors* that collect particles from flowing fluids.

Consider airborne particles of unit specific gravity and 10 μm diameter, having masses of about a nanogram each. If $U=30$ m/s and $L_c=1$ m, roughly the speed of a car and the size of its windshield, then $Stk=0.009$ and the subject particles will be likely to flow around the windshield without striking it. But if $L_c=5$ mm, the diameter of the radio antenna, then $Stk=1.8$ and impaction is much more likely. Calculations like this are useful in the design of particle collectors, the loss of particles during transport in tubes, particle settling time, terminal speed, and the deposition of inhaled particles in the nose and lungs [57,84–86].

2.7 Advection Versus Diffusion. Advection is bulk fluid motion whereas diffusion is the molecular spreading of one fluid into another without bulk motion. These distinct phenomena are often confused in the olfaction literature. In Feynman's [87] classic classroom example gone wrong, diffusion is taught by opening a bottle of ammonia and waiting for the student in the back of the room to say "I smell it." But if diffusion is the only transport mechanism, he will not smell it by the end of the class, or even the end of the semester. In reality, the ammonia molecules are quickly transported by the advection of air currents around the room and by thermal convection currents generated by the people in the room.

This point is often made but the confusion persists, even though it may be just an imprecise choice of terms. Airborne odor transport in the nasal cavities of vertebrates has been attributed to diffusion [3,88,89], but that too is unlikely.

Vogel draws an elegant comparison between diffusion and advection for a popular audience ([90], p. 182). Diffusion only works over short distances and thus depends on the size of the flow in question, "But even in air, diffusion remains glacially slow for what we regard as ordinary distances."

The relative rates of advective versus diffusional transport in fluids are described by the nondimensional Péclet number, $\text{Pé}=L_cU/D$, where D is the diffusion coefficient of an odorant molecule in the fluid of interest. When Pé$=1$, the rates are equal. Returning to the rat's-nose example of Sec. 2.3, let $L_c=1$ mm and $U\sim5$ m/s [53]. Diffusion coefficients of typical odorant molecules in air are broadly in the range of 0.1–0.3 $\mathrm{cm^2/s}$ [91], yielding a rat's-nose Péclet number of several hundred. Only at much-lower airspeeds and length scales can diffusion matter in this sniffing example. But there are certainly cases where diffusion matters in olfactory sensing, such as lobster "sniffing" [92,93].

Griffy [94] calculated the time required for a trinitro-toluene (TNT) bomb to produce a saturated TNT vapor level in a room by pure diffusion: hundreds of days. He concluded that airborne explosive vapor detectors are unlikely to succeed unless they are orders of magnitude more sensitive than needed to detect equilibrium vapor levels. But let us not abandon vapor detection altogether, so long as there are air currents to convey the signal and sniffers poking their noses into nooks and crannies (see also Sec. 5.2.2).

2.8 Vortex Flow. The potential-flow vortex is a rotating flow with a strength determined by its core singularity. It has no radial velocity, circular streamlines, and a circumferential velocity field that dies off as the inverse of radius from the core. Vortex flows are covered in elementary fluids textbooks, but see also Lugt's scholarly book [95] that appeals to a broad audience.

What relevance do vortices have to sniffing? At least one man-made sniffer uses an apparent vortex as its operating principle [96]. The puffs on either side of the dog's nose in Fig. 1(*b*) are the starting vortices of impinging nostril jets. The bellmouth nostril flowfield of Fig. 3(*b*) is produced by twin counter-rotating vortices (hidden inside the nostrils), and so on. Vortices are everywhere.

One vortex of special interest is the *intake* or *inlet* vortex. There

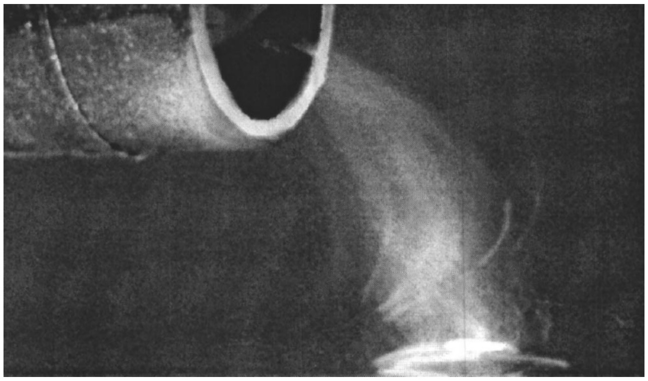

Fig. 5 Inlet vortex into a vacuum cleaner hose with a cross breeze, visualized by coating the ground plane with talcum powder

are photos of vortex cores extending from the idling jet engines of parked aircraft, touching the ground like mini tornadoes and sucking up debris. It is a common fallacy that the jet engine creates its own inlet vortex [97], but researchers in E. M. Greitzer's lab at Massachusetts Institute of Technology have demonstrated that a cross breeze is also required [98] in all cases except those of inlets with swirl vanes [99]. The cross breeze sheds a line vortex from the engine inlet lip that turns downward and attaches to the ground.

The inlet vortex can be duplicated on a tabletop using a vacuum cleaner and fan according to Stong [100]. This instructive demonstration is not difficult (Fig. 5), but its stability is greatly improved if one places a screen or flow straightener after the fan producing the cross breeze.

2.9 Frequency of Animal Sniffing. Although dependable fluid-dynamic data on olfaction are rare, enough exist to estimate the nondimensional sniffing frequency of at least a few animals. This is the Strouhal number, $\mathrm{Str}=fd/U$. For the rat, dog, and human, respectively, the available data are approximately as follows: dimensional sniffing frequency $f=10$, 5, and 2 Hz, characteristic nostril dimensions $d=1$, 7, and 13 mm, and characteristic airspeed $U=8$, 5, and 3 m/s [33,47,53,89]. These values yield Strouhal numbers of about 0.008 for the dog and human and 0.0014 for the rat. Thus sniffing is a slow process compared to the flapping of animal appendages for propulsion, where Strouhal numbers are up to two orders of magnitude larger. A quasisteady-flow approximation is justified in the analysis of sniffing airflows [33] at this low frequency. It may be that animal sniffing rates are based, at least in part, on the need to provide sharp gradients of odorant rather than a constant odorant level to the olfactory sensors. Adaptation works against high sensitivity in the limit as the sniffing rates approaches zero.

3 Traditional Sampling Issues and Methods

Sampling the environment is important to society. So much has been written on this topic, including several thorough reviews, that it serves the present purpose only to give a brief overview with some key references, noting the issues relevant to sniffing.

3.1 Airborne Particle Sampling. The U.S. Clean Air Act controls particles in the atmosphere in order to protect public health and prevent environmental damage. Airborne particulates in the $<10\ \mu$m (PM_{10}) and $<2.5\ \mu$m ($PM_{2.5}$) aerodynamic diameter range are regulated by law according to National Ambient Air Quality Standards. Compliance is monitored by samplers that draw in ambient air and collect the airborne particles by any of several means, including impactors, cyclones, filters, and electrostatic precipitators [13,25,101,102].

The aspiration efficiency of these sampling inlets is one concern, since they must sample a representative population of airborne particles. Isokinetic sampling helps to accomplish this. Outdoor samplers also require inlets that are insensitive to the wind direction. Rooftop inlets are often symmetric about a vertical axis for this reason, while thin-walled sharp-edged inlet tubes can be shrouded to make them less sensitive to variable wind direction. There are many commercial samplers available, from the liters/min range up to about a 19 liters/s flow rate for large rooftop models [84].

Aside from filtration [101], impaction (Sec. 2.5) is the most common means of separating the particles from the airstream in these samplers [13,84,102]. Multistage impactors further classify particles into several size ranges. This matters in air pollution measurement but is not an issue in olfaction; a single-stage impactor can sample all the particles above a minimum diameter together if purely for chemical detection.

A dog's nose collects particles by impaction in the nasal vestibule region, where the respiratory mucosa are moist and sticky [103]. Preventing impacted particles from bouncing or blowing off is likewise an issue in man-made impactors, where a wide variety of sticky coatings is used [13,84,102,104].

Another approach is the virtual impactor, which preconcentrates particles in the sampled airstream by a factor of 6:1, 20:1 [84] or even 25:1 [105]. The particles remain airborne, which helps transport them to an analyzing instrument. Design rules for virtual impactors are given in [84].

Other than inert particles, there are also bioaerosols to be sampled [12,25,106–108]. With such a bewildering array of species already present in the air, detecting a biological warfare attack is a problem [109]. The sampling step must not harm these live airborne particles, since a culture is often required to identify them [110]. The analysis step may also require a liquid sample like that provided by impingers and some cyclone samplers, purification may be needed, and a high sample concentration is called for [12].

3.2 Indoor Sampling. Indoor air quality considers the adverse health effects of smoking, sick building syndrome, insufficient ventilation, etc. [111–113]. Airborne sampling indoors began with the realization that the dangerous pollution sources are under our noses, including chlorinated water, dry-cleaned clothes, mothballs, air fresheners, cooking, paint strippers, solvents, radon gas, and especially tobacco smoke [112]. Large government-sponsored studies like Particle Total Exposure Assessment Methodology (PTEAM) [114–116] in the United States and others abroad showed that personal PM_{10} exposure levels measured by lapel samplers are significantly higher than either outdoor or indoor levels measured by fixed samplers.

3.2.1 Personal activity cloud or human boundary layer? Without questioning the results or significance of PTEAM, here is an alternative fluid-dynamic interpretation. A "personal activity cloud" was proposed by PTEAM investigators as the source of the measured discrepancy in exposure levels [116,117]. Wallace [118] explains: "It is almost as if the participants were walking about in their own personal cloud of particles, a sort of Pigpen effect, after the character in the (Charles Schulz) *Peanuts* comic strip."

The cloud analogy and the comic-strip reference are sadly misleading, though, for what actually happens is not a cloud at all but rather a rising thermal boundary layer that separates to form the *human thermal plume* (Fig. 6(*a*) [46]). It was first shown by Clark and Cox [24], Lewis et al. [119], and Clark and Edholm [120] that the temperature difference between people and ambient air drives a natural-convection boundary layer beginning at the feet and separating from the head and shoulders. Thus the "cloud" analogy overlooks the strong vertical transport ($U\sim 0.25$ m/s, Q up to 50 liters/s [121]) in the airflow about a person. This transport not only presents floor-level contaminants to one's breathing zone, but also entrains the surrounding air and its particle burden at all other levels below the breathing zone. Quoting [122], "The natural con-

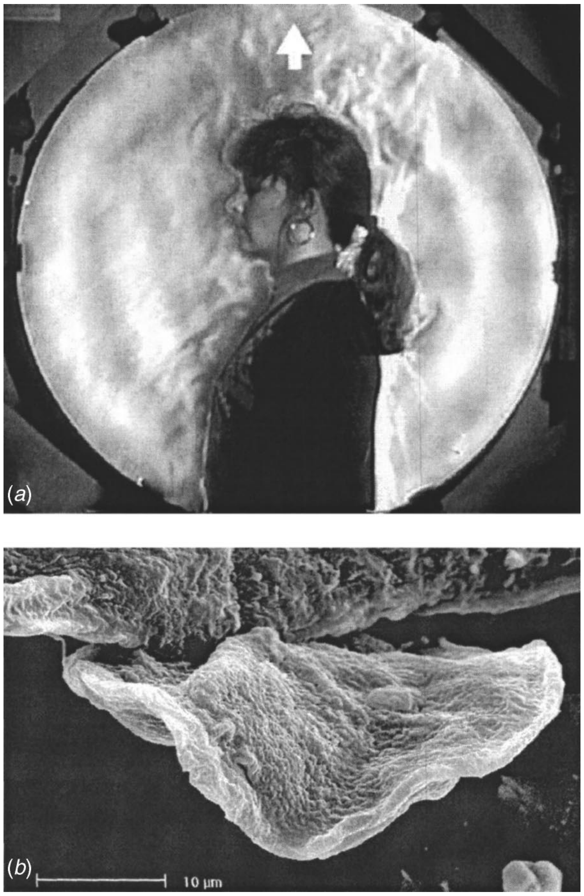

Fig. 6 (*a*) Schlieren image of the rising boundary layer and thermal plume from a human being (L. J. Dodson) [46] and (*b*) scanning electron microscopy image of a desquamated human skin flake, H. A. Gowadia [123,124]. According to Syrotuck [125], "They are cornflake in shape which gives them an aerodynamic characteristic."

vection boundary layer around the human body is capable of transporting particles such as dust, skin scales, pollens, and spores and provides a link in the chain of airborne infection."

A second problem with the PTEAM interpretation is its disregard for the role of human skin flakes: "body cloud emissions are…not considered here as a component of the personal activity cloud effect" [117]. In fact, human skin is easily the most prevalent particulate in the human thermal boundary layer and plume. A complete layer of human skin is desquamated every 1–2 days [24], releasing a million skin scales/min with a 14 μm average diameter and a size range of 5–50 μm (see Fig. 6(*b*) [123,124]). Most inhaled air comes from the human boundary layer that contains these particles, from which 6000 to 50,000 5–50 μm particles/liter of air enter the human nose. Most clothing is permeable to this particle stream. Ordinary house dust is found under microscopic examination to consist of 70%–90% human skin flakes covered with microorganisms. According to Syrotuck [125], if you walk at 1 1/3 m/s (3 mph) you leave behind 500 skin flakes/m. The weight of this evidence on the significance of skin flakes in the human microenvironment ought to be hard to ignore (see also [125–128]).

Moreover, human skin flakes contain mitochondrial DNA, even though they have no cell nuclei and thus no nuclear DNA [129]. We thus continuously shed gross samples of our mitochondrial DNA into the surrounding air. Anthropologists sequencing tiny remnants of ancient mitochondrial DNA must be scrupulous to avoid contamination from their own airborne skin. We cannot suppress this shedding of our DNA, and collecting it for analysis is certainly possible according to principles to be described later (Sec 6.3). Ethical questions about this possibility remain to be resolved, however.

Meanwhile note that a thorough study of the airflow in the human breathing zone, including flow visualization, quantitative measurements, and CFD [130] has apparently not been done, so there is much still to learn about the reach of inhalation, the penetration of exhaled nostril jets, particle intake, and the proper location of personal samplers. Where to locate a personal sampler on a breathing person, considering the nose inlet flow and upward boundary layer motion, still remains an open question. In seeming proof that nothing is sacred, even intranasal samplers are used to sample incoming particles inside human nostrils, thus avoiding this pitfall [131].

3.2.2 Personal samplers. References [14,15] describe the state-of-the-art of small battery-powered personal samplers to be worn by human subjects for particle exposure monitoring in studies like those just described and in industrial hygiene assessments. Typically a battery-powered diaphragm pump draws in the sampled air at a few liters/min through a sorbent tube, filter, impactor, or cyclone. The inlet is usually connected by tubing to the pump, and is attached to a subject's collar or lapel to sample breathing-zone air. A miniaturized five-stage personal cascade impactor is available [132] to classify particle sizes. The SKC Corporation's Button Sampler is a collar-clip filter sampler with a porous curved-surface inlet having low wind sensitivity [133].

Mannequins are used to test personal samplers [134,135], but they do not always properly simulate people. A department-store mannequin is the worst case, for it has neither body heat nor skin flakes and it cannot breathe [136]. Human subjects are thus preferable to mannequins here and in any experiments involving the human thermal boundary layer and plume.

3.2.3 Hand vacuums. Hand vacuums are simple, versatile, filter-type "dustbuster" sniffers. They see regular use in sampling the clothing and luggage of aircraft passengers. The filters are made of cellulose fibers, glass or quartz fibers, membranes, polycarbonate pore material, or plastic foam. In security screening the filter is removed and heated in a desorber, driving off collected traces to be detected, usually, by an ion mobility spectrometer [137].

3.2.4 Wand-type sniffer probes. Wand-type sniffer probes were singled out in Sec. 2.4 for their short reach. Nevertheless a simple probe or wand at the end of a hose is a popular way to poke around and sniff for something. Leak detectors often use wands for gas collection and they are considered prior art in several inventions, e.g., [138]. A search of the technical and patent literature for the term "sniffers" mostly yields such leak-detection equipment with long hoses and hand-held, pointed wands intended to pinpoint leaks [69,139]. In one case a filter at the end of a long hand-held hose samples particles in clean room environments [140], while in another a heated probe tube feeds a portable gas sampling system [141]. A person probing with a sniffer wand is like an elephant exploring with its trunk: Both animals are too bulky to get into tight places without the aid of an olfactory extension tube.

3.3 Outdoor Sampling. Sniffing outdoors raises further complicating issues having to do with flight, the weather, and chemical plumes.

3.3.1 Sampling by flight vehicles. Sampling by flight vehicles involves a mobile sniffer moving rapidly through a relatively immobile atmosphere. Man-made flight platforms for air sampling range from miniature unmanned aerial vehicles (UAVs) [142–145] to full-sized aircraft [146–148]. Beginning in the 1970s, NASA's 5.5 m-wingspan Mini-Sniffers [149] pioneered UAV sampling of the atmosphere at high altitudes. Since then the potential of UAVs

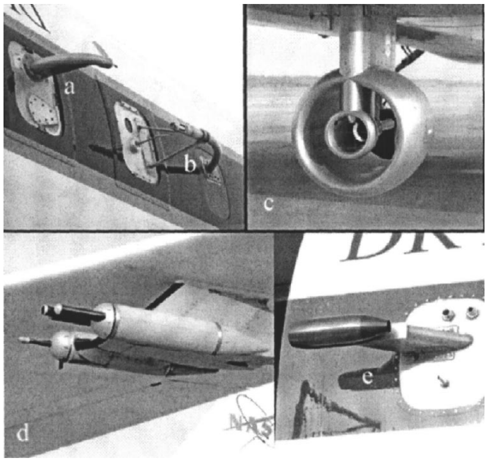

Fig. 7 Sampling inlet probes on the NASA-Dryden DC-8, (*a*) heated, Teflon-lined PANAK probe, (*b*) U. Hawaii shrouded probe [147], (*c*) nacelle-mounted ATHOS probe [146], (*d*) wing-tip mounted aerosol scattering spectrometer probes, and (*e*) shrouded POPS probe (NASA photos)

for biological agent detection has been explored [144,145], and a recent Defense Advanced Research Projects Administration (DARPA) program spawned microair vehicles that could be similarly employed for sniffing [142,150].

In contrast, take the current Intercontinental Chemical Transport Experiment-North America as an example of sampling from full-scale aircraft [151]. Its principal flight vehicle, the NASA-Dryden DC-8, bristles with sampling probes of all sorts. Five are shown in Fig. 7 [146,147]. Most of these feature shrouded inlets to minimize flow angularity effects, after Kiel's original shrouded Pitot probe from the early days of aeronautics [152].

In principle, it appears easy enough to extend a tube through an airplane window and sample the air. Some further design refinements are obvious, like mounting the probe on a strut to get it outside the airplane's boundary layer. For chemical species in the upper atmosphere, though, there is the concern that they will react with the walls of the tube. Particle sampling is an even greater concern: Recalling the Stokes number from Sec. 2.5, when U is hundreds of m/s it becomes hard to prevent particles from impacting inside the probe rather than being conveyed to the instruments inside the aircraft. Likewise the airflow angle with respect to the probe axis is not well known. These issues combine to make airborne sampling probe design challenging.

Wind-tunnel tests [153] are often used to verify that new probe types can achieve isokinetic sampling and deliver a true particle sample. A good reference summarizing inlet probe design for aircraft samplers is [154]. The topic is revisited in Sec. 4.3.13, where we will see how birds solve this problem.

3.3.2 Micrometeorology. In nature, sniffing must take place outdoors under all manner of weather conditions. Sun or clouds; calm, steady, or gusty winds; moisture levels; the temperatures of the air and terrain, all play a role. The broad field of micrometeorology [155,156] is not reviewed here, rather just a few issues pertinent to sniffing.

First, consider the wind [157]. The lowest atmospheric level is a turbulent planetary boundary layer (PBL) that we perceive as wind. Meteorological calm, 2.2 m/s or 5 mph, is still a significant breeze for bioaerosols [107], insects, and even people, whose thermal plumes become wakes at a much-lower airspeed (Sec. 6.3). Sniffers operate in the smallest local regime of micrometeorology, the bottom 2 m or so of the PBL's roughness layer [156]. Even so, ill winds readily disrupt sniffing by dispersing chemical traces [158]. Moths, for example, cannot track pheromone plumes when

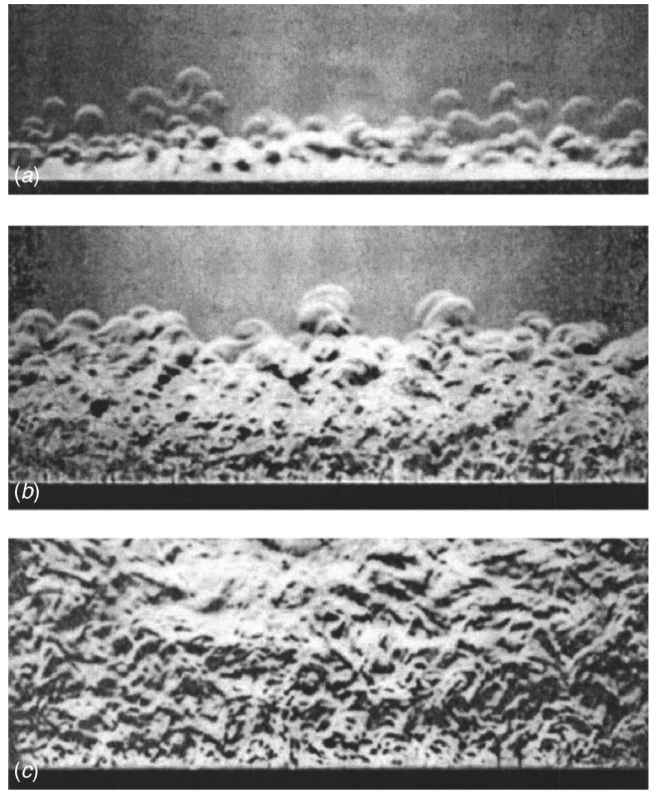

Fig. 8 Schlieren images of high-Rayleigh-number thermal convection from a suddenly heated horizontal surface, simulating the earth at sunup on a windless day, courtesy J. C. Mollendorf [167]. (*a*) Early thermals, (*b*) a forest of starting thermal plumes develops, with both their crowns and stalks visible, and (*c*) fully developed thermal convection field. These pictures compliment those in the literature using tracer-particle visualization. Here an integrated view is shown, though one can imagine the depth effect

the breeze is too stiff [159]. On the other hand wind interactions with obstacles offer opportunities for olfaction, such as sniffing the recirculating flow downstream of a building [160].

Moisture levels are still another matter. Although the effect of temperature and humidity on human olfaction is controversial [59], various investigators [161,162] show that an increased soil moisture level generally aids olfactory trace detection by animals, whether of buried food or land mines. Extreme aridity, on the other hand, may so dry the mucous membranes of a dog's nose as to inhibit olfaction.

Also there is the issue of the buoyant odor-bearing thermal plume [70,155,163–165]. As an example, consider the following landmine detection scenario [125,166]: The surface temperature of the soil varies some 30°C daily, depending on local conditions. This desorbs some trace explosives—where present—from the soil surface over a buried landmine, creating an airborne vapor signal. What becomes of this signal, however, depends on micrometeorology. On sunny days a strong temperature gradient develops above the soil, which can be 40°C hotter than desert air. This produces unstable thermal convection, transporting any desorbed explosive vapor upward and away. Measurements show that typical thermals arise from surface areas of 1 or more m^2, rise at speeds of about 1/4 m/s, and occur at frequencies in the range of 4/min [155]. Visualized thermals (Fig. 8 [167]) show typical mushroom-shaped convection cells. Under such adverse micrometeorological conditions no stable layer of trace explosive can be expected above a buried landmine.

The situation improves, though, from sunset until morning. A stable boundary layer often forms above cool soil in the summer.

Through the night, explosive vapor from buried landmines can accumulate in this layer. Thus mines are most detectable during the evening, night, and early morning in calm weather when the ground is moist.

Given a prevailing wind, however, the situation is dramatically complicated by mixed free and forced convection, both unstationary and fully turbulent. In sunny weather, thermals are sheared horizontally and mixed out by turbulence. A light horizontal breeze, less than 1 m/s, is enough to tilt the thermals over significantly. For higher wind speeds, forced convection dominates and any explosive vapor from a minefield is quickly diluted and transported away in the PBL. Not even trained dogs can locate landmines under such adverse weather conditions.

3.3.3 Chemical plume tracing. This naturally leads to a recent "hot" research topic, chemical plume tracing. The ability to follow tenuous outdoor plumes in nature rewards many animals with food or sex. The fluid dynamics of plumes and how to follow them is thus a part of sniffing as we define it here. It was also the subject of a recent DARPA/Office of Naval Research (ONR) program that funded multidisciplinary studies to understand chemical plumes in nature and to develop artificial plume tracing systems. More details are available in [41,92,168,169].

Briefly, much of the research to date concerned insects in the atmosphere and crustaceans in the ocean. The small-scale plumes these creatures track are nonetheless large enough that the Reynolds number dictates fully turbulent flow. They are highly intermittent, having large scales comparable to the plume width and a cascade of finer-scale eddies [41,170]. They spread downstream and contain streamwise and cross-stream chemical gradients in their mean structure [43,171–174].

An animal's response to this intermittent stimulus is complicated. Insects and crustaceans have sensory appendages that provide them with plume information [42,175,176]. Lobsters, for example, flick their antennules to sample the environment [92,93,177]. Both chemical orientation (chemotaxis) and flow orientation (anemotaxis) are invoked [175,178,179]. Generally upwind progress toward the plume source is modulated by turns and sometimes by "casting" [168,180]. Weissburg takes an overall view of the fluid dynamics underlying this animal behavior [170].

Robots employ such natural plume-tracing principles with varying degrees of success. Man-made chemosensors are currently inferior to natural ones in terms of speed [169], but nevertheless several robotic plume tracers have been developed and tested [41,181–185], including the "Robolobster" [186].

Standoff detection of small localized chemical plumes is a current security concern [48]. Understanding explosive vapor plume dynamics, for example, is helpful in the development of spectroscopic standoff detectors. Such plumes may have very low concentrations of chemical vapor (see Sec. 2.6), but they can be sought and interrogated based on their buoyancy or momentum, which drives the trace chemical transport.

These small-scale plumes are in stark contrast to the huge natural and man-made plumes that have grave environmental and security implications [187]. They are sometimes visibly tagged with particles, as in Fig. 9, but also sometimes quite invisible. Several horrific plume accidents now serve as case studies, including Bhopal and Chernobyl [188–190]. Large-scale computational plume modeling, e.g., [191], is driven by the knowledge that plume-generating weapons of mass destruction are within the grasp of terrorists. Plume dispersion in cities, driven by convoluted local meteorology due to buildings, is especially challenging [192,193].

4 Nature's Sniffers and Biomimicry

4.1 Narial Morphology and Evolution. Almost no one except Negus [194] and Bang [195] has shown enough interest in the external animal nares—the nostrils—to do a morphological study. It cannot be done justice here for several reasons, but at least one can take a peripheral look and open a prospectus for

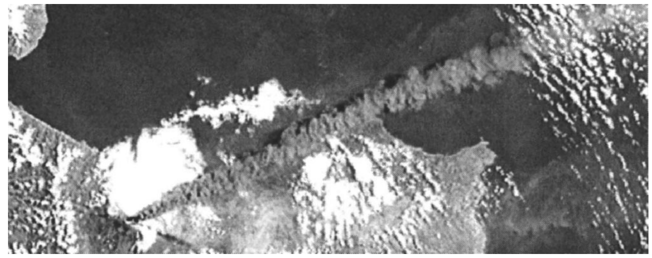

Fig. 9 Satellite photo of the ash plume from the eruption of Mount Etna on October 29, 2002. The plume direction is SSE over eastern Sicily, the city of Siracusa, and the Mediterranean Sea. The lateral scale is roughly 200 km, and the scale of the largest visible eddy (i.e., the plume width) is perhaps 10 km. Photo PIA03733 by the NASA GSFC/LaRC/JPL MISR Team

further study. In that the few fluid-dynamic studies of sniffers conducted to date have yielded interesting results, e.g., [16,32–34,47,65,92,93,176,196], there is clearly more to learn from nature's broad range of sniffing systems. What man-made sniffers have to offer thus far is paltry in comparison.

Here we will examine an abridged but representative phylogenic cross section of the animal kingdom, with at least one example from each vertebrate class (mammals, birds, reptiles, amphibians, and fish), but only examples from the arthropod phylum of invertebrates. Special emphasis is given to the morphology of mammalian sniffers (Fig. 10). Taxonomic and phylogenic information is obtained from [197–200], and anatomical terminology [201] is adopted except for a few common-usage lapses.

Nature, over some 300 million years, has explored animal sniffing systems quite thoroughly. Fossil animal DNA was recently recovered and studied up to about 100,000 years ago; enough to address some far-reaching evolutionary questions and shake up the old phylogeny in places [202]. For example, from fossil mitochondrial DNA and other evidence, the *Canidae* appear to have arisen as a distinct family of carnivores some 50 million years ago [199,200]. Within this family the wolf, dog, fox, raccoon, bear, weasel, and jackal have nearly identical nostrils. The *Hyaenidae* appeared separately about the same time, and are more closely related to the *Viverridae* and *Felidae* than to dogs according to the DNA record [200]. Hyenas nonetheless sport very dog-like muzzles and nares.

Despite all her diversity, though, nature never developed one of our most clever man-made devices: the turbomachine. Bellows action remains the natural way to pump fluids [203]. On this account a small, low-power pump or fan gives artificial olfaction a

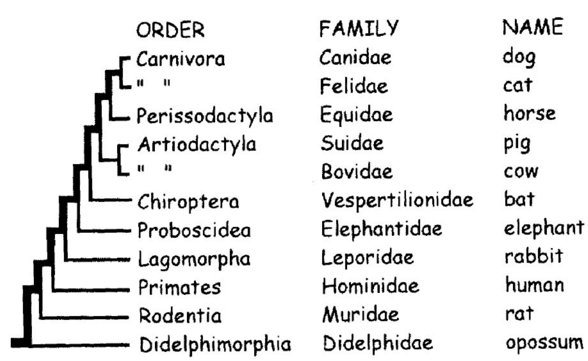

Fig. 10 An abridged phylogeny of mammals for the study of external nares evolution. For brevity the common name is given in place of the scientific species name. Time progresses nonlinearly from left to right for compactness, and branches indicate evolutionary divergences of a group (the lower arm) from the general mammalian stock

certain advantage over nature's devices: It can inhale air continuously and efficiently, and exhale it somewhere else. Even so, when it comes to mimicking nature's olfactory sensors, their fluid-dynamic sophistication and their direct connection to the brain, we are still far behind.

4.2 Biomimicry. T. H. Huxley said "Sit down before fact as a little child, be prepared to give up every conceived notion, follow humbly wherever and whatever abysses nature leads, or you will learn nothing." Biomimicry is innovation inspired by observing nature, learning her lessons and deliberately copying them in man-made devices [204]. Here, for example, the study of narial morphology may lead to better sniffers for the new generation of artificial noses now becoming available. This dual need for fundamental studies of mammalian olfactory systems has been recognized by funding agencies including the U.S. National Science Foundation [205].

4.3 Internal-Flow Noses of the Vertebrates. In mammals and many other vertebrate species, nasal passages lead from the external naris through a maxillo-turbinate region, past the olfactory mucosa—nature's sensor chamber—to the nasopharynx and thence to the lungs [3,206]. Olfaction is further aided in some species by a dedicated olfactomotor system [63] that drives nostril motion during sniffing by way of elaborate musculature.

Every species shown in Fig. 10 is macrosmatic except humans. In two cases, mammals of the same order are compared in order to emphasize diverse narial evolution in closely related species. All species shown are also of the infraclass *Eutheria* (placental mammals) except the opossum, a marsupial, who belongs to the infraclass *Metatheria*.

One must beware here, given nature's penchant for multiple functionality, not to confuse other roles with olfaction. Respiration is intimately connected with olfaction in all of the considered species. Nasal turbinates, for example, are not "turbulators" (mixing devices), but rather air-conditioning devices for heat and moisture exchange [36,206–209]. They provide additional olfactory surface area and generate vorticity even so. Further concern arises in using the fossil record to trace olfactory evolution, since fossils do not preserve the soft nasal tissues.

4.3.1 Dog. The dog's nose is recognized as the gold standard of olfactory acuity. There are many good sniffers shown in Fig. 10, but dogs are easiest to train for olfactory detection. Our closest animal companions, they are the cheerful butt of endless sniffing humor because we cannot appreciate the rich olfactory environment as they can. They are the ultimate mobile, instinctive, intelligent sniffing platforms.

A brief history of canine olfaction research begins in 1938, when it was shown experimentally that the majority of inspired air bypasses the olfactory epithelium, which is offset from the main airway of the nasal cavity [35]. Dawes' experiments [36] then revealed that currents from the main airstream pass freely into the olfactory region during expiration as well. Becker and King [210] likewise found different pathways for inspired and expired air. Neuhaus [211–213], however, was the first to carry out extensive research on canine olfactory acuity in the 1950s. He found that a dog can detect 1 mg of butyric acid dispersed throughout 10^8 m^3 of air, i.e., the volume of an entire town. Negus [194,206] made a broad comparison of olfaction among many species with the dog as chief sniffer. Syrotuck [125] examined canine scenting and tracking in terms of physical and chemical phenomena. He estimated that the detectable "ground scent" left by a human might last 8–16 h. Zuschneid [61] discovered the long canine sniffs. Neuhaus [89] further examined the anatomy of the nasal passages and the role of sniffing in olfaction. Schreider and Raabe [64] showed 29 transverse sections through a beagle's nose, revealing the elaborate scrollwork of the turbinates. Recently Johnston et al. [214,215] and Williams et al. [216,217] developed laboratory olfactometry for dogs and measured the dog's response to trace chemicals (see also Sec. 6.1). Thesen et al. [218] and Steen et al. [219] studied canine olfaction in outdoor tracking experiments. Morrison [62] and Johnston et al. [103] reported basic experiments on the canine olfactory system, including tomography of the nasal cavity and a particle deposition study. Most recently, Settles et al. [47] visualized the airflows associated with the canine external nares during sniffing. Based on this historical record, modern anatomical references now reveal the detailed internal structure of the dog's nose [220,221].

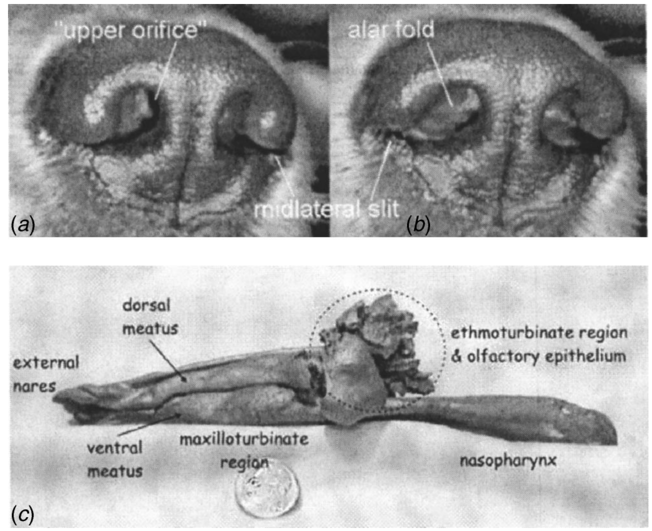

Fig. 11 External nares of a Golden Retriever (*a*) during inhale and (*b*) during exhale portions of sniffing cycle [47], and (*c*) solid cast of the nasal cavity of a dog reconstructed from CAT scans [62] (cast provided courtesy T. S. Denny Jr., Auburn University)

The canine external nares are shown in Figs. 11(*a*) and 11(*b*). Negus [194] first noted that mammalian nostrils give direction to the inspired air, then Stoddart [3] found that the nasal swell body (*alar fold*) just inside the nostril controls the direction of the airflow into the nose. The high-speed video observations underlying Figs. 11(*a*) reveal the opening of an "upper orifice" above the alar fold during the inspiration phase of sniffing. Upon expiration, however, this pathway closes, the nostril flares [Fig. 11(*b*)], and air is ejected ventrally and laterally through the midlateral slits (*nasal sulcae*) [47].

Figure 11(*c*) [62] shows the upper and lower airway (*dorsal* and *ventral meatus*) leading from the external naris into the maxilloturbinate region of the canine nasal cavity. The external naris motion just described, driven by several olfactomotor muscles [220], causes the dorsal meatus to receive inspired air and the ventral meatus to deliver the spent air for expiration. The dorsal and caudal direction of the inspired air channels it directly toward the olfactory region of the dog's nose.

The expired air jets, on the other hand, are vectored by the shape of the "nozzle" formed by the alar fold and the flared nostril wings (*nasal ala*), Fig. 11(*b*). Thus the external naris acts as a variable-geometry flow diverter [47]. This has three advantages: (1) it avoids distributing the scent source by expiring back toward it; (2) it stirs up particles [Fig. 1(*b*)] that may be subsequently inspired and sensed as part of the olfactory process; and (3) it entrains the surrounding air into the vectored expired jets [Figs. 1(*b*), 1(*c*), and 12], thus creating an air current toward the naris from points rostral to it. This "ejector effect," shown in Fig. 12, is an aid to olfaction: "jet-assisted olfaction," in other words.

We also observed that the "reach" of the canine nares during sniffing is up to about 10 cm, though the dog always narrows this distance essentially to zero if allowed. Since the nostril inflow is omnidirectional (Sec. 2.4), the detailed spatial distribution of a

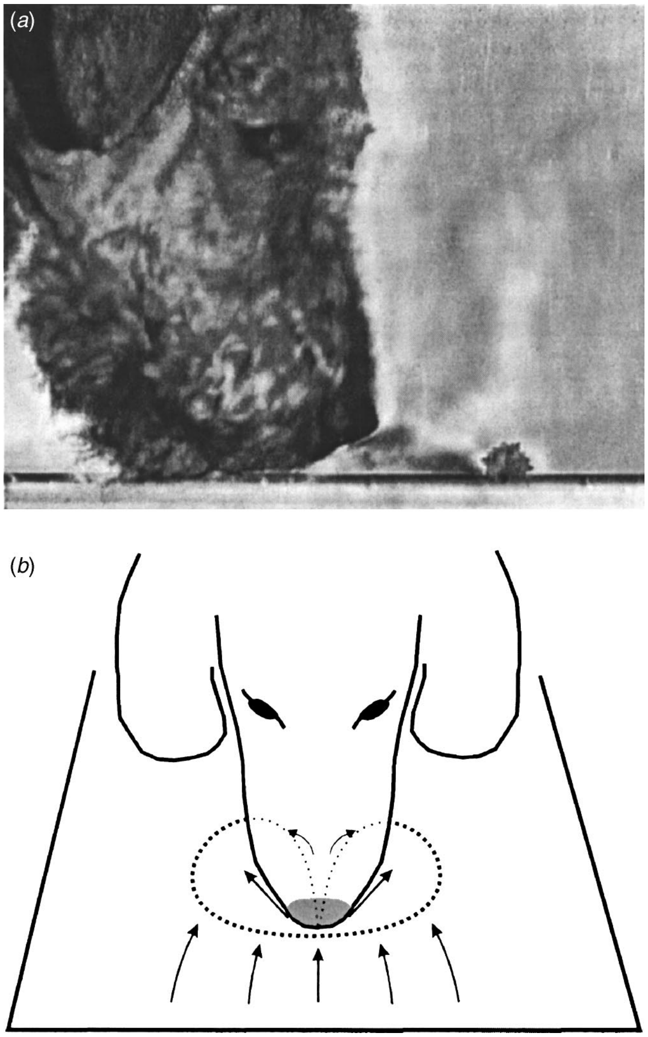

Fig. 12 (***a***) **Schlieren image revealing the "ejector effect" of expired air jets during canine sniffing that draws in air from a warm forward scent source and** (***b***) **diagram illustrating the region of expired jet impact upon a ground plane** (**dotted line**) **and the induced airflow caused by jet entrainment** [**47**]. **See also Fig. 1**(***b***)

scent source is only discernable when the nose is brought into very close proximity with it [47]. Canines [218,222] and other macrosmatic animals [223,224] need to "read" detailed olfactory "messages" such as scent overmarks left by other animals. Their ability to do this requires *proximity sniffing*, and is analogous to our visual reading of text. So, in order to properly interrogate chemical traces it really is necessary for a dog to poke its nose into everyone's business.

Proximity, however, is not required in air scenting of chemical traces borne by plumes, another canine specialty [125]. Steen et al. [219] discovered that an air-scenting bird dog can maintain continuous nasal inspiration for up to 40 s. They propose that open-mouth respiration produces a low nasopharyngeal pressure to induce this continuous olfactory airflow.

Negus [194] suggested that macrosmatic mammals sight down their long snouts to focus upon food they are about to seize. We observed, however, that a dog approaching a scent source on the ground first scanned its vicinity [47]. Instead of aiming directly at the source, the nose was instead lowered to close nostril proximity with the ground before reaching the source [Fig. 12(*a*)]. Then the dog advanced toward the scent source, pausing when the nostrils were directly overhead, sniffing all the while. Often the dog

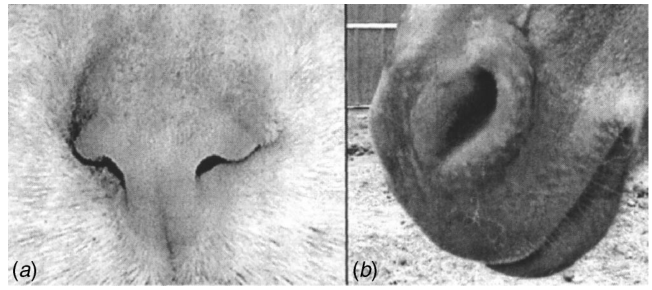

Fig. 13 **External nares of** (***a***) **a domestic shorthaired cat and** (***b***) **a burro, *Equus asinus*, photo by L. J. Dodson**

scanned past the scent source, allowing the expired air jets to impinge directly upon it. Finally the nose returned to a position directly above the source for a few more sniff cycles. This behavior promotes visual as well as olfactory inspection and provides a local survey of the spatial scent distribution. It also disturbs particles in the vicinity of a scent source by the impingement of the expired air jets.

Syrotuck sees this environmental disturbance during sniffing as an aid to olfaction [125]. Morrison examined the uptake of fine ($0.5\ \mu m - 5\ \mu m$) charcoal powder inside the dog's nasal cavity following sniffing [62]. Particles were found predominantly in the anterior nasal cavity ventral to the maxilloturbinates. However, upon vigorous sniffing, particles reached as far into the nasal cavity as the olfactory ethmoturbinates. Moist mucosa are important here, since moisture is the solvent that carries both vapor and particle-borne chemical traces to the olfactory receptors [125]. When the dog's nose is wet and cold, it can act as both a particle and a vapor trap.

Finally, the warmth of the expired canine air jets may act to volatilize latent chemical traces on surfaces. Many biological odors vaporize at or near body temperature, and the vapor pressure of TNT, for example, increases by a factor of 4 between 20 and 30°C [225].

4.3.2 Cat. The cat's nose, Fig. 13(*a*), is in stark contrast with that of its canine relatives. Though macrosmatic, the entire *Felidae* family (ocelot, domestic cat, panther, puma, lynx, Asian leopard cat, caracal, and bay cat [226]) appears to lack the variable geometry and multifunctionality of the canine external nares. While a proper aerodynamic study has not been done, almost no nostril motion is observed when the domestic cat sniffs. Clearly a sophisticated canine-type nostril is not a prerequisite for olfactory ability, even among carnivores.

4.3.3 Horse. The horse *Equus caballus* and its relatives are odd-toed ungulates and prey animals. They have wide oval nostrils and long straight nasal passages allowing a high respiratory airflow rate while running, when dilator muscles cause the nostrils to flare. The nostrils contract upon expiration to produce prominent ventrally-expired jets that are visible due to moisture condensation in winter. Horses sniff to identify food, kin, and sexual status, and to acquire olfactory warnings of the predators that they suspect are lurking behind every bush. Unlike dogs, horses and their relatives have dry rhinaria.

4.3.4 Pig. The swine nose is spade shaped and has several uses. Moulton [207] considers it to be a "chemotactile" organ. Like elephants, pigs use their snouts for tasks that their feet cannot accomplish. The pig nostril inlet orifice, Fig. 14(*a*), is well rounded according to the discussion of Sec. 2.4. In fact, it is a simple flanged bellmouth inlet with a hint of an inverted-comma shape.

4.3.5 Cow. Like pigs, cows are members of the great ungulate prey order *Artiodactyla*, which also includes the antelope, deer,

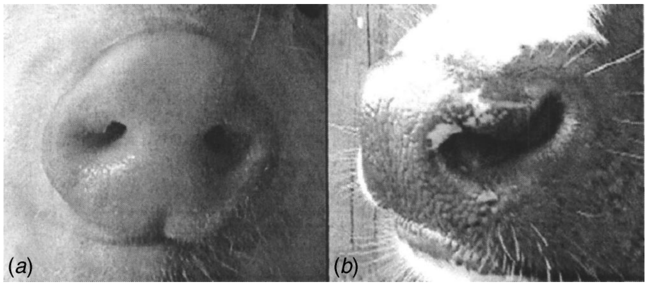

Fig. 14 External nares of (*a*) a piglet and (*b*) a calf, photos by L. J. Dodson

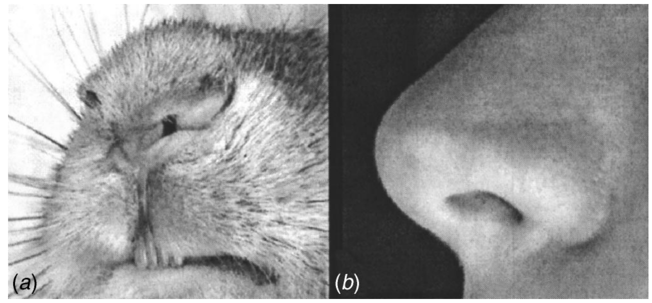

Fig. 15 External nares of (*a*) cottontail rabbit, *Sylvilagus obscurus* and (*b*) human, *Homo sapiens*

goat, sheep, camel, caribou, moose, giraffe, and hippopotamus. Many of these animals have opposed, laterally oriented, inverted-comma-shaped nostrils as seen distinctly in the cow, Fig. 14(*b*). The inverted-comma nostril shape, upon constriction, narrows the air passage to a crescent [194]. This suggests some distant connection with the canine midlateral nostril slit, but in fact none of the prey animals has a nostril of sufficient mobility to modulate the airflow in a canine fashion. At least two ungulates, though, have variable-geometry nostrils for other purposes: The camel's nostrils close to keep out the sand, while the moose's nostrils close underwater [227].

4.3.6 Bat. The bat's naris is some two orders of magnitude smaller than that of the *Bovidae* just discussed. The insectivorous Little Brown Bat, *Myotis lucifugus*, common in North America, has broad nostrils with an inverted-comma shape. The elaborate nose "leaves" of some bat species are for ultrasonics, though, not olfaction. The bat's forwardly oriented nostrils aid olfaction in flight by ram-air sampling. Some bats can discern the edibility of insects they pursue by using "wake olfaction" [3].

4.3.7 Elephant. The elephant's trunk is a unique and celebrated multipurpose chemotactile organ. Elephants are quite macrosmatic even though their external nares and olfactory mucosa are separated by a considerable length of trunk. The trunk not only explores proximity scents but also acts as a periscope for directional air scenting [228]. Other trunk functions include grasping food, drinking, spraying water, respiration, greeting, hand-like tactile operations, trumpeting, and fighting [228]. Its cross section shows two oblong central nasal tubes formed of connective tissue and lined with mucosa. These open into the elephant's nasoturbinates at their posterior extremity [229]. As noted earlier, the elephant is a natural prototype for hand-held wand-type sniffer probes.

4.3.8 Rabbit. Glebovskii and Marevskaya [230] found that rabbit nostril motion, driven by the narial muscles, is directly connected with high olfactory brain activity. Inspiration is accompanied by nostril dilation, reducing airway resistance. "The tip and *alae nasi* move upward while the floor of the nostril sinks." A sharp rise in airway resistance then signals the onset of expiration. Glebovskii and Marevskaya further describe the rabbit narial muscles as "the propriomotor apparatus of the olfactory analyzer." Zwaardemaker mirror tests by Bojsen-Møller and Fahrenkrug [31] showed that expired air is directed ventrally and laterally in the rat and rabbit, as in the dog. The rabbit's nose, Fig. 15(*a*), resembles a cap over a vectored duct. Little else is known about the mobile nostril function of this macrosmatic mammal. A rabbit nostril aerodynamics study along the lines of [47] is certainly called for.

4.3.9 Human. Our nose is retrograde and microsmatic, but heavily investigated. Sources on human nasal airflow include both popular [231] and scholarly [232] accounts, historically significant works [2,233], and recent review articles [5,234–236]. The decline of the primate olfactory genes leading up to humankind is also well documented [237,238]. Though less elaborate than the other animal noses, our nose [Fig. 15(*b*)] is still sensitive, interesting, and comparatively well studied.

Section 3.2.1 described the rising human boundary layer and its particles. We stand erect and our nostrils are directed downward so they inevitably sample this boundary layer, unlike the case of a four-legged animal with a long snout. Expired air jets are directed ventra–rostrally and are usually fast and turbulent, allowing almost no rebreathing of the exhaled air [239].

Keyhani et al. carried out a steady laminar Navier-Stokes solution of airflow into the human nasal cavity with $Re=610$ based on the external-naris hydraulic diameter [240]. Results show that the internal path taken by inspired air depends upon its entry point at the nostril, with only the anterior tip of the orifice supplying the air that eventually reaches the olfactory epithelium. Because of this, 90% of the inspired air is not sampled for olfactory content, as already known from work cited earlier. The flowfield computed by Keyhani et al. was then used to derive an olfaction model [240] that yields the odorant mass flux sensed by the nose and addresses some of the questions raised in Sec. 2.3.

Subramaniam et al. [16] did a similar CFD solution at $Re=1360$ for an inhalation toxicology study. Here, recirculating flow in the nasal vestibule and nasopharynx produced a more-intricate overall flow pattern with even less airflow to the olfactory region.

In vitro flow visualization experiments on human nasal aerodynamics were described in Sec. 2.1. The appearance of turbulence in some of the results [241], however, raises questions about the laminar-flow CFD simulations just described. A low nostril inlet Re does not guarantee laminar flow throughout, especially in such contorted passages, but no turbulent or unsteady CFD results are currently available.

Finally, Sobel et al. [242] study the neurophysiology of human olfaction *in vivo*, finding that it is not the movement of nose muscles that primes the human brain for olfaction, but rather the rush of air up the nose. Differences in the airflow rate between nostrils cause each nostril to be sensitized to different odorants, so each nostril conveys slightly different olfactory information to the brain [242]. Further, sniffing for a scent and actually smelling it activate different brain regions [243], and sniffs are modulated in response to odor content, higher odorant concentrations inducing lower-volume sniffs [63].

4.3.10 Rat. The laboratory rat holds a unique position in science. For reasons similar to those given for humans, we know a lot about rats although, unlike humans, rats are macrosmatic. Lab rats have perhaps 1500 olfactory genes of which only some 20% are "junk" DNA [237].

Human carcinogen response is assessed by two-year, 1/2 million-dollars-each rat studies carried out by the U.S. National Toxicology Program [112]. Extrapolation of the results from lab rats to humans to assess human health risks is problematic, though, given large interspecies differences in nasal respiratory physiology and airway anatomy [16]. Inhalation toxicology nevertheless uses live rats or their nasal molds to measure the depo-

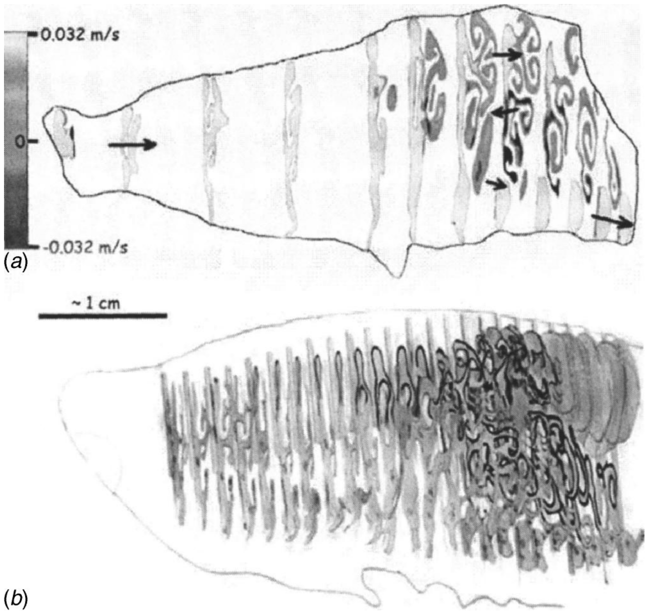

Fig. 16 (*a*) CFD solution of airspeed in the F344 rat's nasal cavity [53,247], courtesy J. S. Kimbell and (*b*) sectional anatomy of an albino rat's nasal cavity with darkened olfactory epithelium [248], courtesy J. S. Kauer

sition of respirable particulates [244–246]. The albino lab rat is thus the key to determining safe levels of human exposure to toxic inhalants.

A CFD solution of the Navier-Stokes equations for the airflow in the passages of a lab rat's nose yields some insight into this process, Fig. 16(*a*) and [53,247]. As in dogs and humans, most of the inspired air bypasses the rat's olfactory zone and exits via the nasopharynx. However, the airstream that actually reaches the sensory ethmoturbinates enters dorsally, reverses direction medially, and finally exits ventrally through the nasopharynx as indicated by arrows in Fig. 16(*a*). Of course CFD only approximates the convoluted geometry of an actual rat's nose, Fig. 16(*b*) [248].

Like the rabbit and dog, the rat has active, variable-geometry external nares. In both ground and air scenting the nose pitches and the nostril twitches [249]. In some rats the external nares flare and the nose hairs (*vibrissae*) move rhythmically, projecting during inspiration and retracting during expiration [3]. The inverse-comma-shaped narial orifice directs expired airflow ventrally and laterally, causing relatively little anterior air exchange [250] and forming two fan-shaped areas of condensation on the Zwaardemaker mirror, Fig. 1(*a*) [31]. A bout of sniffing grows to yield a maximum airflow rate at its conclusion. Youngentob et al. suggest a "sniffing index" describing many characteristics of the rat's sniffing strategy [251]. During a discrimination task, rats suddenly switch from a low (2–5 Hz) sniffing rate to a high rate of 8 Hz–10 Hz for unknown reasons [252]. Here, too, a proper aerodynamic study of external nostril airflows is needed.

4.3.11 Opossum. While dogs and cats diverged from a common ancestor some 50 million years ago, the opossum has not changed significantly in 90 million years. He is both ancient and modern, since he continues to compete effectively with placentals today. His chief current challenge is to stay out of the road.

The opossum has the long, well-equipped snout and multiple turbinates of a macrosmatic animal [194]. The external naris aperture, Fig. 17(*b*), is laterally oriented and not obviously variable in geometry, although there are no known studies of it. Moulton [207] notes that olfactory structures are most prominent among older animals like the opossum, not in the higher primates and

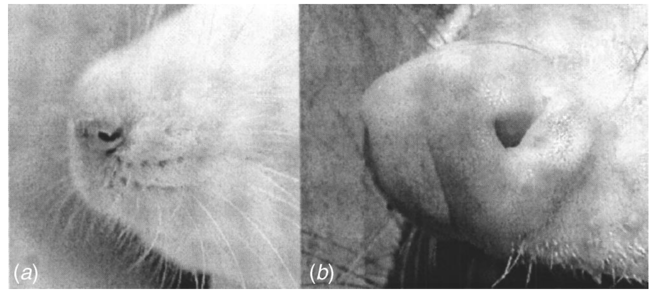

Fig. 17 (*a*) External nares of a Sprague-Dawley lab rat provided by M. J. Kennett, Penn State University and (*b*) external nares of the opossum *Didelphis virginiana*

aquatic mammals.

4.3.12 Fish. Here we leave the mammalia to consider other vertebrates, many of whom have simple immobile external nares compared to those of the dog, rabbit, and rat. Like mammals, fish need their sense of smell for habitat and kin recognition, food, reproduction, and predation avoidance. Detailed accounts of fish olfaction are given by Negus [194], Kleerekoper [253], and Stoddart [3].

The key issue in fish olfaction for present purposes is its separation from the respiratory gill flowfield. Anterior and posterior naris holes or slits supply through flow to a chamber filled with *lamellae* that provide a large sensory surface area (see also Sec. 5.3.1). To overcome the internal olfactory pressure drop, fish use either passive or active water circulation. The former requires relative motion between fish and water, where sometimes a ridge or scoop just aft of the anterior naris assists olfaction by recovering dynamic pressure there while the flow vents to local static pressure downstream. Active olfactory water circulation may be driven by cilia or may occur as an accessory to respiratory jaw motion.

Some fish feature highly specialized naris adaptations. *Polypterus bichir*, for example, has a fluted Pitot-tube-like anterior naris extension [3], while in moray eels both anterior and posterior nares may be extended. Some *Tetraodon* species have their entire olfactory apparatus out on a stalk [253].

Shark olfaction is almost as adept as their ability to generate interest and fear in people. The Great White and many other shark species have flush anterior nares located on the underside of the snout, feeding water to an olfactory chamber of spectacular sensitivity. Sharks track prey wakes [254] by the chemical plume tracing methods described in Sec. 3.3.3. Here is yet another opportunity to study, for the first time, the fluid dynamics of shark olfaction.

4.3.13 Birds. Birds sometimes have only rudimentary sniffing apparatus [3], but in other species olfaction is key to their feeding and nesting behavior, and even to navigation. Airborne sniffing, for example, allows scavengers like the turkey vulture to locate their malodorous meals. Atmospheric trace gases also provide olfactory navigational cues to some birds [255], the young learning prevalent trace gradient patterns at home [256] and then using this knowledge to navigate by olfactory detection of natural airborne volatiles [257].

Many birds have simple round or oval nostril holes in the posterior region of the beak. They also have turbinates [209] that function much like those of mammals. Sometimes the naris is covered by skin or feathers, and often the anterior turbinate protrudes into the orifice [195]. Such obstructions suggest that these species are not keen sniffers.

Only one bird, the highly specialized kiwi, has its nostril orifice at the tip of a long beak like a wand-type sniffer. It probes the soil for worms, so a posterior naris location would be worthless. The beak tip, Fig. 18(*a*), consists of an anterior probe, a longitudinal

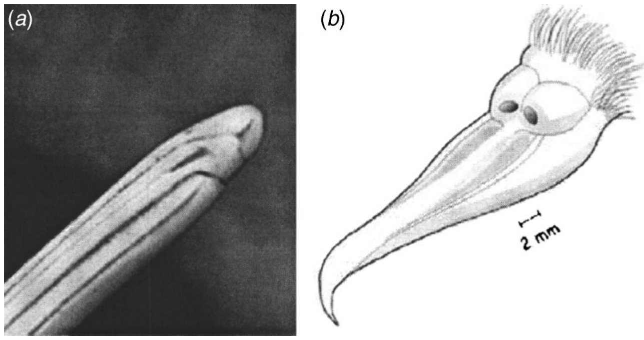

Fig. 18 (***a***) **Close-up image of the Great Spotted Kiwi's beak tip, copyright Chris Smuts-Kennedy, reproduced by permission. (*b*) The upper beak of the tube-nosed Dove Prion, *Pachyptyla desolata*, redrawn from [258]**

slit nostril, and a lower mandible. One wonders if naris plugging by soil and olfactory signal deposition in the long nostril tubes are worrisome to the macrosmatic kiwi.

The *Procellariiformes* [195,258] are seabirds that include petrel and albatross species, all with highly developed olfactory systems and distinct tubular nostrils. They can follow the trace odor of a food source for many km over the ocean. Following the discussion of airborne sampling in Sec. 3.3.1, it is hard for a fluid dynamicist to see such nostrils, Fig. 18(*b*), without thinking "Pitot tubes." These nostril protrusions recover the impact pressure or velocity head $1/2\rho U^2$ during flight, automatically providing a pressure boost to overcome losses in the olfactory system, and doing so without additional effort from the bird. Pennycuick also suggests a related Pitot-tube function—that of an airspeed indicator—allowing the bird to sense and take advantage of gust energy in the separated flows downstream of oceanic wave crests [259]. Procellariiformes tap this unlimited energy source in order to soar almost effortlessly over long distances.

4.3.14 Reptiles and amphibians. Reptiles and amphibians generally have rudimentary olfactory apparatus. Most have only a simple pair of external naris holes flush with the front or top of the head [3]. Olfactory power varies among species, though, and some lizards, snakes and crocodilia are macrosmatic. Waterproof naris closure and "snorkel" nostrils adorn the newt, crocodile, salamander, and frog [3,260]. Frogs even have flap-separated anterior and posterior olfactory regions suited for sniffing in water or air, respectively [237].

Not much is known about dinosaur olfaction, but Witmer [261] places the *T. rex* external naris well forward of its usually-depicted location in order to provide room for a more significant internal olfactory apparatus. Also *Rhomaleosaurus* is believed to have had National Advisory Committee for Aeronautics (NACA)-scoop-type naris inlets inside its mouth, venting externally [262].

4.4 External-Flow Noses of the Invertebrates. Here the sensor chamber of the vertebrates is turned inside out: no chamber at all, just sensor-bearing antenna stalks extending into the surrounding fluid. Treelike sensor structures have evolved in both air and water to present a large surface area for olfaction. The fluid dynamics of these *aesthetascs* has received a lot of recent attention [93,170,176,196,263].

For brevity we consider here the morphology of only a few invertebrate sniffers from the phylum *Arthropoda*.

4.4.1 Crustaceans. Lobster "sniffing" was introduced in Sec. 2.7 in terms of diffusion and in Sec. 3.3.3 in terms of chemical plume tracing. Lobsters have twin antennae with lateral flagella bearing fine sensory aesthetascs, Fig. 19. There are differences in species [41], but in general the antennae are flicked in order to sample the environment [92,93]. This sniffing behavior is governed by the aesthetasc Reynolds number Re which determines "leakiness," i.e., how much water passes between them. This Re tends to be near unity, so the lobster can sample with a fast downstroke and hold the signal with a slower upstroke [176,264]. Péclet numbers are large for these motions, but diffusion acts when the antennae are still.

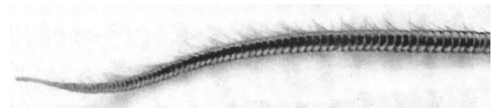

Fig. 19 Lateral flagellum of one antennule of the clawed lobster *Homarus americanus*. Proximal diameter shown is 1.4 mm. Hairlike projections are aesthetascs and guard hairs (out of water and in disarray). See [92] for electron microscopy images

Similar principles apply to other crustaceans, including the crayfish, crab, and Mantis shrimp [41,65,177,196]. These sought-after species take advantage of zones of high mean flow speed, which increases turbulence and degrades a predator's ability to track a chemical plume. Thus fast flows provide a hydrodynamic refuge from olfactory-mediated predation [179].

4.4.2 Insects. Chemical plumes are as important to insects in the air as to crustaceans underwater [168,265,266]. Moths tracing a pheromone plume are the classic example. The same Reynolds number effect on the apparent porosity of branched antennae [90,267,268] arises, though the comblike moth antennae do not flick and are spectacularly different in appearance than those of the lobster (Fig. 20). Some moths respond to pheromone signals by flapping their wings to induce airflow through their antennae without flying [268], an aspect of insect behavior that has already attracted biomimicry [182].

Here briefly consider mankind's worst enemy, that supreme terrorist and chief vector of biological warfare, the mosquito (Fig. 21). With a human death toll of over one million/year, mosquitoes as killers easily outrank all the worst human tyrants combined [269].

Mosquito host location is known to be an insect-sniffing and chemical-plume-tracing issue [168,270,271]. Humans give off a variety of *kairomones*, chemical signals (CO_2, lactic acid, etc.) that attract mosquitoes [272]. The thermal convection currents produced by vertebrates carry these trace chemicals [270,273], and mosquitoes fly upwind to locate their sources [180]. *Anopheles gambiae*, for example, flew an upstream zigzag path in a wind tunnel odor plume [272]. In another study, smelly human feet were a noteworthy mosquito attractant [274].

An important human goal is to interrupt mosquito-host interactions, thus inhibiting the spread of disease [275]. The host-location sensilla are on the mosquito antennae, Fig. 21, and palps [272,276,277]. At normal flight speed a 1-μm-diameter mosquito sensillum hair has a Reynolds number of about 0.06.

An outsider needs extra caution around this intricate topic. There are many mosquito species with different behaviors, for example [272]. Nonetheless some fluid dynamics seems to be missing here, namely: (1) a proper understanding of the human

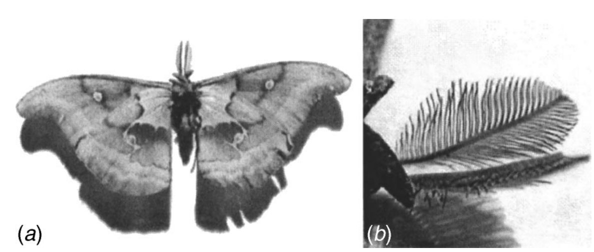

Fig. 20 (***a***) **Giant silkworm moth, *Antheraea polyphemus*, wingspan 8 cm and (*b*) closeup of feathery antennae**

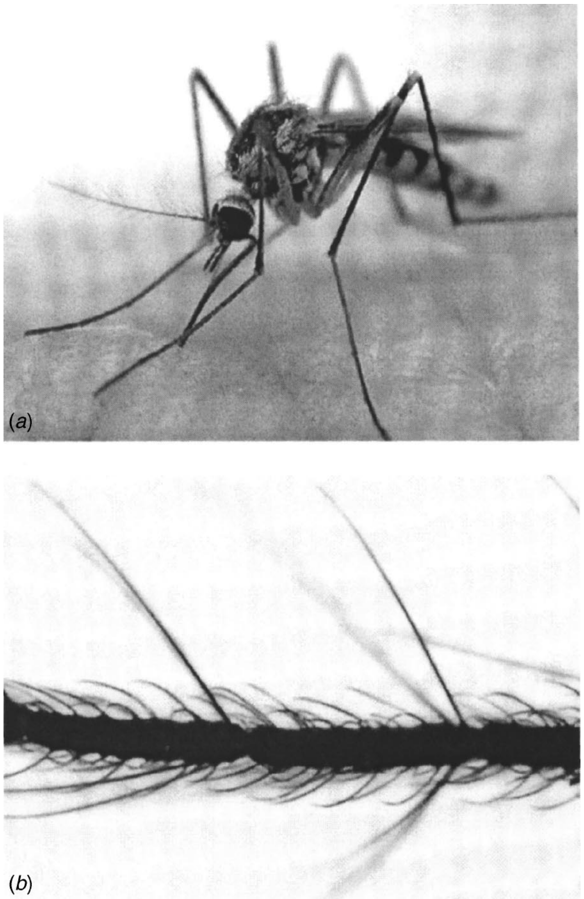

Fig. 21 (*a*) Mosquito feeding on a human hand. Courtesy Philip Myers, http://animaldiversity.ummz.umich.edu. One antennal flagellum is visible. (*b*) Microgram of a mosquito antennal flagellum, about 20 μm in diameter, showing two complete segments, the long *sensilla chaetica*, and the numerous shorter *sensilla trichodea*, photo by J. M. Listak

thermal plume and wake behavior (Secs. 3.2.1 and 6.3.3) and (2) a knowledge of the mosquito's flight envelope and limitations. For example, in one popular book on mosquitoes the human scent plume is said to be heavier than the surrounding air [269]. Normal flight speed is quoted at 1 m/s and maximum speed at 1 1/3 m/s [269,278], yet there is little information on the inhibition of mosquito bites as a function wind speed or host motion. Finally, although our knowledge of insect aerodynamics has benefited greatly from studies of the innocuous dragonfly, where are the parallel studies of mosquito aerodynamics? The mosquito appears to be a fragile insect, all rickety and strung out like a Wright Flyer. If we knew more about her aerodynamics, it might suggest ways to push her beyond her flight envelope.

4.5 Directional Olfaction. Von Békésy claimed directional odor perception if as little as a 10% concentration difference was presented to the left and right human nostrils [279]. Later research questioned this [280], but there is still considerable evidence that at least some animals practice and depend upon "stereolfaction" [3,242,281]. In addition to *chemotaxis* and *anemotaxis*, described earlier, the terms *klinotaxis*, swinging the head from side to side, and *tropotaxis*, stereolfaction via widely-separated naris inlets, are used.

Stoddart [3] suggests that nostril adaptation goes with neck stiffness, and that stiff-necked fish need tropotaxis more than supple-necked land species. Tube-nosed bats appear to use tropotactic olfaction in flight, where turning the head would produce unwanted aerodynamic forces. Dogs practice klinotaxis, moving their heads while tracking or scenting, and probably also anemotaxis based on the differential wind cooling of their wet noses [125,218]. Moulton [207], on the other hand, notes that the close narial spacing of many mammals does not apparently provide a sufficient lateral signal difference to discern an odor gradient by tropotaxis. The myth of tropotaxis due to the widely spaced nares of hammerhead sharks was debunked by Kajiura et al. [282], who found that an anterior groove on the shark's cephalofoil integrates the olfactory input, thus providing no more tropotactic separation than that of any other shark species.

Finally, Atema [42] demonstrated that the lateral separation of lobster antennae is sufficient for "eddy chemotaxis" in turbulent odor plumes. He also found that the sharpness of odor peaks in passing eddies can provide "odor landscape" information about the lobster's location relative to the plume's source.

5 Artificial Olfaction

5.1 Artificial (Electronic) Noses. Artificial noses are devices featuring several nonspecific odorant sensors interrogated by a pattern-recognition system in order to identify a broad range of odorants [9]. This definition excludes specific sensors like gas leak detectors and mass spectrometers, but these will also be considered later. Still very much a work-in-progress since they were introduced a few decades ago, artificial noses already augment limited human olfactory skills by being less subjective, and they may even supplant the trained canine sniffer someday by having similar sensitivity but being willing to work longer hours.

5.1.1 Overview of current artificial noses. Gardner and Bartlett [9] give a brief history of electronic noses and a discussion of current commercial devices. Similar overviews are found in [283,284], while Yinon [285] summarizes "e-noses" for explosive detection. Artificial noses currently have nonspecific sensors based on a variety of principles including quartz microbalances, surface acoustic wave (SAW) technology, capacitance, metal oxide semiconductors, calorimetric or amperometric sensors, and photopolymers.

Most of the present commercial devices are ponderous benchtop analytical instruments that do not sniff and are not considered further here. A few portable or handheld noses deserve further attention, but most of them also lack any real ability to sniff. Only the Smiths Detection Cyranose [286] has both an internal sampling pump and a wand-type inlet with a flared end that can be considered a sniffer. The Applied Sensor VOCcheck and Microsensor Systems Vaporlab handheld e-noses have pumps but no sniffers (apparently only fittings are provided for direct connection to an odor source).

The Nomadics "FIDO" artificial nose can be either handheld or wand-mounted (for landmine detection) [287]. Ambient air is drawn through the sensor, after which there is a clean-air purge. A similar prototype device employs a small vacuum tank to sniff air at ground level [288]. The Z-nose [289] uses SAW and gas-chromatograph technology in a hand-held sensor with a 10 s sampling time. Gelperin's e-nose [290,291] inhales the air surrounding an object through a perforated platform located over a sensor array.

The Tufts Medical School/CogniScent Inc. Scentinel [6,292,293] is not yet a commercial device, but is nonetheless notable for the biological inspiration behind its sensors and its pattern matching [294]. Moreover it is a true sniffer with a snout, a flanged inlet and a through-flow sensor chamber. It can even inhale and exhale like an animal.

5.1.2 Related nonartificial-nose handheld detectors. A popular and useful nonartificial-nose detector for explosives, drugs, and chemical agents is the ion mobility spectrometer or IMS [295,296]. At least two commercial handheld devices are available, the GE Security VaporTracer, Fig. 22, and the Smiths Detection Sabre 2000. Both have internal pumps to acquire air samples,

Fig. 22 The GE Infrastructure Security VaporTracer sniffing a briefcase

but the volume of air that an IMS can directly accept is only some ml/min. A third IMS device, the Implant Sciences Quantum Sniffer, takes a different approach discussed in Sec. 5.2.4.

The Sandia Microhound [297] uses a micro-IMS and a SAW sensor, and inhales air through a flanged inlet. The Mesosystems Biocapture [298] impacts and liquefies samples for analysis, but details of its sniffer are not available. Finally, two Thermedics Inc. patents [299,300] describe handheld shrouded sampling guns that apply heat and air-jet puffers to surfaces, then inhale air across a preconcentrator. These devices are without any known commercialization.

5.1.3 Desired characteristics of sniffers for artificial noses. Ideally an optimum sniffer ought to:

1. Have sufficient "reach" to acquire the desired explosive trace signal without physical contact,
2. Localize the scent source (except for those special sniffer types designed to sample broad areas like the sides of vehicles),
3. Display immunity to ambient conditions, especially the breeze,
4. Have simplicity, mobility, light weight, small size, and reasonable power requirements, and
5. Have the ability to disturb surface environments enough to dislodge and collect particles as well as vapor traces.

5.2 Airborne Trace Sampling for Artificial Olfaction.

5.2.1 Headspace sampling versus sniffing. In most benchtop instruments of analytical chemistry, including the majority of commercial e-noses, the saturated vapor above a sample in a container is drawn by carrier gas through tubing into the input of the instrument. This is headspace sampling [301], and while it is essential in laboratory practice, it is distinct from aerodynamic sampling—sniffing—as defined here. Few animals have the luxury to squat on a lab bench, have odor samples delivered to them, and suck the samples through a straw.

5.2.2 Particles versus vapor. There is a controversy in explosive detection circles over whether one actually detects particles or vapor traces or both. A key paper on this topic is Davidson and Stott [302], who draw a distinction between volatile explosives (vapor pressure higher than nitroglycerin) and nonvolatiles: vapor detection of nonvolatiles usually depends upon solvents, impurities, or breakdown products, whereas the vapor of volatile explosives like tri-acetone-tri-peroxide (TATP) is directly detectable. Such volatile vapors are readily adsorbed, however, by such things as the packing materials found inside cargo containers.

In general we should be ready to sniff and detect both particles and vapors, since they provide complimentary information about the odorant source. Particle sampling is the more difficult of the two, but it has the advantages of larger signal levels and of indicating the actual chemical species, not just its vapor byproducts.

Approaches to resuspend particles from surfaces include mechanical agitation and vacuuming, swabbing, vibration, thermal desorption, shock waves, pulse-pressurization, and jet puffers (Sec. 2.5). Wrapping and handling an improvised explosive device, for example, is likely to generate a particle field that may be detectable even if the vapor of the explosive is not [303,304].

Griffy's calculation [94] was mentioned in Sec. 2.7 with a caution about giving up on vapor detection. Vapor diffusion is a slow process, but some sniffers can get in such close proximity to an odorant source that they can get a good sniff even so. Further, vapors are readily transported in thermal plumes [48].

On the other hand, given the extremely low vapor pressure of explosives like pentaerythritol-tetranitrate (PETN) and RDX, it is certain that particles, however small, play a role in the detection of these substances by sniffing. Nonvolatile explosives strongly adsorb to solids [305], including the ever-present airborne particles in the human thermal plume (Sec. 3.2.1).

5.2.3 Preconcentration. Preconcentration and the "impedance mismatch" were introduced in Sec. 2.3, while impactors were described in Sec. 3.1. How it is done in practice, though, deserves a little further elaboration.

Traditional preconcentration methods of analytical chemistry involve passing an air sample through a permeation tube filled with a sorbent material, such as activated charcoal, silica gel or Tenax™. That material is subsequently thermally desorbed to release trapped chemical traces [306–309]. Personal samplers, Sec. 3.2.2, often work this way. But given the small size and high pressure drop of a typical sorbent tube, this approach is slow and ineffective for high-flow-rate sniffing.

Membrane filters can serve the same purpose as permeation tubes and can be desorbed in a similar fashion [13,101,310], but are likewise not suited for high flow rates.

A third approach, more adaptable to rapid sniffing of larger air volumes, is to collect the trace odorant on a metal surface in a flow-through preconcentrator [310–313]. Depending upon the odorant, various treatments can be applied to the metal to enhance molecular or particle deposition. The metal can then be heated electrically to quickly desorb captured traces. A secondary carrier gas flow is needed during desorption, when the main airstream either stops or is shunted away. Cold metal surfaces especially attract trace chemicals like explosives, but moisture condensation is an associated problem [314].

When the desired airborne trace material is in particulate form, impactors or cyclones (Sec. 3.1) make suitable preconcentrators. For example, biological pathogens like spores and bacteria are usually impactable, as are explosives or chemical agents attached to human skin flakes or textile fibers. Virtual impactors preconcentrate such particle-laden airstreams by discarding most of the airflow while keeping the particles.

5.2.4 Jet-assisted olfaction. One of nature's lessons (Sec. 4.3.1 and Figs. 1 and 12) is to put exhaled air jets to work assisting the sniffing process. Thus the dog and probably the rat and rabbit can disturb surface particles, inhale them, and desorb odorants from them in the nasal mucosa—a natural preconcentration system.

How can we use this knowledge in a man-made sniffer? Since respiration is unnecessary, auxiliary air jets adjacent to the sniffer inlet are required to disturb surface particles, as first suggested by McGown, Bromberg, and Noble [299]. Beyond that, though, it was also shown in Sec. 4.3.1 that the dog's exhaled jets produce an ejector effect that can improve the reach of the sniffer. Extended reach is just as important for man-made sniffers, since proximity sniffing is not always possible and is occasionally even dangerous.

At least two schemes are available to extend the reach of a sniffer, the first borrowed from the field of ventilation. C. P. N. Aaberg [315] invented an elegant inlet reach extender using auxiliary jets, Fig. 23. The central inlet, facing downward in the figure, takes in flow rate Q_i while an additional airflow $2Q_j$ at above-ambient pressure discharges laterally forming turbulent jets. The

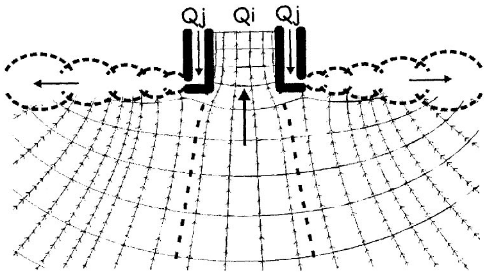

Fig. 23 2D potential-flow simulation of an Aaberg inlet

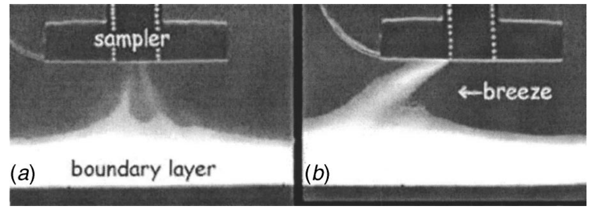

Fig. 25 Schlieren photos of a flanged inlet sampling a thermal boundary layer (*a*) in still air and (*b*) with a light lateral breeze from the right [47]

jet entrainment makes this device appear to be a much larger inlet with an extended reach, but only the central streamtube between the vertical dashed lines is actually taken into the inlet. Thus the otherwise-omnidirectional potential-flow inlet is effectively focused toward the forward direction by jet assistance.

The ventilation community has embraced this concept for local fume exhaust (usually axisymmetric rather than planar as in Fig. 23), and several studies are reported [316–319]. The ratio of the jet to inlet momentum flux is found to control the reach, which can be several times that without jets [320]. This jet assist is not free, but is well worth it in the exhaust of welding fumes, where the extended reach avoids having the inlet in the welder's face.

The Aaberg principle has never been applied to chemical trace sniffing and is suggested here for the first time. It has the advantage that the large volume of air that must be moved in order to achieve a long reach is not all inhaled, thereby reducing the preconcentration chore.

The second jet-assisted sniffer scheme is that of Motchkine, Krasnobaev, and Bunker [96]. Here the auxiliary jet flow is passed through tangential nozzles or vanes to produce swirl between the inlet (right) and the surface being sampled (left) in Fig. 24. On the centerline of this "cyclone" a sampling orifice withdraws a flow rate Q_i. According to [96] "The cyclonic motion…creates a tube consisting of a wall of moving gas that behaves like an extension of the tube that formed the external sampling orifice." No mention is made of a vortex core, but data are shown indicating a favorable pressure gradient along the centerline from the sampled surface to the sampling orifice over separation distances up to 15 cm. This jet-assisted inlet is used in the Implant Sciences Quantum Sniffer, a commercial IMS detector that was developed under U.S. Navy funding.

5.2.5 Isolation from ambient wind. All of the sniffing inlets discussed thus far, whether jet assisted or not, are subject to disruption by a lateral breeze. The effect is shown qualitatively in Fig. 25, where a mild breeze interrupts the sampling of a boundary layer by a simple flanged inlet [47].

In the animal world, the only remedy for this is proximity: If your nostrils are touching the sampled surface, then the wind is not an issue. However, practical considerations require man-made sniffers to have a finite standoff distance and no hard contact (especially in landmine detection).

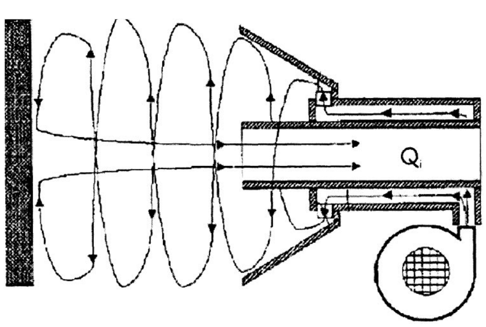

Fig. 24 Diagram of a cyclone sampling nozzle for an ion mobility spectrometer, from [96]

No real solutions to this problem are available, just a few ideas. Baturin, [17] Chap. 6, for example, describes a method to estimate inlet streamlines in a crossflow. No remedy is given other than increasing the inlet suction. Likewise shrouded probes are effective against cross flows in flight and wind tunnels, Sec. 3.3.1, but are not a cure for the present difficulty.

One approach that might work is a "soft" shroud made of rubber, brush fibers, screen, or porous filter material. To succeed, the lateral pressure drop across it must balance the dynamic pressure of the crossflow. Experiments by Cant, Castro, and Walklate [321] reveal that high-porosity screens have little effect, whereas low-porosity screens act like solid surfaces to the crossflow. Near 50% porosity, interesting things happen.

An air curtain [322] has also been suggested for this purpose. It might succeed if its entrainment can be made to serve the purpose of jet-enhanced olfaction described above; otherwise it is likely to exacerbate the problem.

In any case, aerodynamic sniffer isolation from the effects of an ambient breeze is an important topic for further research.

5.2.6 Signal loss in sampling tubes. Signal loss in sampling tubes is an analytical chemistry concern that carries over to the present topic. Most animals have short sampling tubes, the elephant and kiwi excepted. Man-made tubes cannot be inert to all trace chemicals, and explosive molecules, for example, adhere to Teflon, glass, Pyrex, quartz, nickel, stainless steel, gold, platinum, copper, fused silica, aluminum, and plastic [307,310]. Heated transfer lines are used to avoid such deposition except when particles are being transferred [302]. In that case there is also the concern that particles will impact and stick to tubing walls downstream of bends, etc. [13,57,323].

5.3 Sensor Chamber Fluid Dynamics for Artificial Olfaction. Sensor chamber fluid dynamics is virgin territory: only one previous investigation is known [324]. Insofar as all present artificial noses carry their olfactory sensors internally like vertebrates, we consider only that case here. Further, we avoid the confusing multifunctionality of the mammalian nasal cavity (olfaction+respiration+air-conditioning) by examining the separate olfactory chambers of fish. Reynolds number scaling allows us to move freely between air and water in this regard.

5.3.1 The eel as a role model. Specifically, consider the common freshwater eel, *Anguilla anguilla*, as a role model for sensor chamber fluid dynamics [3,40,253,325]. As shown in Fig. 26, a simple anterior naris on the left leads directly onto the medial passage of a chamber packed full of olfactory lamellae. Acting as flow turning vanes as well as sensor surfaces, the lamellae direct the water laterally and ventrally (into the page). Cilia induce rotation between the lamellae as shown, bringing the flow up along the sides of the chamber to its roof, where it is collected and discharged out the posterior naris.

This highly three-dimensional flow encounters a large sensory surface, ensures that the entire flow is thoroughly sampled, and

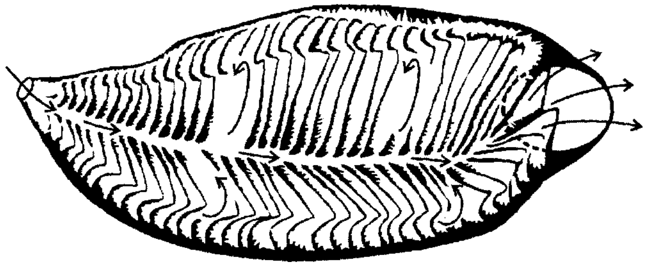

Fig. 26 The path of water through the olfaction chamber of an eel, top view, redrawn from illustrations in [40,253,325]

does it all in a compact volume. (The scale shown is at most a few centimeters, but could be an order of magnitude larger in air at the same Re.) This compactness is an asset to the animal and it provides a quick olfactory response time. Artificial nose designers can scarcely find a better natural example than this.

Though air-breathing vertebrates favor turbinates over lamellae, this sort of olfactory sensor chamber is nonetheless broadly characteristic of all vertebrates. According to Stoddart [3], "There is an inlet to, and an outlet from, a chamber in which is held a thin sensory membrane of sometimes immense area."

5.3.2 Pressure losses, fans, and pumps. In Sec. 2.3 the flow losses in a sensor chamber and the energy required to overcome them were introduced. These pressure losses need to be frictional, as required by the analogy described below, not due to flow separation. Separation losses do not arise from effective olfaction, just bad design. Principles of good design can be found, for example, in [326,327].

In artificial olfactory systems a pump or fan supplies the motive power to overcome losses and induce a flow through a sensor chamber [14]. Such a device produces its maximum overall pressure differential (head) when there is no flow, thus no loss through the sensors. As the flow rate (capacity) Q through the sensors rises, the pump or fan's ability to sustain a given pressure differential drops. Where the two curves meet is the operating point of the olfactory system. Every undergraduate fluids engineering student learns to draw such head/capacity curves for pumping systems. Designers of artificial noses should learn to draw them too (see, e.g., [49]).

5.3.3 Expansion of a sensor chamber from a small inlet. What limits how fast the eel's olfaction chamber in Fig. 26 expands in area downstream of the tiny anterior naris? Lighthill [7] first considered this issue in terms of the branching of the arteries and bronchial tubes. Briefly, the area increase slows the flow and raises the static pressure, so except at low Reynolds numbers there is a danger of flow separation. Lighthill's rule-of-thumb to avoid this allows no more than a 20% increase in flow cross-sectional area per channel bifurcation. At least in the arteries, nature seems to obey this rule. Cross-sectional area data are not available for the eel's olfactory chamber, but are available for the comparable case of a beagle's nose [64]. These data show that the maxilloturbinate region expands about linearly in cross section to seven times its initial area over a downstream distance of only 35 mm. According to Lighthill's rule, a bifurcation should occur initially every mm or so to prevent separation. This is hard to check with the available data, but it is clear that the maxilloturbinates burgeon with branching complexity in this region. Thus separation prevention goes hand-in-hand with the need for large heat-exchanger surface area in the beagle's maxilloturbinates.

5.3.4 Heat and mass transfer analogy. Osborne Reynolds (1842–1912) recognized that mass, heat, and momentum are transferred by similar physical mechanisms (molecular motion in laminar flow, eddy motion in turbulent flow). The analogy between these fluxes—Reynolds analogy—is useful in sensor chamber design, where a high mass transfer rate of odorant molecules to olfactory surfaces is desired. Concomitant momentum transfer by friction is required by the analogy, and heat transfer may also occur. Thus odorant mass transfer is related to the fluid power required to overcome sensor-chamber friction losses. The empirical relations describing Reynolds analogy are well-known and readily available, e.g., [91,327,328], and do not bear repeating here.

The utility of Reynolds analogy in sniffing for chemical traces was first recognized by Fraim et al. [311], who designed an explosives preconcentrator based on heat exchanger technology. In modern microelectronics, strong thermal generation occurs in a small confined space and must be removed by a fluid flow. The analogy with an olfactory sensor chamber is obvious from the above, so we can learn design principles from the volumes that have been written on electronics cooling, e.g., [21,22,327,329].

Finned heat exchangers expose large surface areas to the flow for efficient heat transfer, a principle already in use in nature in the nasal turbinates, as well as in the air-conditioning industry [91]. One must make sure the flow is along the fin channels and not across them, or the process becomes stalled. For flow in odd-shaped ducts the Reynolds number is based on the hydraulic diameter $D_h=4A/P$, where A is the cross-sectional area and P is the duct perimeter. Loss coefficients are known for many situations, e.g., discharging the flow abruptly from a small tube into a large chamber (which dissipates one velocity head, Sec. 2.3). Loss formulas are likewise known for screens, grids, protuberances, and rough channel walls.

In particular, the stacked eel lamellae of Fig. 26 are strikingly similar to the finned heat sinks used to cool electronics [21]. Heat-sink design principles encourage low flow speeds to minimize the pressure loss for a given performance level. Straight fins are shown to outperform other fin shapes (e.g., cylinders) [327]. Fins and lamellae should also be aerodynamic, with rounded leading edges and tapered trailing edges.

6 Homeland Security Applications

Down through the ages, civilization only flourished in enclaves sufficiently well-defended to prevent the ravages of barbarians. The terms "homeland security" and "terrorism" were not popular then, but the results of a security failure were nonetheless devastating. Fluid mechanics has been important in homeland security all along, providing standoff barriers against invasion, weapons technologies, mobility, etc. [330].

Many believe that the modern solution to the asymmetry of the terrorist threat lies in technology. Here we discuss a piece of that technology that concerns gaining information by detecting chemical traces in the air or water. Like the prey animals discussed earlier, we need constant environmental awareness but, unlike them, we cannot sleep standing up.

Homeland security thus requires continuous environmental monitoring. The unusual, however minor, can be a crucial warning of an impending attack. For example Carranza et al. [331], while monitoring the atmosphere for heavy metal traces, noticed a magnesium spike on the July 4th holiday—not terrorism that time, but it could have been.

6.1 Canine Detection. So much has been written about training dogs for chemical trace detection that it serves present purposes merely to cite some key references and give a brief commentary.

Much of the scientific basis of canine detection was learned recently at the Auburn University College of Veterinary Medicine, Auburn, Alabama [66,332,214–217]. There, operant conditioning experiments yielded sensitivity curves like those of Fig. 27, that quantify the threshold levels of specific trace chemicals that dogs can detect. These data also set the sensitivity standard for artificial noses, a standard that has already been exceeded in at least one case [292].

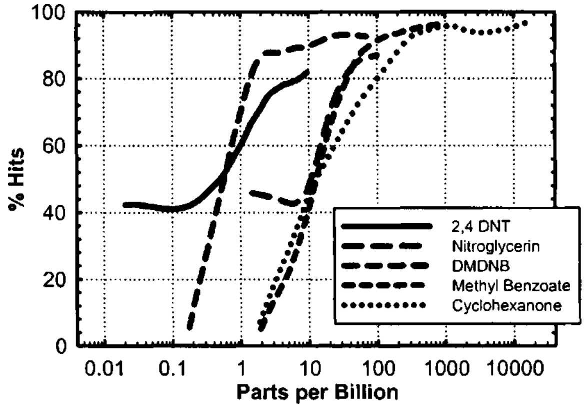

Fig. 27 Canine olfaction sensitivity curves measured at Auburn University, redrawn from http://www.vetmed.auburn.edu/ibds/. Except for methyl benzoate, a cocaine derivative, all trace chemicals shown are explosive-related

Extraneous odors present while sniffing can interfere with a dog's ability to detect a scent and can therefore raise the thresholds shown in Fig. 27, but to do so requires a comparatively enormous extraneous odorant level [217].

Dogs respond to the most-volatile compounds present in an explosive, not necessarily to the explosive species itself. For example in detecting C-4 plastic explosive, the dog is not likely to respond directly to the explosive component RDX, which has a very low vapor pressure, but rather to compounds like cyclohexanone, a solvent used in RDX production [215,216,333].

Gazit and Terkel report [334] that heavy exercise interferes with a dog's olfactory ability, since the dog cannot sniff while panting. They also use a microphone to pick up the sound of sniffing, which provides useful feedback to the dog handler [335].

While handlers have commented on the most desirable traits of their dogs [336], the desirable traits of handlers appear to need more work [332,337]. Being the brains of the team, the dog handler has a responsibility to be aware of the issues discussed here, such as human skin flakes, chemical plumes, micrometeorology, and the aerodynamics of air and ground sniffing. Syrotuck [125] should be required reading. Thermal plumes can also sometimes be visible to the unaided eye of the handler [46,48,338]. These fluid-dynamic issues might well be illustrated in a training video for dog handlers.

Despite the issues of expense and limited duty cycle, canine trace detection is a trusted mainstay of homeland security that will not soon be replaced by artificial nose technology. Furton and Myers [333] found that detector dogs still represent the best explosive detection means available, since artificial sniffers suffer from poor sampling systems, interference from masking odorants, and limited mobility.

6.2 Cargo Screening. Cargo screening has become politicized because of the high cargo volume crossing national borders and the extreme measures that are needed to screen a significant fraction of it for explosive, chemical, or biological weapons. Air, sea, rail, and truck cargo are all at risk. Methods that rely upon radiation to probe cargo containers are cumbersome and expensive, detection dogs do not have access to cargo interiors, and manual unloading for inspection requires far too much time and labor to be practical.

Still, sniffing the air inside cargo containers—without opening them—for trace contraband is an approach that can be both effective and affordable, and there is a precedent for it. Fine et al. [339], for example, patented a method to do this by injecting compressed air into a cargo container, applying suction, collecting the sampled air in a hood, and interrogating its contents for trace chemicals.

Another example is the MDS Sciex CONDOR system, which searched cargo containers for explosive traces using a suction probe fitted with a brush that fed an adsorption cartridge with an airflow flow rate of 25 liters/s [340]. The interior of containers or the exterior of cargo pallets was sampled by contact with the brush for about 30 s, whereupon the cartridge was removed and desorbed into a mass spectrometer. Cargo containers were also sampled through their ventilator ports or through a 10 cm array of drilled holes that ended up not being acceptable to the cargo industry [302]. This substantial system employed a 9 m heated sampling line and applied mechanical agitation even to full-sized sea containers. Inside the container they found a gradient of particle dispersion leading up to the source [302]. Trace contamination was even detected in some containers not holding any bulk explosives: Once upon a time Kilroy had been there.

Still another approach to cargo sampling is the British Remote Air Sampling for Canine Olfaction (RASCO) system [341,342]. A probe inserted into a cargo container pumps out a volume of air through a polymer mesh sample canister that is later presented to a detection dog for analysis. Sixty liters/min are drawn through the canister for 2 min. Success appears to depend upon a significant explosive vapor headspace inside the container. A related general discussion of collecting and transporting chemical traces in evacuated flasks, canisters, sampling bags, and sorbent canisters is given in [306]. If you cannot get the proboscis to the signal, take the signal to the proboscis.

Jenkins [343] patented a method to interrogate baggage by placing it in a compartment provided with vacuum and vibration. Airborne chemical traces thus liberated are drawn into a detector. A recent adaptation of this approach to cargo trace detection is the Ray Detection Discovery CERT system [344], which uses heat, pressurization, vibration, and gas jets to dislodge explosive traces from palletized air cargo in an airtight enclosure.

Finally, research on cargo trace detection is currently under way at Penn State, University Park, PA [345], funded by the U.S. Transportation Security Administration. The goal is to understand the internal airflows of cargo containers and to sample these flows for trace detection without opening the containers.

6.3 People Sampling. People sampling is a unique topic in all of chemical trace detection. Aircraft passengers are aware of the danger of terrorism, but are also very sensitive to the invasion of their personal space. A NRC study of passenger screening found that there is a strong relationship between public acceptance and the perception of risk [346]. It nonetheless irks passengers to wait in long lines, parcel out their belongings, and take off their shoes. Being sniffed by a dog is particularly offensive. People-sniffer developers need to be aware of these issues, just as terrorists are surely aware of them. But despite all this, the total U.S. annual people-screening outlay is expected to grow from $590 million in 2001 to $9.9 billion in 2010 [347].

Hallowell [348] reviewed the available technology for people screening in 2001. Since then several approaches have seen further development. One study recommended that research into the "vapor space" surrounding a suicide bomber might lead to improved means of detection [48]. Misconceptions about that space and its true nature—the human thermal plume—were described in Sec. 3.2.1. Here we discuss recent people-sampling developments in light of what is now known about the aerodynamics and heat transfer around people.

6.3.1 Human olfactory signature. The human olfactory signature was pioneered as a topic of study by Dravnieks [314,349]. Human scent arises from bioeffluents and from bacteria acting upon the skin and its secretions [125]. People also carry with them an olfactory image of their recent environment [222,314]. Any successful scheme to detect trace chemicals on people must take account of this olfactory signature and its conveyance by the human thermal plume and wake.

Dravnieks developed a "body tube" sampler to acquire chemical trace signals from people [349]. Bethune et al. [350] and May and Pomeroy [126] used similar "dispersal chambers" for bacteriological studies of human subjects. Such enclosures are only practical for people-sampling in the lab, but they have been instrumental in contamination studies [351,352] and in aviation security research leading up to the present portal technology [123,124,353,354].

There is anecdotal evidence that artificial noses were deployed to detect troops in the Vietnam jungle, and more recently in the caves of Afghanistan. Building upon genetic research with mice, the current DARPA Unique Signatures program seeks an exploitable chemosignal corresponding to an individual's genetically determined odor type. If found, it will be used to develop a detector for the presence of "high-level-of-interest individuals within groups of enemy combatants."

6.3.2 Portals for screening people. Portals for screening people have generated many patents, e.g., [355–358], but only a few practical devices. Some of the approaches that failed include "wind-tunnel" portals that moved massive amounts of air, "saloon-door" portals that required physical contact with subjects, and "telephone-booth" portals that were too confining or too slow. During the development of these devices a goal of 6 s/person sampling time was set by the U.S. Federal Aviation Administration (FAA), but was difficult to achieve.

General reviews of people-screening portals are given in [348,310]. The role of air jets was described earlier in Sec. 2.5, and related material on explosive trace standards and computations of the human thermal plume is found in [130,359–363].

The first published investigation of portal aerodynamics is probably Schellenbaum [364], who examined various airflow directions in tube-type and booth-type portals. He used a department-store mannequin (see Sec. 3.2.2), so his results take no account of the human thermal plume. He recommended a downward airflow over the subject with collection at foot level.

Hobbes and Conde [365] studied the aerodynamics of an "open-clamshell"-type portal by CFD simulation. This portal drew a large flux of air—350 liters/s for 10 s—horizontally across the human subject and into inlets for subsequent interrogation. The induced airspeed was up to 2.4 m/s, more than ten times the commonly accepted maximum for comfortable room ventilation [366]. Vortical recirculation was generated on the lee side of the subject. Air-jet puffer effects and the release of explosive vapor as a passive contaminant were also simulated. Although this portal design lacked sophistication, it was the first study to apply the tools of fluid dynamics to people sampling.

Sandia National Laboratories developed a vertical-downflow portal in the 1990s [356,368,367,358], a version of which is now commercialized as the Smiths Detection Sentinel II. A human subject enters the portal and turns 90 deg, whereupon an array of air-jet puffers and two ceiling slot-jets sweep the body for chemical traces. The cross-sectional area of the open portal is reduced near the floor, where a portion of the induced downflow is collected for analysis by an IMS detector. This is purely jet-assisted sniffing, since thermal convection from the human subject cannot play a significant role. It bears a similarity to air-shower or air-douche devices used for particle removal from clothing in clean room practice ([17] Chap. 14, and [369]).

Quite a different approach is taken in the GE Security EntryScan[3], Fig. 28, which uses the natural upward motion of the human thermal plume to collect and preconcentrate the plume overhead for IMS interrogation [357]. This is convection-assisted sniffing, but air-jet puffers also play a role in both ruffling the subject's clothing to release particles and in encouraging the upward airflow. An aerodynamic contraction (see, e.g., [370]) is used overhead to capture the human thermal plume at a flow rate up to 50 liters/s and pass it through a 10×10 cm metal-mesh preconcentrator.

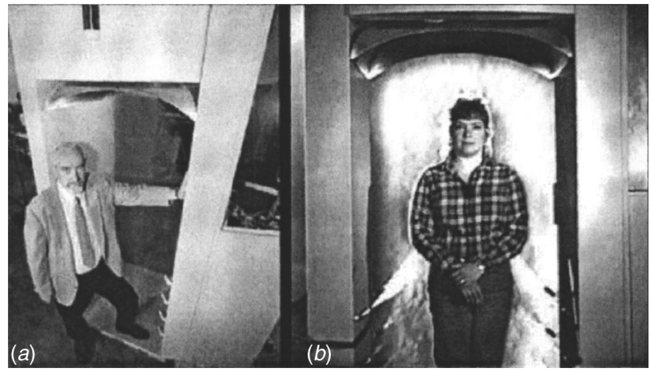

Fig. 28 (*a*) The author standing in a prototype version of the GE Infrastructure EntryScan[3] explosive detection portal (Penn State photo by Greg Grieco) and (*b*) schlieren image of portal with subject (L.J. Dodson) and with air-jet puffers firing

Several years of research on this portal at Penn State [83,124,353,354,371] have yielded the following results, summarized briefly:

1. The human thermal plume is a natural whole-body sampling system, from the toes to the top of the head.
2. As shown in Fig. 4, *brief* puffer-jet impingement (e.g., 50 ms) is the principal means of liberating trace particles for detection.
3. Most of the readily-available signal from a human subject can be had in a few seconds of overhead sampling time.
4. The detectability of 10 μm-range explosive particulate traces originating beneath the clothing is affected by clothing porosity only when the porosity is less than about 4%.
5. Layered clothing reduces the chemical trace signal level, but the signal remains measurable.
6. Trace explosive sources beneath the clothing transfer to both the clothing and the skin, but remain highest in the vicinity of the source.
7. Human skin flakes do not figure prominently in the transport of dry crystalline explosive traces in the human thermal plume.
8. Lateral air currents in the range of normally acceptable ventilation drafts do not substantially affect the performance of an open portal such as the one tested here.
9. When pure explosive vapor was released inside the portal, up to 25% of it was captured and detected by the present metal-mesh pre-concentrator.

6.3.3 Human aerodynamic wake. For a lateral airspeed U (or walking speed in still air) of more than about 0.2 m/s the human thermal plume ceases to exist. Instead, the thermal boundary layer of a person is swept downstream to form a wake. This can be seen by comparing the Reynolds number Re and the Grashof number $\mathrm{Gr}=g\beta\Delta TL^3/\nu^2$, where β is the volumetric thermal expansion coefficient, ΔT is the temperature difference, and L is the characteristic width of the human body [372]. Without lateral airspeed U, $\mathrm{Re}\rightarrow 0$ and $\mathrm{Gr}/\mathrm{Re}^2\gg 1$, meaning that the flow is dominated by free convection. On the other hand, for ordinary walking speeds in the $U=1$ m/s range, $\mathrm{Gr}/\mathrm{Re}^2\ll 1$ and the flow is dominated by forced rather than free convection. Since ΔT no longer matters in the latter flow regime, we use the expression "human aerodynamic wake."

Several investigators have studied lateral airflow effects on the flow about stationary humans, mostly motivated by air pollution control and the reduction of worker exposure [135,373–377]. In a different reference frame, however, a person walking with speed U in still air produces an aerodynamic wake in which the wake

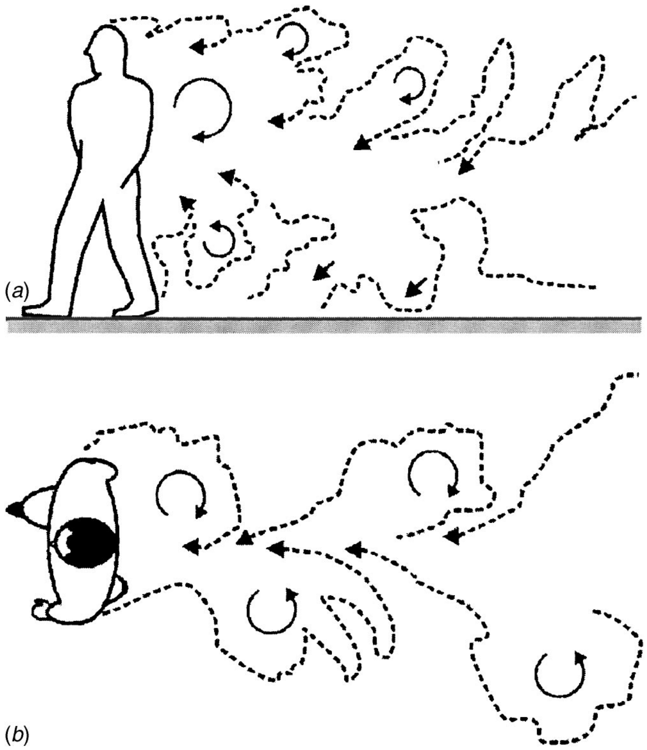

Fig. 29 Diagrams of motion in the human aerodynamic wake from smoke flow visualization experiments [372,378], (*a*) median plane and (*b*) dorsal plane

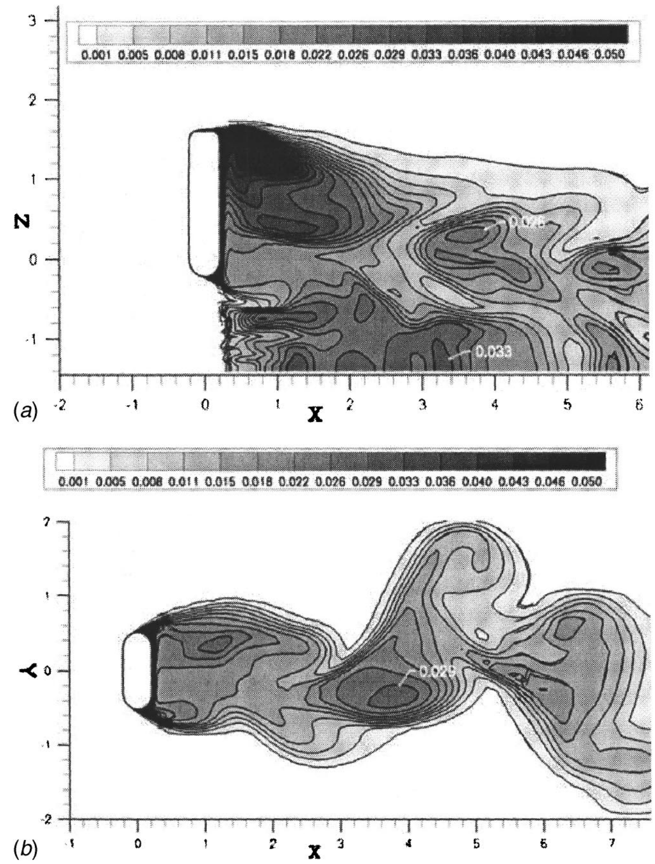

Fig. 30 Corresponding to Fig. 29, computed instantaneous motion of a scalar contaminant in the aerodynamic wake of a simulated human [372], (*a*) median plane and (*b*) dorsal plane

flow follows the person. The human chemical trace signature, formerly in the human boundary layer, becomes distributed in this wake. It is common experience that a walking person's scent in still air is noticeable to a fixed observer only after that person walks by.

This has been exploited as a means of "sniffing" human chemical traces by sampling the wakes of walking people [372,378,379]. The advantage over the portal technology described above is that people are already walking in security scenarios such as airports and, by not making them stop and stand, the sampling time can be reduced substantially. For example, experiments [378] have shown that the wakes of two walking people, one following the other, are aerodynamically independent for separation times greater than about 2 s.

The Penn State work [372,378,379], still in progress, has characterized the human aerodynamic wake as the unsteady vortex shedding from an irregular 3D cylindrical body (Fig. 29). The irregularity mostly concerns the legs, which act as individual shedding cylinders with through-flow between them. This causes the wake to dissipate more rapidly downstream of the legs than downstream of the torso, where a large recirculation zone occurs. There is also a downwash component that causes the lower wake to interact with the ground and to spread laterally. Despite these several complicating aspects, the human wake nevertheless shows unmistakable Kármán vortex shedding in the dorsal plane shown in Figs. 29(*b*) and 30(*b*).

A CFD solution of the Reynolds-averaged Navier-Stokes equations [372], despite a simplified representation of the human body, is able to portray all the significant aspects of the human wake flow that are seen in the experiments. For example, a scalar contaminant representing a chemical trace from the human body decays exponentially with distance downstream as the wake mixes out with the surrounding air. Thus one should sample the early wake just downstream of a walking person in order to acquire the maximum trace signal strength.

The design of a portal to sample the human aerodynamic wake was first suggested in [357]. It appears possible to take advantage of the wake's momentum in this regard [378,379]. However, compared to the case of the human thermal plume, sampling a much larger volume of air over a shorter time interval will be a severe test of pre-concentrator technology.

6.4 Landmine Detection. Landmine detection is another severe test for sniffers, as described in Sec. 3.3.2, because of weak trace signals outdoors in the weather and terrain. At the same time the global landmine crisis [380–383] extracts a shocking human and economic price and demands solutions.

Dogs are the principal detectors of buried landmines, even though it puts them and their handlers at risk. The DARPA Dog's Nose program in the late 1990s sought to produce artificial noses of similar sensitivity, and several of such were actually developed [287,288,292,384], though none has supplanted the dog so far. Yinon [310] and Pamula [384] have both surveyed this topic in more detail than present space allows.

Briefly, as part of the mentioned DARPA program an Explosives Fate and Transport Team characterized the trace signal level that one can expect to find above a buried landmine [162,385–387]. Trace explosives and related mine compounds enter the surrounding soil, collect below the mine, and percolate to the surface in a "halo" pattern about the mine location. Moisture and daily variations in soil temperature aid this process. For the ubiquitous 2,4,6-TNT mine, the prevalent trace signal is from 2,4-DNT, which is more volatile than TNT and is present in the military-grade explosive as a contaminant. It is this "odor signature" that a dog actually detects, rather than the bulk explosive [215].

The mass of explosive-related compounds in contaminated soil above a buried mine was found to be on the order of tens of micrograms/kilogram of soil. 2,4-DNT vapor is also present in the boundary layer directly above a typical anti-personnel mine, but only at a concentration of perhaps 100 picograms/liter at equilibrium under ideal atmospheric conditions, and such conditions are not usual [387].

Overall, then, the chances are bleak of sniffing explosive-related vapor in the air above a buried mine. Anecdotal evidence from dog handlers that their dogs air-scented landmines at 5 m must describe extraordinary rather than usual circumstances.

Soil particles, though, are another matter, since they carry a thousand-fold higher concentration of explosive-related signal. A dog's ability to stir up, inspire, and probably desorb trace chemicals from such particles was discussed in Sec. 4.3.1 and in [103,166]. Some developers of landmine sniffers also attempt to take advantage of soil particles by thermally desorbing traces from the soil using laser radiation before sniffing [388], by disturbing loose particles using air jets [310,384] or ultrasonics [389], or by collecting particles electrostatically [390].

Finally, Mineseeker.com [391] floats a mini blimp over a minefield and uses radar to locate landmines. One could lower an elephantlike sampling trunk with assisting air jets almost to ground level and sniff for them as well.

6.5 Biohazard Detection. The topic of sniffing for bioaerosols was introduced in Sec. 3.1, including some unique sampling and detection problems and the issue of distinguishing biowar agents from the natural airborne background. Chemical plumes—one way of dispersing biowar agents—were likewise covered in Sec. 3.3.3 and aerobiology was introduced in Sec. 1.1. Further references are also available on sampling biological aerosols [106,108], biosensors [392], and chemical and biological terrorism [12].

Consider the anthrax letters that were mailed in the United States in late 2001. Finely powdered anthrax spores in ordinary paper envelopes became airborne due to handling, costing several lives and contaminating two large mail-handling facilities [393]. Postal delivery-bar-code sorters squeezed the air and spores out of the envelopes by belts and rollers. 1 μm–3 μm anthrax spores can pass easily through the 20 μm pores of a typical paper envelope even if it remains unopened. Tearing open an anthrax-filled envelope was found to cause massive airborne contamination.

The Northrop-Grumman Corporation, Baltimore, MD, subsequently developed a biohazard detection system (BDS) for the U.S. Postal Service to detect any such future attacks upon the postal system. BDS compresses mail to force the air out of envelopes and captures it in a sampling hood positioned over the first pinch point in the mail processing operation. From the sampled airflow a Spincon high-volume liquid-based cyclone collector acquires biological particles and uses the polymerase chain reaction and DNA matching to detect the trace presence of such species as *Bacillus anthracis* in the mail. BDS is a fully automated system that sounds an alert when a biohazard is detected.

7 Other Applications

7.1 Medical Diagnosis. Since the beginning of medicine, human body and breath odors have been used to diagnose disease [394,395]. Dozens of diseases are known by their characteristic odors, such as acetone breath from diabetes [396], the putrid odor of scurvy, and the sour odor that precedes mononucleosis [397]. Also included are characteristic odors due to chemical poisoning and substance abuse, and even schizophrenia [398]. The popular press has made much of pet dogs purportedly sniffing out cancer in their owners. However, lacking quantification and in the face of modern laboratory analysis, olfaction in medical diagnosis has languished.

One reason for this is that most methods of artificial olfaction for medical diagnosis are intrusive and slow. Dravnieks et al. [314,349] and Distelheim and Dravnieks [399] used a "body tube" sampler (Sec. 6.3.1) and gas chromatograph (GC)-mass-

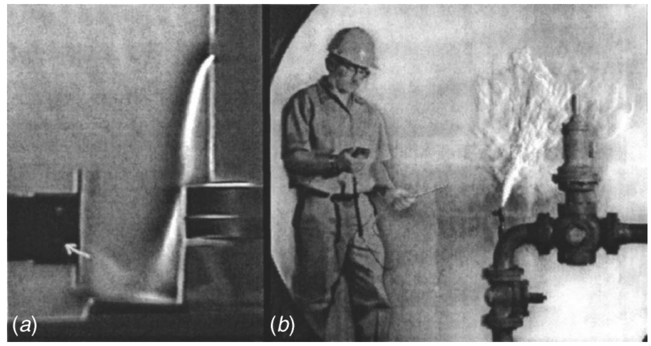

Fig. 31 (*a*) Schlieren image of an acetone vapor leak cascading downward and being inhaled (arrow) by the snout of the Cogniscent artificial nose (*b*) a hand-held, wand-type sniffer probe is used to search for a natural gas leak, visualized by large-field schlieren optics [46,408,411]

spectrometric analysis. Cotton swabs, breath bags [400,401], and skin headspace collectors [402,403] all work without the need for actual sniffing.

Gardner and Bartlett [9] speculated that "Perhaps in the future the electronic nose will be able to sniff the human body directly…" That future has already arrived in the form of portals that sample the human thermal plume, Sec. 6.3 and [83,120,124,357,371]. However, modern nonintrusive portal technology has yet to be applied outside the realm of explosive trace detection for security screening.

Nonetheless there is considerable recent activity in artificial olfaction for medical diagnosis, mostly using only intrusive sampling methods. Applications include staph, strep, and e-coli infections, breath signals for uremia and liver cirrhosis, urinary tract infections, tuberculosis, and airway inflammation [9,404,405]. Continuous e-nose monitoring of disease stages and global disease surveillance have been suggested [406] but not yet realized.

Clearly, modern sniffing for medical diagnosis still has many hurdles to overcome, as described by Persaud, Pisanelli, and Evans [407]. Despite its enormous potential, this application is presently more driven by sensor research and development [392] than by sampling issues, and there is not yet a commercial realization even of a breath analyzer. The medical arena is a difficult one; human variations can produce different odors from the same disease, misdiagnoses are bad news, and chemical interference is common. Also the funding tends to favor therapeutic rather than diagnostic instrument development. Finally, even though current lab analyses of blood samples and cultures take days, any replacement technology must at least achieve the accuracy of the current methods.

7.2 Leak Detection. Wand-type leak-detector sniffer probes, Fig. 31 [408], were discussed in Sec. 3.2.4 and elsewhere. They have very broad industrial applications in leak-testing turbines, condensers, heat exchangers, tanks, refrigerant systems, and pipelines. Explosive rocket propellant leaks must be found, as must leaking solvents or fuels that pose fire, explosion, or environmental hazards. Natural gas leaks are expensive as well as dangerous.

Usually a hand-held sniffer probe acquires a sample by suction and conveys it to a sensor such as a helium or flame-ionization detector. The sampling time rises rapidly with the hose length, and for long hoses of typical 1-cm-or-less diameter it becomes prohibitive. Example calculations for sensitivity, standoff distance, linear speed of probe motion, response time, and calibration are given in [139].

Some other sniffer types are not hand held, but rather vehicle mounted. In one case, Boreal Laser's aircraft-mounted GasFinderAB system is flown over natural gas pipelines, sampling and analyzing the air for leaks. Dogs are also trained to sniff for gas leaks.

Hand-held sniffer probes are accurate and sensitive, but searching is slow and coverage of large areas is labor intensive. Broad-field standoff optical methods can supplement probe detection by covering large areas quickly at reduced sensitivity levels. At least three such approaches have been suggested: (1) IR thermography [409], which depends upon a thermal difference between leaking gas and the ambient air and usually only examines ground signatures; (2) Schlieren imaging [46,410,411], which requires a small refractive-index difference but images the air itself rather than the ground; and (3) laser absorption [412], which can detect isothermal airborne leak plumes but requires expensive and cumbersome equipment.

8 Summary and Future Directions

8.1 Summary. For convenience, the high points of this tour of the world of sniffers are repeated in list form:

1. Little previous effort has been spent on the biofluid dynamics of sniffing or on the design of sniffers for artificial olfaction.
2. Nature favors energy-efficient faired bellmouth-type inlets rather than sharp-edged holes.
3. Brief air-jet impingement is the principal means of liberating trace particles from surfaces for detection by sniffing.
4. The proper model for airflow about the human body in still air is the human thermal boundary layer and plume, not the "personal activity cloud."
5. Plumes bearing chemical traces can be classified and understood based on their buoyancy and momentum.
6. Nature teaches proximity sniffing, but the most advanced natural nostrils, such as the variable-geometry dog's nose, also use exhaled air jets to enhance the reach and particle uptake of the process.
7. A vertebrate does not require variable-geometry external nares in order to be macrosmatic, but several of those examined here do have them. We know something of their function in dogs, but almost nothing in the case of other animals.
8. The natural narial sampling orifice of terrestrial vertebrates is typically either round, inverse-comma shaped, or slit shaped.
9. A proboscis, nostril, and mobile platform are required for vertebrate sniffing, but proboscis length is only weakly constrained by nature, as demonstrated by the elephant and kiwi.
10. Small turbomachines can move fluids for olfaction more effectively than nature's usual bellows action.
11. Macrosmatic terrestrial vertebrates usually have large nostrils for high airflow rates and long straight snouts to provide enough space for both the olfactory and the air-conditioning apparatus.
12. None of the animals can afford the time to collect and later desorb odorants. They acquire the odorant by sensor cells generating neuronal signals that are sent directly to the brain in real time.
13. The peak mammalian sniff rate of a few hertz ignores higher-frequency information, such as some of that contained in chemical plumes. This suggests that a man-made continuously-inhaling sniffer could gain an advantage in frequency response by not having to accommodate respiration.
14. For olfactory sensor chamber design the best model is the fish: simple, elegant, and not complicated by dual use. Mounting the sensor chamber off to the side, as in the dog's nose, appears just to be nature's way of accommodating olfaction with respiration.
15. Reynolds analogy plays an important role in olfactory sensor chamber design.
16. Mankind's worst enemy, the mosquito, has received little attention from fluid dynamicists.
17. Invertebrates who track chemical plumes use the Reynolds number to control the effective porosity of their antennae sensor hairs during sniffing.
18. We can understand a lot about natural sniffers but not all, because biomimicry is a sort of reverse engineering: The final product is available, but no logical path is revealed to get there.
19. Compared to nature, the sniffers now used in man-made detectors and artificial noses are almost devoid of sophistication. Several possibilities are suggested for their improvement.
20. Vapor and particle sampling are both important in nature as well as in artificial olfaction.
21. In people sniffing, the human thermal plume is a natural whole-body sampler, from the toes to the top of the head.
22. The human aerodynamic wake has been characterized, at least initially, by both experiments and computations.
23. Modern nonintrusive portal technology for sniffing people has yet to be applied to medical diagnosis or anything else outside the realm of explosive trace detection for security screening.
24. This paper has collected scattered information and has associated diverse fields in the hope of establishing a "new" topic in biofluid dynamics.

8.2 Future Directions. Future directions for the further understanding and development of sniffers are summarized in the following list:

1. Study the nostril aerodynamics of the rabbit, rat, and opossum in order to broaden the present knowledge of natural sniffing systems.
2. Carry out an experimental and computational fluid-dynamic study of an eel's or shark's olfactory capsule as a primary example for sensor chamber design in artificial olfaction.
3. Study the internal aerodynamics of the dog's nose by particle image velocimetry (PIV) measurements and CFD simulation as another important example for artificial olfaction sensor chamber design.
4. Carry out flow visualization, PIV velocity measurements, and a CFD simulation of the airflow around the upper human body, breathing zone, exhaled jets, cough, and sneeze.
5. Perform turbulent and unsteady-flow CFD simulations of the flow inside the human and dog's nose.
6. Gain a better understanding of mosquito aerodynamics, the effects of ambient wind, mosquito plume tracing, and potential aerodynamic strategies to defeat mosquito host location.
7. Beginning at the fundamental level, examine current and prospective new artificial sniffer types in terms of practicality, efficiency, proper use of fluid-dynamic principles, and the performance criteria stated in Sec. 5.1.3.
8. Conduct research to better understand jet-assisted olfaction.
9. Study more effective means of aerodynamic sniffer isolation from the effects of an ambient breeze.
10. Develop ways to replace the present adsorb-desorb-analyze-detect cycle with more direct olfactory sensing, as in nature.
11. Develop flexible, controllable "elephant trunk" snouts for land-based robot sniffers in order to improve their olfactory mobility and performance by aiming their trunks at local regions of interest.
12. Apply modern nonintrusive portal sampling technology to human medical diagnosis.
13. Produce an educational film on the fluid mechanics of scent plumes, skin flakes, and the aerodynamics of scenting for the dog handler and the artificial nose user.

Finally, various studies and working groups have made similar suggestions for future research, including more study of mammalian olfaction, sampling, and preconcentration [205], biomimetic sensing focused on distributed low-cost sensors [48], factories of the future filled with cheap tiny olfactory and other sensors [413], rapid wristwatch-sized biodetectors [414], low-power, distributed, unattended, miniaturized remote sensors, robotic "insects" with onboard sampling and sensors, and rat packs with global positioning system transponders trained to detect explosives in city sewers [48]. Some of this speculation is far fetched, but we can reasonably expect that sniffers will eventually no longer be *ad hoc* afterthoughts in artificial olfaction, as they are now in almost every case. Small, portable, inexpensive e-noses with integral sniffers will eventually become common useful tools, although trained canine detectors will not soon become obsolete. The genetic detectives, e.g., [237,415], will also have more to say about the origin and function of the various noses reviewed here. Meanwhile fluid dynamicists have a lot of interesting work to do on this topic.

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References

[1] Eisenberg, J. F., and Kleiman, D. G., 1972, "Olfactory Communication in Mammals," Annu. Rev. Ecol. Syst., **3**, pp. 1–32.
[2] Zwaardemaker, H., 1895, *Die Physiologie des Geruchs*, W. Engelmann, Leipzig, Germany.
[3] Stoddart, D. M., 1980, *The Ecology of Vertebrate Olfaction*, Chapman & Hall, New York, pp. 1–33.
[4] Axel, R., 1995, "The Molecular Logic of Smell," Sci. Am., **273**(4), pp. 154–159.
[5] Doty, R. L., 2001, "Olfaction," Annu. Rev. Psychol., **52**, pp. 423–452.
[6] Kauer, J. S., and White, J. E., 2001, "Imaging and Coding in the Olfactory System," Annu. Rev. Neurosci., **24**, pp. 963–979.
[7] Lighthill, M. J., 1975, *Mathematical Biofluiddynamics*, SIAM, Philadelphia.
[8] Weinbaum, S., 1996, "Biofluid Mechanics," in *Research Trends in Fluid Dynamics: Report from US National Commission on Theoretical & Applied Mechanics*, J. L. Lumley, ed., Springer, New York, pp. 296–309.
[9] Gardner, J. W., and Bartlett, P. N., 1999, *Electronic Noses—Principles and Applications*, Oxford University Press, Oxford.
[10] Pearce, T. C., Schiffman, S. S., Nagle, H. T., and Gardner, J. W., eds., 2002, *Handbook of Machine Olfaction*, Wiley, New York.
[11] Rouhi, A. M., 1997, "Detecting Illegal Substances," Chem. Eng. News, **75**(39), pp. 24–29.
[12] National Research Council, 1999, *Chemical and Biological Terrorism: Research and Development to Improve Civilian Medical Response*, National Academy Press, Washington, DC.
[13] Watson, J. G., and Chow, J. C., 2001, "Ambient Air Sampling," in *Aerosol Measurement: Principles, Techniques, and Applications*, 2nd Ed., P. A. Baron and K. Willeke, eds., Wiley, New York, pp. 821–844.
[14] Monteith, L. E., and Rubow, K. L., 2001, "Air Movers and Samplers," in *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, 9th Ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 233–280.
[15] Singh, M., and Sioutas, C., 2003, "Assessment of Exposure to Airborne Particles," in *Indoor Environment: Airborne Particles and Settled Dust*, L. Morowska and T. Salthammer, eds., Wiley, New York, pp. 374–386.
[16] Subramaniam, R. P., Richardson, R. B., Morgan, K. T., Kimbell, J. S., and Guilmette, R. A., 1998, "Computational Fluid Dynamics Simulations of Inspiratory Airflow in the Human Nose and Nasopharynx," Inhalation Toxicol., **10**(5), pp. 473–502.
[17] Baturin, V. V., 1972, *Fundamentals of Industrial Ventilation*, Pergamon, New York, pp. 12–24.
[18] Heinsohn, R. J., 1991, *Industrial Ventilation*, Wiley, New York.
[19] Heinsohn, R. J., and Cimbala, J. M., 2002, "Ideal Flow," in *Indoor Air Quality Engineering*, Marcel Dekker, New York, pp. 517–580.
[20] Goodfellow, H. D., and Tähti, E., eds., 2001, *Industrial Ventilation Design Guidebook*, Elsevier, New York.
[21] Kordyban, T., 1998, *Hot Air Rises and Heat Sinks: Everything You Know About Cooling Electronics is Wrong*, ASME, New York.
[22] Remsburg, R., 2001, *Thermal Design of Electronic Equipment*, CRC, Boca Raton.
[23] Cox, C. S., 1987, *The Aerobiological Pathway of Microorganisms*, Wiley-Interscience, New York.
[24] Clark, R. P., and Cox, R. N., 1973, "The Generation of Aerosols from the Human Body," in *Airborne Transmission and Airborne Infection: Concepts and Methods*, J. F. Hers and K. C. Winkler, eds., Wiley, New York, pp. 413–426.
[25] Burge, H. A., 1995, "Aerobiology of the Indoor Environment," Occup. Med., **10**(1), pp. 27–40.
[26] Higson, S. P. J., 2003, *Analytical Chemistry*, Oxford University, Oxford, UK.
[27] Kline, S. J., 1960, "The Importance of Flow Visualization," *Symposium on Flow Visualization*, ASME, New York, 1, pp. 1–9.
[28] Roshko, A., 1995, "Flow Visualization As a Basic Research Tool," in *Flow Visualization VII*, Crowder, J. P. ed., Begell House, New York, pp. 983–994.
[29] Merzkirch, W., 1987, *Flow Visualization*, Academic, New York.
[30] Paulsen, E., 1882, "Experimentelle Untersuchungen Über Die Strömungen Der Luft in Der Nasenhöhle," Sitzungsber. K. Preuss. Akad. Wiss., **85**, p. 348ff.
[31] Bojsen-Møller, F., and Fahrenkrug, J., 1971, "Nasal Swell-Bodies and Cyclic Changes in the Air Passage of the Rat and Rabbit Nose," J. Anat., **110**(1), pp. 25–37.
[32] Hornung, D. E., Leopold, D. A., Youngentob, S. L., Sheehe, P. R., Gagne, G. M., Thomas, F. D., and Mozell, M. M., 1987, "Airflow Patterns in a Human Nasal Model," Arch. Otolaryngol. Head Neck Surg., **113**(2), pp. 169–172.
[33] Hahn, I., Scherer, P. W., and Mozell, M. M., 1993, "Velocity Profiles Measured for Airflow Through a Large-Scale Model of the Human Nasal Cavity," J. Appl. Physiol., **75**(5), pp. 2273–2287.
[34] Keyhani, K., Scherer, P. W., and Mozell, M. M., 1997, "Numerical Simulation of Airflow in the Human Nasal Cavity," ASME J. Biomech. Eng., **117**, pp. 429–441.
[35] Brueggemann, J., and Jeckstadt, S., 1938, "Über Den Weg Des Luftstromes Durch Die Nase Des Hundes (On the Direction of the Airstream Through the Dog's Nose)," Pflugers Archiv, European Journal of Physiology, **239**, pp. 293–303.
[36] Dawes, J. D. K., 1952, "The Course of the Nasal Airstreams," J. Laryngol. Otol., **66**(12), pp. 583–593.
[37] Ishida, H., Yamanaka, T., Kushida, N., Nakamoto, T., and Moriizumi, T., 2000, "Study of Real-Time Visualization of Gas/Odor Flow Image Using Gas Sensor Array," Sens. Actuators B, **65**(1–3), pp. 14–16.
[38] Yamanaka, T., Ishida, H., Nakamoto, T., and Moriizumi, T., 1998, "Analysis of Gas Sensor Transient Response by Visualizing Instantaneous Gas Concentration Using Smoke," Sens. Actuators, A, **69**(1), pp. 77–81.
[39] Saunders, C. J., and Fletcher, B., 1996, "Jet Enhanced Local Exhaust Ventilation," Ann. Occup. Hyg., **37**(1), pp. 15–24.
[40] Teichmann, H., 1959, "Vergleichende Untersuchungen an Der Nase Der Fische (Comparative Investigations on the Nose of the Fish)," Z. Morphol. Oekol. Tiere, **43**, pp. 171–212.
[41] Grasso, F. W., and Basil, J. A., 2002, "How Lobsters, Crayfishes, and Crabs Locate Sources of Odor: Current Perspectives and Future Directions," Curr. Opin. Neurobiol., **12**(6), pp. 721–727.
[42] Atema, J., 1996, "Eddy Chemotaxis and Odor Landscapes: Exploration of Nature with Animal Sensors," Biol. Bull., **191**(1), pp. 129–138.
[43] Webster, D. R., and Weissburg, M. J., 2001, "Chemosensory Guidance Cues in a Turbulent Chemical Odor Plume," Limnol. Oceanogr., **46**(5), pp. 1034–1047.
[44] Stuiver, M., 1958, "Biophysics of the Sense of Smell," PhD thesis, University of Groningen, Germany.
[45] Schreck, S., Sullivan, K. J., Ho, C. M., and Chang, H. K., 1993, "Correlations Between Flow Resistance and Geometry in a Model of the Human Nose," J. Appl. Physiol., **75**(4), pp. 1767–1775.
[46] Settles, G. S., 2001, *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*, 1st Ed., Springer, New York.
[47] Settles, G. S., Kester, D. A., and Dodson-Dreibelbis, L. J., 2003, "The External Aerodynamics of Sniffing," in *Sensors and Sensing in Biology and Engineering*, F. G. Barth et al., eds., Springer, New York, pp. 323–355.
[48] Board on Chemical Sciences and Technology, 2004, "Existing and Potential Standoff Explosives Detection Technologies," US National Research Council Report, National Academies Press, Washington DC.
[49] White, F. M., 2002, *Fluid Mechanics*, McGraw-Hill, Boston.
[50] Batchelor, G. K., 2000, *An Introduction to Fluid Mechanics*, Cambridge University, Cambridge, UK.
[51] Chahine, A., Chahine, G. L., Duraiswami, R., Billard, J. Y., and Nieuwstadt, F. T. M., 1995, "Two-Dimensional Potential Flow Instruction and Analysis on Personal Computers," ASME J. Fluids Eng., **220**, pp. 89–93.
[52] Kimbell, J. S., Gross, E. A., Joyner, D. R., Godo, M. N., and Morgan, K. T., 1997, "Application of Computational Fluid Dynamics to Regional Dosimetry of Inhaled Chemicals in the Upper Respiratory Tract of the Rat," Toxicol. Appl. Pharmacol., **121**(2), pp. 253–263.

[53] Kimbell, J. S., Godo, M. N., Gross, E. A., Joyner, D. R., Richardson, R. B., and Morgan, K. T., 1997, “Computer Simulation of Inspiratory Airflow in All Regions of the F344 Rat Nasal Passages,” Toxicol. Appl. Pharmacol., **145**(2), pp. 388–398.
[54] Kepler, G. M., Richardson, R. B., Morgan, K. T., and Kimbell, J. S., 1998, “Computer Simulation of Inspiratory Nasal Airflow and Inhaled Gas Uptake in a Rhesus Monkey,” Toxicol. Appl. Pharmacol., **150**(1), pp. 1–11.
[55] Kimbell, J. S., and Subramaniam, R. P., 2001, “Use of Computational Fluid Dynamics Models for Dosimetry of Inhaled Gases in the Nasal Passages,” Inhalation Toxicol., **13**(5), pp. 325–334.
[56] Koch, D. A., Arnold, S., Hubler, M., and Montavon, P. M., 2003, “Brachycephalic Syndrome in Dogs,” Compendium on Continuing Education for the Practicing Veterinarian, **25**(1), pp. 48.
[57] Brockmann, J. E., 2001, “Sampling and Transport of Aerosols,” in *Aerosol Measurement: Principles, Techniques, and Applications*, 2nd Ed., P. A. Baron and K. Willeke, eds., Wiley, New York, pp. 143–195.
[58] Hahn, I., Scherer, P. W., and Mozell, M. M., 1994, “A Mass-Transport Model of Olfaction,” J. Theor. Biol., **167**(2), pp. 115–128.
[59] Anonymous, 2001, “Odors,” in *ASHRAE Fundamentals Handbook*, American Society of Heating, Ventilation, and Air-Conditioning Engineers, Atlanta, pp. 13.1–13.8.
[60] Mozell, M. M., Hornung, D. E., Sheehe, P. R., and Kurtz, D. B., 1986, “What Should be Controlled in Studies of Smell?,” in *Clinical Measurement of Taste and Smell*, H. L. Meiselman and R. S. Rivlin, eds., MacMillan, New York, pp. 154–169.
[61] Zuschneid, K., 1973, “The Olfactory Acuity of the Dog (Die Riechleistung Des Hundes),” PhD thesis, School of Veterinary Medicine, Free University of Berlin, Berlin, Germany.
[62] Morrison, E. E., 2000, “Canine Detection of Illicit Drugs: Sensory Apparatus Technology,” Battelle Report A185183, Columbus, OH.
[63] Johnson, B. N., Mainland, J. D., and Sobel, N., 2003, “Rapid Olfactory Processing Implicates Subcortical Control of an Olfactomotor System,” J. Neurophysiol., **90**(2), pp. 1084–1094.
[64] Schreider, J. P., and Raabe, O. G., 1981, “Anatomy of the Nasal-Pharyngeal Airway of Experimental Animals,” Anat. Rec., **200**, pp. 195–205.
[65] Mead, K. S., Koehl, M. A. R., and O’Donnell, M. J., 1999, “Stomatopod Sniffing: the Scaling of Chemosensory Sensillae and Flicking Behavior with Body Size,” J. Exp. Mar. Biol. Ecol., **241**(2), pp. 235–261.
[66] Vogel, S., 1994, *Life in Moving Fluids: The Physical Biology of Flow*, Princeton University, Princeton, NJ.
[67] Olander, L., 2001, “Exhaust Hoods,” in *Industrial Ventilation Design Guidebook*, H. D. Goodfellow, and E. Tähti, eds., Elsevier, New York, pp. 814–916.
[68] Anonymous, 1999, “Industrial Local Exhaust Systems,” in *ASHRAE Applications Handbook*, ASHRAE, Atlanta, pp. 29.1–29.21.
[69] Jackson, C. N., Sherlock, C. N., and Moore, P. O., 1998, “Leak Testing, Part 3: Test Techniques Providing Electronic Indications of Leak Locations,” in *Nondestructive Testing Handbook, Second Edition*, ASNT, Columbus, OH, 1, pp. 30–33.
[70] List, E. J., 1982, “Mechanics of Turbulent Buoyant Jets and Plumes,” in *Turbulent Buoyant Jets and Plumes*, W. Rodi, ed., Pergamon, New York, pp. 1–68.
[71] Abramovich, G. N., and Schindel, L., 1963, *The Theory of Turbulent Jets*, MIT, Cambridge, MA.
[72] Zhivov, A., 2001, “Air Jets,” in *Industrial Ventilation Design Guidebook*, H. D. Goodfellow, and E. Tähti, eds., Elsevier, New York, pp. 446–517.
[73] Glezer, A., and Amitay, M., 2002, “Synthetic Jets,” Annu. Rev. Fluid Mech., **34**, pp. 503–529.
[74] Lai, H. Z., Naughton, J. W., and Lindberg, W. R., 2003, “An Experimental Investigation of Starting Impinging Jets,” ASME J. Fluids Eng., **125**(2), pp. 275–282.
[75] Glauert, M. B., 1956, “The Wall Jet,” J. Fluid Mech., **1**(5), pp. 625–643.
[76] Phares, D. J., Smedley, G. T., and Flagan, R. C., 2000, “The Inviscid Impingement of a Jet with Arbitrary Velocity Profile,” Phys. Fluids, **12**(8), pp. 2046–2055.
[77] Smedley, G. T., Phares, D. J., and Flagan, R. C., 1999, “Entrainment of Fine Particles From Surfaces by Gas Jets Impinging at Normal Incidence,” Exp. Fluids, **26**(4), pp. 324–334.
[78] Smedley, G. T., Phares, D. J., and Flagan, R. C., 2001, “Entrainment of Fine Particles From Surfaces by Gas Jets Impinging at Oblique Incidence,” Exp. Fluids, **30**(2), pp. 135–142.
[79] Phares, D. J., Smedley, G. T., and Flagan, R. C., 2000, “The Wall Shear Stress Produced by the Normal Impingement of a Jet on a Flat Surface,” J. Fluid Mech., **418**, pp. 351–375.
[80] Phares, D. J., Smedley, G. T., and Flagan, R. C., 2000, “Effect of Particle Size and Material Properties on Aerodynamic Re-Suspension From Surfaces,” J. Aerosol Sci., **31**(11), pp. 1335–1353.
[81] Ibrahim, A. H., Dunn, P. F., and Brach, R. M., 2003, “Microparticle Detachment From Surfaces Exposed to Turbulent Air Flow: Controlled Experiments and Modeling,” J. Aerosol Sci., **34**(6), pp. 765–782.
[82] Ziskind, G., Yarin, L. P., Peles, S., and Gutfinger, C., 2002, “Experimental Investigation of Particle Removal From Surfaces by Pulsed Air Jets,” Aerosol Sci. Technol., **36**(5), pp. 652–659.
[83] Settles, G. S., Thomas, M. A., Ferree, H. C., Jonassen, D. R., Miller, J. D., and Dodson, L. J., 2005, “The Aerodynamics of a Chemical Trace Detection Portal for Screening People,” in preparation.
[84] Marple, V. A., Olson, B. A., and Rubow, K. L., 2001, “Inertial, Gravitational, Centrifugal, and Thermal Collection Techniques,” in *Aerosol Measurement: Principles, Techniques, and Applications*, 2nd Ed., P. A. Baron and K. Willeke, eds., Wiley, New York, pp. 229–260.
[85] Baron, P. A., and Willeke, K., 2001, “Gas and Particle Motion,” in *Aerosol Measurement: Principles, Techniques, and Applications*, 2nd Ed., P. A. Baron and K. Willeke, eds., Wiley, New York, pp. 61–82.
[86] Morawska, L., and Salthammer, T., 2003, “Fundamentals of Indoor Particles and Settled Dust,” in *Indoor Environment: Airborne Particles and Settled Dust*, L. Morowska and T. Salthammer, eds., Wiley, New York.
[87] Feynman, R. P., 1999, “Diffusion,” in *The Feynman Lectures on Physics, Vol. 6, Kinetics and Heat*, Audio Recording, Basic Books, New York.
[88] Stitzel, S. E., Stein, D. R., and Walt, D. R., 2003, “Enhancing Vapor Sensor Discrimination by Mimicking a Canine Nasal Cavity Flow Environment,” J. Am. Chem. Soc., **125**(13), pp. 3684–3685.
[89] Neuhaus, W., 1981, “The Importance of Sniffing in Canine Olfaction (Die Bedeutung des Schnüffelns für das Riechen des Hundes),” Zeitschrift für Saugetierkunde, **46**, pp. 301–310.
[90] Vogel, S., 2003, *Comparative Biomechanics: Life’s Physical World*, Princeton University, Princeton, NJ.
[91] Anonymous, 2001, “Mass Transfer,” in *ASHRAE Fundamentals Handbook*, ASHRAE, Atlanta, pp. 5.1–5.13.
[92] Goldman, J. A., and Koehl, M. A. R., 2001, “Fluid Dynamic Design of Lobster Olfactory Organs: High Speed Kinematic Analysis of Antennule Flicking by Panulirus Argus,” Chem. Senses, **26**(4), pp. 385–398.
[93] Koehl, M. A. R., Koseff, J. R., Crimaldi, J. P., McCay, M. G., Cooper, T., Wiley, M. B., and Moore, P. A., 2001, “Lobster Sniffing: Antennule Design and Hydrodynamic Filtering of Information in an Odor Plume,” Science, **294**(5548), pp. 1948–1951.
[94] Griffy, T. A., 1992, “A Model of Explosive Vapor Concentration II,” in *Proceedings of the Fourth International Symposium on the Analysis and Detection of Explosives*, J. Yinon, ed., Kluwer-Academic, New York, pp. 503–511.
[95] Lugt, H. J., 1983, *Vortex Flow in Nature and Technology*, Wiley, New York.
[96] Motchkine, V. S., Krasnobaev, L. Y., and Bunker, S. N., Aug. 21, 2003, “Cyclone Sampling Nozzle for an Ion Mobility Spectrometer,” U.S. Patent App. US2003/0155506A1.
[97] Colehour, J. L., and Farquhar, B. W., 1971, “Inlet Vortex,” J. Aircr., **8**(1), pp. 39–43.
[98] De Siervi, F., Viguier, H. C., Greitzer, E. M., and Tan, C. S., 1982, “Mechanisms of Inlet Vortex Formation,” J. Fluid Mech., **124**, pp. 173–207.
[99] Chen, P., Soundra-Nayagam, M., Bolton, A. N., and Simpson, H. C., 1996, “Unstable Flow in Centrifugal Fans,” ASME J. Fluids Eng., **118**(1), pp. 128–133.
[100] Stong, C. L., 1971, “Experiments With Wind: A Pendulum Anemometer and Miniature Tornadoes,” Sci. Am., **224**(10), pp. 108–112.
[101] Lippmann, M., 2001, “Filters and Filter Holders,” in *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, 9th Ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 281–314.
[102] Hering, S. V., 2001, “Impactors, Cyclones, and Other Particle Collectors,” in *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, 9th Ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 315–375.
[103] Johnston, J. M., Morrison, E. E., and Boussom, T. M., 2002, “The Role of Particles in Canine Olfactory Detection,” unpublished.
[104] Chang, M. C., Kim, S., and Sioutas, C., 1999, “Experimental Studies on Particle Impaction and Bounce: Effects of Substrate Design and Material,” Atmos. Environ., **33**(15), pp. 2313–2322.
[105] Misra, C., Geller, M. D., Shah, P., Sioutas, C., and Solomon, P. A., 2001, “Development and Evaluation of a Continuous Coarse (PM10-PM2.5) Particle Monitor,” J. Air Waste Manage. Assoc., **51**(9), pp. 1309–1317.
[106] Macher, J. M., and Burge, H. A., 2001, “Sampling Biological Aerosols,” in *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, 9th Ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 662–701.
[107] Solomon, W. R., 2003, “How Ill the Wind? Issues in Aeroallergen Sampling,” J. Allergy Clin. Immunol., **112**(1), pp. 3–8.
[108] Mehta, S. K., Bell-Robinson, D. M., Groves, T. O., Stetzenbach, L. D., and Pierson, D. L., 2000, “Evaluation of Portable Air Samplers for Monitoring Airborne Culturable Bacteria,” Am. Ind. Hyg. Assoc. J., **61**(6), pp. 850–854.
[109] Lacey, J., 1997, “Guest Editorial: Sampling and Rapid Assay of Bioaerosols,” J. Aerosol Sci., **28**(3), pp. 345–348.
[110] Griffiths, W. D., Stewart, I. W., Futter, S. J., Upton, S. L., and Mark, D., 1997, “Development of Sampling Methods for the Assessment of Indoor Bioaerosols,” J. Aerosol Sci., **28**(3), pp. 437–457.
[111] Heinsohn, R. J., and Cimbala, J. M., 2002, *Indoor Air Quality Engineering*, Marcel Dekker, New York.
[112] Wallace, L. A., 2001, “Human Exposure to Volatile Organic Pollutants: Implications for Indoor Air Studies,” Annu. Rev. Energy Envir., **26**, pp. 269–301.
[113] Anonymous, 2001, “Indoor Environmental Health,” in *ASHRAE Fundamentals Handbook*, ASHRAE, Atlanta, GA, pp. 9.1–9.20.
[114] Thomas, K. W., Pellizzari, E. D., Clayton, C. A., Whitaker, D. A., Shores, R. C., Spengler, J., Ozkaynak, H., Froelich, S. E., and Wallace, L. A., 1993, “Particle Total Exposure Assessment Methodology (PTEAM) 1990 Study—Method Performance and Data Quality for Personal, Indoor, and Outdoor Monitoring,” J. Expo Anal Environ. Epidemiol., **3**(2), pp. 203–226.
[115] Clayton, C. A., Perritt, R. L., Pellizzari, E. D., Thomas, K. W., Whitmore, R. W., Wallace, L. A., Ozkaynak, H., and Spengler, J. D., 1993, “Particle Total Exposure Assessment Methodology (PTEAM) Study-Distributions of Aerosol and Elemental Concentrations in Personal, Indoor, and Outdoor Air

Samples in a Southern California Community," J. Expo Anal Environ. Epidemiol., **3**(2), pp. 227–250.
[116] Ozkaynak, H., Xue, J., Spengler, J., Wallace, L., Pellizzari, E., and Jenkins, P., 1996, "Personal Exposure to Airborne Particles and Metals: Results From the Particle Team Study in Riverside, California," J. Expo Anal Environ. Epidemiol., **6**(1), pp. 57–78.
[117] Rodes, C. E., Kamens, R. M., and Wiener, R. W., 1991, "The Significance and Characteristics of the Personal Activity Cloud on Exposure Assessment Measurements for Indoor Contaminants," Indoor Air, **2**, pp. 123–145.
[118] Wallace, L. A., 1993, "The TEAM Studies," EPA Journal, **19**(4).
[119] Lewis, H. E., Foster, A. R., Mullan, B. J., Cox, R. N., and Clark, R. P., 1969, "Aerodynamics of the Human Microenvironment," Lancet, **322**(7609), pp. 1273–1277.
[120] Clark, R. P., and Edholm, O. G., 1985, *Man and His Thermal Environment*, E. Arnold, London.
[121] Homma, H., and Yakiyama, M., 1991, "Examination of Free Convection Around Occupant's Body Caused by Its Metabolic Heat," ASHRAE Trans., **94** Part 1(3118), pp. 104–124.
[122] Clark, R. P., and Cox, R. N., 1974, "An Application of Aeronautical Techniques to Physiology. 2. Particle Transport within the Human Microenvironment," Med. Biol. Eng., **12**(3), pp. 275–279.
[123] Gowadia, H. A., 2000, "The Natural Sampling of Airborne Trace Signals Associated with the Human Body," PhD thesis, Pennsylvania State University, University Park, PA.
[124] Gowadia, H. A., and Settles, G. S., 2001, "The Natural Sampling of Airborne Trace Signals From Explosives Concealed Upon the Human Body," J. Forensic Sci., **46**(6), pp. 1324–1331.
[125] Syrotuck, W. G., 1972, *Scent and the Scenting Dog*, Arner, Rome, NY.
[126] May, K. R., and Pomeroy, N. P., 1973, "Bacterial Dispersion from the Body Surface," in *Airborne Transmission and Airborne Infection: Concepts and Methods*, J. F. Hers and K. C. Winkler, eds., Wiley, New York, pp. 426–432.
[127] Clark, R. P., and Shirley, S. G., 1973, "Identification of Skin in Airborne Particulate Matter," Nature (London), **246**(5427), pp. 39–40.
[128] Clark, R. P., 1974, "Skin Scales Among Airborne Particles," J. Hyg. (Lond), **72**(1), pp. 47–51.
[129] Sykes, B., 2001, *The Seven Daughters of Eve*, Norton, New York.
[130] Murakami, S., 2002, "CFD Study on the Micro-Climate Around the Human Body with Inhalation and Exhalation," in *Proceedings of ROOMVENT 2002, 8th International Conference on Air Distribution in Rooms*, Copenhagen, 8–11, Technical University of Denmark.
[131] Renstrom, A., Karlsson, A. S., and Tovey, E., 2002, "Nasal Air Sampling used for the Assessment of Occupational Allergen Exposure and the Efficacy of Respiratory Protection," Clin. Exp. Allergy, **32**(12), pp. 1769–1775.
[132] Misra, C., Singh, M., Shen, S., Sioutas, C., and Hall, P. A., 2002, "Development and Evaluation of a Personal Cascade Impactor Sampler (PCIS)," J. Aerosol Sci., **33**(7), pp. 1027–1047.
[133] Hauck, B. C., Grinshpun, S. A., Reponen, A., Reponen, T., Willeke, K., and Bornschein, R. L., 1997, "Field Testing of New Aerosol Sampling Method With a Porous Curved Surface As Inlet," Am. Ind. Hyg. Assoc. J., **58**(10), pp. 713–719.
[134] Aizenberg, V., Choe, K., Grinshpun, S. A., Willeke, K., and Baron, P. A., 2001, "Evaluation of Personal Aerosol Samples Challenged with Large Particles," J. Aerosol Sci., **32**(6), pp. 779–793.
[135] Guffey, S. E., Flanagan, M. E., and van Belle, G., 2001, "Air Sampling at the Chest and Ear As Representative of the Breathing Zone," Am. Ind. Hyg. Assoc. J., **62**(4), pp. 416–427.
[136] Fletcher, B., and Johnson, A. E., 1989, "Comparison of Personal and Area Concentration of Measurements, and the Use of a Mannequin in Sampling," *Proceedings Ventilation '88*, Vincent, J. H., ed., BOHS, London, pp. 161–167.
[137] Fetterolf, D. D., and Clark, T. D., 1993, "Detection of Trace Explosive Evidence by Ion Mobility Spectrometry," J. Forensic Sci., **38**(1), pp. 28–39.
[138] Baret, G., and Gevaud, R., Aug. 30, 1994, "Helium Leak Detector," U.S. Patent 5,341,671.
[139] Jackson, C. N., Sherlock, C. N., and Moore, P. O., 1998, "Leak Testing, Part 5: Sampling Detector Probe Testing of Systems Pressurized with Helium Tracer Gas," in *Nondestructive Testing Handbook*, 2nd Ed., ASNT, Columbus, OH, 1, pp. 478–489.
[140] DeSorbo, M. A., 2001, "Fingerprinting Particles 'Automatically'," Cleanrooms, **15**(10), pp. 1–54.
[141] Anonymous, 2004, "Portable Gas Sample Extraction Probe PSP4000-H/C/T," M&C Products Analysertechnik Gmbh, Ratingen, Germany.
[142] Grasmeyer, J. M., and Keennon, M. T., 2001, "Development of the Black Widow Micro Air Vehicle," AIAA Paper No. 2001-0127.
[143] Mueller, T. J., and DeLaurier, J. D., 2003, "Aerodynamics of Small Vehicles," Annu. Rev. Fluid Mech., **35**, pp. 89–111.
[144] Anderson, G. P., King, K. D., Cuttino, D. S., Whelan, J. P., Ligler, F. S., MacKrell, J. F., Bovais, C. S., Indyke, D. K., and Foch, R. J., 1999, "Biological Agent Detection With the Use of an Airborne Biosensor," Field Anal. Chem. Tech., 3(4–5), pp. 307–314.
[145] Ligler, F. S., Anderson, G. P., Davidson, P. T., Foch, R. J., Ives, J. T., King, K. D., Page, G., Stenger, D. A., and Whelan, J. P., 1998, "Remote Sensing Using an Airborne Biosensor," Environ. Sci. Technol., **32**, pp. 2461–2466.
[146] Brune, W. H., Faloona, I. C., Tan, D., Weinheimer, A. J., Campos, T., Ridley, B. A., Vay, S. A., Collins, J. E., Sachse, G. W., Jaegle, L., and Jacob, D. J., 1998, "Airborne in-Situ OH and HO2 Observations in the Cloud-Free Troposphere and Lower Stratosphere During SUCCESS," Geophys. Res. Lett., **25**(10), pp. 1701–1704.
[147] Porter, J. N., Clarke, A. D., Ferry, G., and Pueschel, R. F., 1992, "Aircraft Studies of Size-Dependent Aerosol Sampling Through Inlets," J. Geophys. Res., [Atmos.], **97**(D4), pp. 3815–3824.
[148] Sheridan, P. J., and Norton, R. B., 1998, "Determination of the Passing Efficiency for Aerosol Chemical Species Through a Typical Aircraft-Mounted, Diffuser-Type Aerosol Inlet System," J. Geophys. Res., [Atmos.], **103**(D7), pp. 8215–8225.
[149] Reed, R. D., 1978, "High-Flying Mini-Sniffer RPV—Mars Bound," Astronaut. Aeronaut., **16**(6), pp. 26–39.
[150] Spedding, G. R., and Lissaman, P. B. S., 1998, "Technical Aspects of Microscale Flight Systems," Journal of Avian Biology, **29**(4), pp. 458–468.
[151] Singh, H., Jacob, D., Pfister, L., and Crawford, J., 2002, "INTEX-NA: Intercontinental Chemical Transport Experiment—North America," National Aeronautics and Space Administration While Paper, http://cloud1.arc.nasa.gov/intex-na/overview/white_paper.pdf.
[152] Kiel, G., 1935, "Total-Head Meter with Small Sensitivity to Yaw," National Advisory Committee for Aeronautics, Technical Memorandum 775, http://naca.larc.nasa.gov/reports/1935/naca-tm-775/
[153] Cain, S. A., Ram, M., and Woodward, S., 1998, "Qualitative and Quantitative Wind Tunnel Measurements of the Airflow Through a Shrouded Airborne Aerosol Sampling Probe," J. Aerosol Sci., **29**(9), pp. 1157–1169.
[154] Soderman, P. T., Hazen, N. L., and Brune, W. H., 1991, "Aerodynamic Design of Gas and Aerosol Samplers for Aircraft," National Aeronautics and Space Administration Technical Memorandum 103854.
[155] Sutton, O. G., 1953, *Micrometeorology*, McGraw-Hill, New York.
[156] Arya, P. S., 2001, *Introduction to Micrometeorology*, Academic, New York.
[157] DeBlieu, J., 1998, *Wind: How Air Flow Has Shaped Life, Myth, and the Land*, Houghton Mifflin, Boston, MA.
[158] Shivik, J. A., 2002, "Odor-Adsorptive Clothing, Environmental Factors, and Search-Dog Ability," Wildlife Soc. Bull., 30(3), pp. 721–727.
[159] Schouest, L. P., and Miller, T. A., 1994, "Automated Pheromone Traps Show Male Pink-Bollworm (Lepidoptera, Gelechiidae) Mating Response Is Dependent on Weather Conditions," J. Econ Entomol., **87**(4), pp. 965–974.
[160] Anonymous, 2001, "Airflow Around Buildings," in *ASHRAE Fundamentals Handbook*, ASHRAE, Atlanta, GA, pp. 16.1–16.12.
[161] Vander Wall, S. B., 1998, "Foraging Success of Granivorous Rodents: Effects of Variation in Seed and Soil Water on Olfaction," Ecology, **79**(1), pp. 233–241.
[162] Jenkins, T. F., Walsh, M. E., Miyares, P. H., Kopczinski, J. A., Ranney, T. A., George, V., Pennington, J. C., and Berry, T. E., 2000, "Analysis of Explosives-Related Chemical Signatures in Soil Samples Collected Near Buried Land Mines," U.S. Army Corps of Engineers Report ERDC TR-00-5, Hanover, NH.
[163] Turner, J. S., 1973, *Buoyancy Effects in Fluids*, Cambridge University, Cambridge, UK.
[164] List, E. J., 1982, "Turbulent Jets and Plumes," Annu. Rev. Fluid Mech., **14**, pp. 189–212.
[165] Scorer, R. S., 1958, *Natural Aerodynamics*, Pergamon, New York.
[166] Settles, G. S., and Kester, D. A., 2001, "Aerodynamic Sampling for Landmine Trace Detection," in *Proc. SPIE—Detection and Remediation Technologies for Mines and Minelike Targets*, VI, Dubey, A. C., et al., eds., International Society for Optical Engineering, Bellingham, WA, 4394, pp. 890–898.
[167] Mollendorf, J. C., Arif, H., and Ajiniran, E. B., 1996, "Developing Flow and Transport Above a Suddenly Heated Horizontal Surface in Water," Int. J. Heat Mass Transfer, **27**(2), pp. 273–289.
[168] Carde, R. T., 1996, "Odour Plumes and Odour-Mediated Flight in Insects," in Ciba Foundation Symposium on Olfaction in Mosquito-Host Interactions, Associated Scientific, Amsterdam, pp. 54–70.
[169] Ishida, H., and Moriizumi, T., 2003, "Machine Olfaction for Mobile Robots," in *Handbook of Machine Olfaction*, T. C. Pearce et al., eds., Wiley, New York, pp. 399–417.
[170] Weissburg, M. J., 2000, "The Fluid Dynamical Context of Chemosensory Behavior," Biol. Bull., **198**(2), pp. 188–202.
[171] Murlis, J., Willis, M. A., and Carde, R. T., 2000, "Spatial and Temporal Structures of Pheromone Plumes in Fields and Forests," Phys. Entomol., 25(3), pp. 211–222.
[172] Vickers, N. J., 2000, "Mechanisms of Animal Navigation in Odor Plumes," Biol. Bull., **198**(2), pp. 203–212.
[173] Finelli, C. M., Pentcheff, N. D., Zimmer-Faust, R. K., and Wethey, D. S., 1999, "Odor Transport in Turbulent Flows: Constraints on Animal Navigation," Limnol. Oceanogr., **44**(4), pp. 1056–1071.
[174] Moore, P. A., and Atema, J., 1991, "Spatial Information in the Three-Dimensional Fine Structure of an Aquatic Odor Plume," Biol. Bull., **181**(12), pp. 408–418.
[175] Moore, P. A., Zimmer-Faust, R. K., Bement, S. L., Weissburg, M. J., Parrish, J. M., and Gerhardt, G. A., 1992, "Measurement of Microscale Patchiness in a Turbulent Aquatic Odor Plume Using a Semiconductor-Based Microprobe," Biol. Bull., **183**(8), pp. 138–142.
[176] Koehl, M. A. R., 1996, "Small-Scale Fluid Dynamics of Olfactory Antennae," Marine Freshwater Behav. Physiol., **27**(2–3), pp. 127–141.
[177] Mead, K. S., Wiley, M. B., Koehl, M. A. R., and Koseff, J. R., 2003, "Fine-Scale Patterns of Odor Encounter by the Antennules of Mantis Shrimp Tracking Turbulent Plumes in Wave-Affected and Unidirectional Flow," J. Exp. Biol., **206**(1), pp. 181–193.
[178] Murlis, J., Elkington, J. S., and Carde, R. T., 1992, "Odor Plumes and How Insects Use Them," Annu. Rev. Entomol., **37**, pp. 505–532.

[179] Weissburg, M. J., and Zimmer-Faust, R. K., 1993, "Life and Death in Moving Fluids: Hydrodynamic Effects on Chemosensory-Mediated Predation," Ecology, **74**, pp. 1428–1443.
[180] Geier, M., Bosch, O. J., and Boeckh, J., 1999, "Influence of Odour Plume Structure on Upwind Flight of Mosquitoes Towards Hosts," J. Exp. Biol., **202**(12), pp. 1639–1648.
[181] Ishida, H., Nakamoto, T., and Moriizumi, T., 1998, "Remote Sensing of Gas/Odor Source Location and Concentration Distribution Using Mobile System," Sens. Actuators B, **49**(1–2), pp. 52–57.
[182] Ishida, H., Nakamoto, T., Moriizumi, T., Kikas, T., and Janata, J., 2001, "Plume-Tracking Robots: A New Application of Chemical Sensors," Biol. Bull., **200**(2), pp. 222–226.
[183] Deveza, R., Thiel, D., Russell, A., and Mackay-Sim, A., 1994, "Odor Sensing for Robot Guidance," Int. J. Robot. Res., **13**, pp. 232–239.
[184] Li, W., Farrell, J. A., and Carde, R. T., 2001, "Tracking of Fluid-Advected Odor Plumes: Strategies Inspired by Insect Orientation to Pheromone," Adaptive Behavior, **9**(3–4), pp. 143–170.
[185] Dusenbery, D. B., 2003, "Mechanisms for Gradient Following," in *Sensors and Sensing in Biology and Engineering*, Springer-Verlag, Vienna, Chap. 21, pp. 291–303.
[186] Grasso, F., Consi, T., Mountain, D., and Atema, J., 1996, "Locating Odor Sources in Turbulence with a Lobster Inspired Robot," in *From Animals to Animats: Proceedings of the International Conference on Simulation Adaptive Behavior*, P. Maes et al., eds., MIT, Cambridge, MA, pp. 104–112.
[187] Anonymous, 2003, "Following Toxic Clouds: Science and Assumptions in Plume Modeling" *Hearing Before Subcommittee on National Security, Emerging Threats & International Relations, Committee on Government Reform, U.S. House of Representatives, 108th Congress, 1st Session, Serial No. 108-91*, US GPO Report 1016-A, http://purl.access.gpo.gov/GPO/LPS47967
[188] Sharan, M., and Gopalakrishnan, S. G., 1997, "Bhopal Gas Accident: a Numerical Simulation of the Gas Dispersion Event," Environ. Model. Software, 12(2–3), pp. 135–141.
[189] Gudiksen, P. H., Harvey, T. F., and Lange, R., 1989, "Chernobyl Source Term, Atmospheric Dispersion, and Dose Estimation," Health Phys., **57**(5), pp. 697–706.
[190] List, E. J., 1996, "Environmental Fluid Mechanics," *Research Trends in Fluid Dynamics: Report from US National Commission on Theoretical & Applied Mechanics*, J. L. Lumley ed., Springer, New York, pp. 148–166.
[191] Sullivan, T. J., Ellis, J. S., Foster, C. S., Foster, K. T., Baskett, R. L., Nasstrom, J. S., and Schalk, W. W., 1993, "Atmospheric Release Advisory Capability-Real-Time Modeling of Airborne Hazardous Materials," Bull. Am. Meteorol. Soc., **74**(12), pp. 2343–2361.
[192] Cowan, I. R., Castro, I. P., and Robins, A. G., 1997, "Numerical Considerations for Simulations of Flow and Dispersion Around Buildings," J. Wind. Eng. Ind. Aerodyn., **67–68**, pp. 535–545.
[193] Boris, J., 2002, "The Threat of Chemical and Biological Terrorism: Preparing a Response," Comput. Sci. Eng., **4**(2), pp. 22–32.
[194] Negus, V. E., 1958, *The Comparative Anatomy and Physiology of the Nose and Paranasal Sinuses*, Livingstone, London.
[195] Bang, B. G., 1971, "Functional Anatomy of the Olfactory System in 23 Orders of Birds," Acta Anat. Suppl. (Basel), **79**, pp. 1–76.
[196] Stacey, M. T., Mead, K. S., and Koehl, M. A. R., 2002, "Molecule Capture by Olfactory Antennules: Mantis Shrimp," J. Math. Biol., **44**(1), pp. 1–30.
[197] U.S. Department of Agriculture, 2004, "Integrated Taxonomic Information System On-Line Database," http://www.itis.usda.gov.
[198] Arnason, U., Adegoke, J. A., Bodin, K., Born, E. W., Esa, Y. B., Gullberg, A., Nilsson, M., Short, R. V., Xu, X. F., and Janke, A., 2002, "Mammalian Mitogenomic Relationships and the Root of the Eutherian Tree," Proc. Natl. Acad. Sci. U.S.A., **99**(12), pp. 8151–8156.
[199] Carroll, R. L., 1997, *Patterns and Processes of Vertebrate Evolution*, Cambridge University, Cambridge, England.
[200] Wayne, R. K., 1993, "Molecular Evolution of the Dog Family," Trends Genet., **9**(6), pp. 218–224.
[201] International Committee on Veterinary Gross Anatomical Nomenclature, 1972, *Nomina Anatomica Veterinaria*, World Association of Veterinary Anatomists, New York.
[202] Wayne, R. K., Leonard, J. A., and Cooper, A., 1999, "Full of Sound and Fury: The Recent History of Ancient DNA," Annu. Rev. Ecol. Syst., **30**, pp. 457–477.
[203] Vogel, S., 1994, "Nature's Pumps," Am. Sci., **82**(5), pp. 464–471.
[204] Benyus, J. M., 1997, *Biomimicry*, William Morrow & Co., New York.
[205] Moniz, E. J., and Baldeswieler, J. D., 2003, "Approaches to Combat Terrorism (ACT): Opportunities for Basic Research," National Science Foundation, http://www.mitre.org/public/act/10_22_final.pdf
[206] Negus, V. E., 1960, "Further Observations on the Air-Conditioning Mechanism of the Nose," Ann. R. Coll. Surg. Engl., **27**, pp. 171–204.
[207] Moulton, D. G., 1967, "Olfaction in Mammals," Am. Zool., **7**, pp. 421–429.
[208] Hillenius, W. J., 1992, "The Evolution of Nasal Turbinates and Mammalian Endothermy," Paleobiology, **18**, pp. 17–29.
[209] Geist, H. R., 2000, "Nasal Respiratory Turbinate Function in Birds," Physiological and Biochemical Zoology, **73**(5), pp. 581–589.
[210] Becker, R. F., and King, J. E., 1957, "Delineation of the Nasal Airstreams in the Living Dog," Arch. Otolaryngol., **65**(5), pp. 428–436.
[211] Neuhaus, W., 1953, "Über die Riechschärfe des Hundes für Fettsäuren," Zeitschrift für Vergleichende Physiologie, 35, pp. 527–552.
[212] Neuhaus, W., 1955, "Die Unterscheidung von Luftquantitaeten bei Mensch und Hund nach Versuchen Mit Buttersäure," Zeitschrift für Vergleichende Physiologie, 37, pp. 234–252.
[213] McCartney, W., 1968, *Olfaction and Odours: An Osphrésiological Essay*, Springer-Verlag, Berlin.
[214] Johnston, J. M., Myers, L. J., Waggoner, L. P., and Williams, M., 1994, "Determination of Canine Olfactory Thesholds using Operant Laboratory Methods," *Proceedings Substance Detection Systems*, Proc. SPIE, **2092**, pp. 238–243.
[215] Johnston, J. M., Williams, M., Waggoner, L. P., Edge, C. C., Dugan, R. E., and Hallowell, S. F., 1998, "Canine Detection Odor Signatures for Mine-Related Explosives," in *Proceedings of SPIE, Detection Remediation Technology for Mines and Minelike Targets III*, Proc. SPIE, **3392**, Part 1, pp. 490–501.
[216] Williams, M., Johnston, J. M., Cicoria, M., Paletz, E., Waggoner, L. P., Edge, C. C., and Hallowell, S. F., 1998, "Canine Detection Odor Signatures for Explosives," Proc. SPIE, **3575**, pp. 291–301.
[217] Williams, M., Johnston, J. M., Cicoria, M., Paletz, E., Waggoner, L. P., Edge, C. C., and Hallowell, S. F., 1998, "Effects of Extraneous Odors on Canine Detection," Proc. SPIE, **3575**, pp. 355–362.
[218] Thesen, A., Steen, J. B., and Doving, K. B., 1993, "Behaviour of Dogs During Olfactory Tracking," J. Exp. Biol., **180**, pp. 247–251.
[219] Steen, J. B., Mohus, I., Kvesetberg, T., and Walloe, L., 1996, "Olfaction in Bird Dogs During Hunting," Acta Physiol. Scand., **157**(1), pp. 115–119.
[220] Evans, H. E., 1993, *Miller's Anatomy of the Dog*, Saunders, Philadelphia.
[221] Anderson, W., Anderson, B. G., and Smith, B. J., 1994, *Atlas of Canine Anatomy*, Lea & Febiger, Philadelphia.
[222] Thomas, E. M., 1993, *The Hidden Life of Dogs*, Houghton Mifflin, Boston, MA.
[223] Johnston, R. E., and Bhorade, A., 1998, "Perception of Scent Over-Marks by Golden Hamsters (Mesocricetus Auratus): Novel Mechanisms for Determining Which Individual's Mark is on Top," J. Comp., Psych., **112**(3), pp. 230–243.
[224] Ferkin, M. H., Dunsavage, J., and Johnston, R. E., 1999, "What Kind of Information do Meadow Voles, *Microtus Pennsylvanicus*, Use to Distinguish Between the Top and Bottom Scent of an Over-Mark?," J. Comp., Psych., **113**(1), pp. 43–51.
[225] Achter, E. K., Hobbs, J. R., Fine, D. H., Dionne, B. C., and Rounbehler, D. P., 1986, "Vapor Pressure of Explosives," J. Energ. Mater., **4**(1–4), pp. 447–472.
[226] Johnson, W. E., and O'Brien, S. J., 1997, "Phylogenetic Reconstruction of the Felidae Using 16S RRNA and NADH-5 Mitochondrial Genes," J. Mol. Evol., **44**(Suppl 1), pp. S98–S116.
[227] Clifford, A. B., and Witmer, L. M., 2004, "Case Studies in Novel Narial Anatomy: 2. The Enigmatic Nose of Moose (Artiodactyla: Cervidae: Alces Alces)," J. Zool., **262**, pp. 339–360.
[228] Shoshani, J., 1997, "It's a Nose! It's a Hand! Its an Elephants' Trunk!," Natural History, **106**(10), pp. 37–43.
[229] Mariappa, D., 1986, *Anatomy and Histology of the Indian Elephant*, Indira Publishing House, Oak Park, MI.
[230] Glebovskii, V. D., and Marevskaya, A. P., 1968, "Participation of Muscles of the Nostrils in Olfactory Analysis and Respiration in Rabbits," Fiziol. Zh., **54**(11), pp. 1278–1286.
[231] Le Guerer, A., 1992, *Scent: The Essential and Mysterious Powers of Smell*, Turtle Bay Books/Random House, New York.
[232] Stoddart, D. M., 1990, *The Scented Ape: The Biology and Culture of Human Odour*, Cambridge University, Cambridge, England.
[233] Proetz, A. W., 1941, *Essays on the Applied Physiology of the Nose*, Annals Publishing Co., St. Louis, Mo.
[234] Eccles, R., 2000, "Nasal Airflow in Health and Disease," Acta Oto-Laryngol., **120**(5), pp. 580–595.
[235] Cole, P., 2000, "Biophysics of Nasal Airflow: A Review," Am. J. Rhinol., **14**(4), pp. 245–249.
[236] Lin, S. J., and Danahey, D. G., 2002, "Nasal Aerodynamics," eMedicine, **3**(4).
[237] Zimmer, C., 2002, "The Rise and Fall of the Nasal Empire," Natural History, **111**(5), pp. 32–35.
[238] Shepherd, G. M., 2004, "The Human Sense of Smell: Are We Better Than We Think?," PLoS Biology, **2**(5), pp. 572–575.
[239] Haselton, F. R., and Sperandio, P. G. N., 1988, "Convective Exchange Between the Nose and the Atmosphere," J. Appl. Physiol., **64**(6), pp. 2575–2581.
[240] Keyhani, K., Scherer, P. W., and Mozell, M. M., 1997, "A Numerical Model of Nasal Odorant Transport for the Analysis of Human Olfaction," J. Theor. Biol., **186**(3), pp. 279–301.
[241] Simmen, D., Scherrer, J. L., Moe, K., and Heinz, B., 1999, "A Dynamic and Direct Visualization Model for the Study of Nasal Airflow," Arch. Otolaryngol. Head Neck Surg., **125**(9), pp. 1015–1021.
[242] Sobel, N., Khan, R. M., Saltman, A., Sullivan, E. V., and Gabrieli, J. D. E., 1999, "Olfaction-The World Smells Different to Each Nostril," Nature (London), **402**(6757), p. 35.
[243] Sobel, N., Prabhakaran, V., Desmond, J. E., Glover, G. H., Goode, R. L., Sullivan, E. V., and Gabrieli, J. D. E., 1998, "Sniffing and Smelling: Separate Subsystems in the Human Olfactory Cortex," Nature (London), **392**(6673), pp. 282–286.
[244] Cheng, Y. S., Hansen, G. K., Su, Y. F., Yeh, H. C., and Morgan, K. T., 1990, "Deposition of Ultrafine Aerosols in Rat Nasal Molds," Toxicol. Appl. Pharmacol., **106**, pp. 222–233.
[245] Kelly, J. T., and Asgharian, B., 2003, "Nasal Molds as Predictors of Fine and

Coarse Particle Deposition in Rat Nasal Airways," Inhalation Toxicol., **15**(9), pp. 859–875.
[246] Kelly, J. T., Kimbell, J. S., and Asgharian, B., 2001, "Deposition of Fine and Coarse Aerosols in a Rat Nasal Mold," Inhalation Toxicol., **13**(7), pp. 577–588.
[247] Morgan, K. T., Kimbell, J. S., Monticello, T. M., Patra, A. L., and Fleischman, A., 1991, "Studies of Inspiratory Air-Flow Patterns in the Nasal Passages of the F344 Rat and Rhesus-Monkey Using Nasal Molds-Relevance to Formaldehyde Toxicity," Toxicol. Appl. Pharmacol., **110**(2), pp. 223–240.
[248] Kauer, J. S., 1968, "A Study of the Structure and Function of the Vomeronasal (Jacobson's) Organ," MA thesis, Clark University, Worcester, MA.
[249] Welker, W. I., 1964, "Analysis of Sniffing of the Albino Rat," Behaviour, **22**, pp. 223–244.
[250] Wilson, D. A., and Sullivan, R. M., 1999, "Respiratory Airflow Pattern at the Rat's Snout and an Hypothesis Regarding its Role in Olfaction," Physiol. Behav., **66**(1), pp. 41–44.
[251] Youngentob, S. L., Mozell, M. M., Sheehe, P. R., and Hornung, D. E., 1987, "A Quantitative Analysis of Sniffing Strategies in Rats Performing Odor Detection Tasks," Physiol. Behav., **41**(1), pp. 59–69.
[252] Kepecs, A., 2004 (unpublished).
[253] Kleerekoper, H., 1969, *Olfaction in Fishes*, Indiana University, Bloomington, IN.
[254] Pohlmann, K., Grasso, F. W., and Breithaupt, T., 2001, "Tracking Wakes: The Nocturnal Predatory Strategy of Piscivorous Catfish," Proc. Natl. Acad. Sci. U.S.A., **98**(13), pp. 7371–7374.
[255] Wallraff, H. G., 2003, "Olfactory Navigation by Birds," Journal für Ornithologie, **144**(1), pp. 1–32.
[256] Wallraff, H. G., 2000, "Simulated Navigation Based on Observed Gradients of Atmospheric Trace Gases (Models on Pigeon Homing, Part 3)," J. Theor. Biol., **205**(1), pp. 133–145.
[257] Wallraff, H. G., and Andreae, M. O., 2000, "Spatial Gradients in Ratios of Atmospheric Trace Gases: A Study Stimulated by Experiments on Bird Navigation," Tellus, Ser. B, **52**(4), pp. 1138–1157.
[258] Bang, B. G., 1966, "The Olfactory Apparatus of Tubenosed Birds (*Procellariiformes*)," Acta Anat. (Basel), **65**, pp. 391–415.
[259] Pennycuick, C. J., 2002, "Gust Soaring as a Basis for the Flight of Petrels and Albatrosses (Procellariiformes)," Avian Science, **2**(1), pp. 1–12.
[260] Witmer, L. M., 2001, "A Nose for All Seasons," Natural History, **110**, pp. 64–71.
[261] Witmer, L. M., 2001, "Nostril Position in Dinosaurs and Other Vertebrates and its Significance for Nasal Function," Science, **293**, pp. 850–853.
[262] Cruickshank, A. R. I., Small, P., and Taylor, M., 1991, "Dorsal Nostrils and Hydrodynamically Driven Underwater Olfaction in Plesiosaurs," Nature (London), **352**, pp. 62–64.
[263] Goldman, J. A., and Patek, S. N., 2002, "Two Sniffing Strategies in Palinurid Lobsters," J. Exp. Biol., **205**(24), pp. 3891–3902.
[264] Koehl, M. A. R., 2001, "Transitions in Function at Low Reynolds Number: Hair-Bearing Animal Appendages," Math. Methods Appl. Sci., **24**(17-18), pp. 1523–1532.
[265] Hansson, B. S., 1999, *Insect Olfaction*, Springer-Verlag, Berlin.
[266] Humphrey, J. A. C., and Haj-Hariri, H., 2002, "Detection and Real Time Processing of Odor Plume Information by Arthropods in Air and Water," *Proceedings of the AFI-2002 Mini-Symposium on Advanced Fluids Information—Fusion of EFD and CFD*, Institute of Fluid Science, Tohoku University, Tokyo, pp. 47–67.
[267] Schneider, R. W. S., Lanzen, J., and Moore, P. A., 1998, "Boundary-Layer Effect on Chemical Signal Movement Near the Antennae of the Sphinx Moth, *Manduca Sexta*: Temporal Filters for Olfaction," J. Comp. Physiol. [A], **182**(3), pp. 287–298.
[268] Loudon, C., and Koehl, M. A. R., 2001, "Sniffing by a Silkworm Moth: Wing Fanning Enhances Air Penetration Through and Pheromone Interception by Antennae," J. Exp. Biol., **203**(19), pp. 2977–2990.
[269] Spielman, A., and D'Antonio, M., 2001, *Mosquito*, Hyperion, New York.
[270] Wright, R. H., 1975, "Why Mosquito Repellents Repel," Sci. Am., **233**(7), pp. 104–111.
[271] Fox, A. N., Pitts, R. J., Robertson, H. M., Carlson, J. R., and Zwiebel, L. J., 2001, "Candidate Odorant Receptors from the Malaria Vector Mosquito Anopheles Gambiae and Evidence of Down-Regulation in Response to Blood Feeding," Proc. Natl. Acad. Sci. U.S.A., **98**(25), pp. 14693–14697.
[272] Takken, W., 1991, "The Role of Olfaction in Host-Seeking of Mosquitoes: A Review," Sci. App. 12(1–3), pp. 287–295.
[273] Dekker, T., Takken, W., Knols, B. G. J., Bouman, E., van de Laak, S., de Bever, A., and Huisman, P. W. T., 1998, "Selection of Biting Sites on a Human Host by Anopheles Gambiae, An-Arabiensis and An-Quadriannulatus," Entomol. Exper. App., 87(3), pp. 295–300.
[274] Knols, B. G. J., Takken, W., Cork, A., and DeJong, R., 1997, "Odour-Mediated, Host-Seeking Behavior of Anopheles Mosquitoes: A New Approach," Ann. Trop. Med. Parasitol., **91**, pp. S117–S118.
[275] Takken, W., 1996, "Synthesis and Future Challenges: The Response of Mosquitoes to Host Odours," Ciba Found Symp., **200**, pp. 302–312.
[276] McIver, S. B., 1982, "Sensilla of Mosquitoes (Diptera:Culicidae)," J. Med. Ethics, **19**, pp. 489–535.
[277] Sutcliffe, J. F., 1994, "Sensory Bases of Attractancy: Morphology of Mosquito Olfactory Sensilla—A Review," J. Am. Mosq. Control Assoc., **10**(2), Part 2, pp. 309–315.
[278] Bidlingmayer, W. L., Day, J. F., and Evans, D. G., 1995, "Effect of Wind Velocity on Suction Trap Catches of Some Florida Mosquitos," J. Am. Mosq. Control Assoc., **11**(3), pp. 295–301.
[279] Békésy, G. v., 1964, "Olfactory Analogue to Directional Hearing," J. Appl. Physiol., **19**(3), pp. 369–373.
[280] Kobal, G., Van Toller, S., and Hummel, T., 1989, "Is there Directional Smelling?," Experientia, **45**(2), pp. 130–132.
[281] Stoddart, D. M., 1979, "External Nares and Olfactory Perception," Experientia, **35**, pp. 1456–1457.
[282] Kajiura, S. M., Forni, J. B., and Summers, A. P., 2005, "Olfactory Morphology of Carcharhinid and Sphyrnid Sharks-Does the Cephalofoil Confer a Sensory Advantage?," J. Morphol., in press.
[283] Vanneste, E., and Geise, H. J., 2003, "Commercial Electronic Nose Instruments," in *Handbook of Machine Olfaction*, T. C. Pearce et al., eds., Wiley, New York, pp. 161–179.
[284] Snopok, B. A., and Kruglenko, I. V., 2002, "Multisensor Systems for Chemical Analysis: State-of-the-Art in Electronic Nose Technology and New Trends in Machine Olfaction," Thin Solid Films, **418**(1), pp. 21–41.
[285] Yinon, J., 2003, "Detection of Explosives by Electronic Noses," Anal. Chem., **75**(5), pp. 99A–105A.
[286] Li, J., 2000, "The Cyranose Chemical Vapor Analyzer," Sensors, **17**(8), pp. 56–60.
[287] Cumming, C., Aker, C., Fisher, M., Fox, M., IaGrone, M., Reust, D., Rockley, M., Swager, T., Towers, E., and Williams, V., 2001, "Using Novel Fluorescent Polymers As Sensory Materials for Above-Ground Sensing of Chemical Signature Compounds Emanating From Buried Landmines," IEEE Trans. Geosci. Remote Sens., **39**(6), pp. 1119–1128.
[288] Albert, K. J., Myrick, M. L., Brown, S. B., James, D. L., Milanovich, F. P., and Walt, D. R., 2003, "Field-Deployable Sniffer for 2,4-Dinitrotoluene Detection," Environ. Sci. Technol., **35**(15), pp. 3193–3200.
[289] Staples, E. J., 2001, "The ZNose," Sensors, **18**(6), pp. 92–97.
[290] Gelperin, A., and Hopfield, J. J., 2002, "Electronic and Computational Olfaction," ACS Symposium Series, **825**, pp. 289–317.
[291] Gelperin, A., Oct. 7, 1997, "Olfactory Sensor Identification System and Method," U.S. Patent 5,675,070.
[292] White, J. E., Waggoner, L. P., and Kauer, J. S., 2004, "Explosives and Landmine Detection Using an Artificial Olfactory System," *Proceedings SPIE Security Defense Conference*, Orlando, Proc. SPIE, **5415**, Paper 35, pp. 521–532.
[293] Kauer, J. S., and White, J. E., 2003, "Representation of Odor Information in the Olfactory System: From Biology to an Artificial Nose," in *Sensors and Sensing in Biology and Engineering*, Springer-Verlag, Vienna, pp. 305–322.
[294] White, J. E., Mall, S., and Kauer, J. S., 2002, "Using Biology to Guide Development of an Artificial Olfactory System," in *Neurotechnology for Biomimetic Robots*, J. Ayers, J. L. Davis, and A. Rudolph, eds., MIT, Cambridge, MA.
[295] Eiceman, G. A., 2002, "Ion-Mobility Spectrometry as a Fast Monitor of Chemical Composition," Trends Analyt. Chem., **21**(4), pp. 259–275.
[296] Hill, H. H., Siems, W. F., StLouis, R. H., and McMinn, D. G., 1990, "Ion Mobility Spectrometry," Anal. Chem., **62**(23), pp. A1201–A1209.
[297] Linker, K. L., Adkins, D. R., Mowry, C. D., Trudell, D. E., Pfeifer, K. B., Sanchez, R. C., and Rohde, S. B., 2001, "Micro-Explosives Detection System μHound™," in *Proceedings of the 3rd FAA International Symposium on Explosives Detection and Aviation Security Technologies*, Atlantic City, NJ, U.S. Federal Aviation Administration.
[298] Call, P., Kenning, V., and Moler, C., 2001, "BioCapture Air Sampler," http://www.mesosystems.com/
[299] McGown, J. B., Bromberg, E. A., and Noble, L. W., Mar. 20, 1990, "Vapor Sampling Probe," U.S. Patent 4,909,090.
[300] Carroll, A. L., Miskolczy, G., Fraim, F. W., Achter, E. K., and Lieb, D. P., June 23, 1992, "Hand-Held Sample Gun for Vapor Collection," U.S. Patent 5,123,274.
[301] Kolb, B., and Ettre, L. S., 1997, *Static Headspace-Gas Chromatography: Theory and Practice*, Wiley-VCH, New York.
[302] Davidson, W. R., and Stott, W. R., 1994, "Synergy or Dichotomy—Vapor and Particle Sampling in the Detection of Contraband," *Proceedings SPIE Conference on Substance Detection Systems*, Innsbruck, Austria, Proc. SPIE, **2092**, pp. 108–119.
[303] Fainberg, A., 1992, "Explosives Detection for Aviation Security," Science, **255**(5051), pp. 1531–1537.
[304] Steinfeld, J. I., and Wormhoudt, J., 1998, "Explosives Detection: A Challenge for Physical Chemistry," Annu. Rev. Phys. Chem., **49**, pp. 203–232.
[305] Bender, E., Hogan, A., Leggett, D., Miskolczy, G., and Macdonald, S., 1992, "Surface Contamination by TNT," J. Forensic Sci., **37**(6), pp. 1673–1678.
[306] Brown, R. H., and Monteith, L. E., 2001, "Gas and Vapor Sample Collectors," in *Air Sampling Instruments for Evaluation of Atmospheric Contaminants*, 9th Ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, pp. 415–455.
[307] Anonymous, 1989, "Part I—General Techniques," in *Methods of Air Sampling and Analysis*, 3rd Ed., J. P. Lodge, ed., Lewis Publishers, New York, pp. 3–58.
[308] Brown, H. R., and Purnell, C. J., 1979, "Collection and Analysis of Trace Organic Vapor Pollutants in Ambient Atmospheres," J. Chromatogr., **178**, pp. 97–80.
[309] Bender, F., Barie, N., Romoudis, G., Voigt, A., and Rapp, A., 2003, "Development of a Preconcentration Unit for a SAW Sensor Micro Array and Its Use for Indoor Air Quality Monitoring," Sens. Actuators B, **93**(1–3), pp. 135–141.

[310] Yinon, J., 1999, *Forensic and Environmental Detection of Explosives*, Wiley, New York.
[311] Fraim, F. W., Achter, E. K., Carroll, A. L., and Hainsworth, E., 1992, "Efficient Collection of Explosive Vapors, Particles and Aerosols," *Proceedings of the 1st International Symposium on Explosives Detection Technology, Nov. 1991*, S. M. Khan, ed., Report DOT/FAA/CT-92/11 U. S. Federal Aviation Administration, Atlantic City, NJ, pp. 559–565.
[312] Achter, E. K., Carroll, A. L., Roundbehler, D. P., Fine, D. H., and Fraim, F. W., Mar. 3, 1992, "Vapor Collector/Desorber With Metallic Ribbon," U.S. Patent 5,092,157.
[313] Linker, K. L., 2001, "Large-Volume Sampling and Preconcentration," in *Proceedings of the 3rd FAA International Symposium on Explosives Detection and Aviation Security Techniques*, U. S. Federal Aviation Administration, Atlantic City, NJ.
[314] Dravnieks, A., 1966, "Odors As Signatures," New Sci., **31**, pp. 622–624.
[315] Aaberg, C. P. N., Aug. 23, 1977, "Method and Apparatus for Exhausting Air from a Limited Zone," U.S. Patent 4,043,257.
[316] Kulmala, I., 2000, "Experimental Validation of Potential and Turbulent Flow Models for a Two-Dimensional Jet-Enhanced Exhaust Hood," Am. Ind. Hyg. Assoc. J., **61**(Mar./Apr.), pp. 183–191.
[317] Burton, D. J., 2000, "Practical Applications of an Aaberg Hood," Occup. Health Saf., **69**(11), pp. 37–39.
[318] Heinsohn, R. J., and Cimbala, J. M., 2002, "Present Local Ventilation Practice," in *Indoor Air Quality Engineering*, Marcel Dekker, New York, pp. 437–515.
[319] Rueeg, T., Gubler, D., Sprecher, P., Moser, A., and Weber, R., 2004, "Local Capture of Contaminants," ASHRAE J., **46**(1), pp. 26–29.
[320] Hunt, G. R., and Ingham, D. B., 1996, "Long Range Exhaustion—A Mathematical Model for the Axisymmetric Airflow of a Local Exhaust Ventilation Hood Assisted by a Turbulent Radial Jet," Ann. Occup. Hyg., **40**(2), pp. 171–196.
[321] Cant, R., Castro, I., and Walklate, P., 2002, "Plane Jets Impinging on Porous Walls," Exp. Fluids, **32**(1), pp. 16–26.
[322] Anonymous, 2001, "Air curtains," in *Industrial Ventilation Design Guidebook*, Academic, San Diego, pp. 553–571.
[323] Stenger, J. B., and Bajura, R. A., 1984, "Deposition in Sampling Tubes," in *Aerosols: Science, Technology and Industrial Applications of Airborne Particles, Proceedings of the First International Aerosol Conference*, Elsevier, New York, pp. 175–178.
[324] Falcitelli, M., Benassi, A., Di Francesco, F., Domenici, C., Marano, L., and Pioggia, G., 2002, "Fluid Dynamic Simulation of a Measurement Chamber for Electronic Noses," Sens. Actuators B, **85**(1–2), pp. 166–174.
[325] Laibach, E., 1937, "Das Geruchsorgan des Aals (Anguilla Vulgaris) in Seinen Verschiedenen Entwicklungsstadien," Zoologische Jahrbucher, Abterlung fur Anatomie und Ontogenie der Tiere, **63**, pp. 37–72.
[326] Rae, W. H., and Pope, A. Y., 1984, *Low-Speed Wind Tunnel Testing*, Wiley, New York.
[327] Mälhammar, A., 2004, "A Method for Comparing Heat Sinks Based on Reynolds Analogy," *Proceedings of the 10th International Workshop on Thermal Investigation of ICs and Systems*, Sophia Antipolis, France, pp. 229–234.
[328] Eckert, E. R. G., and Drake, R. M., 1959, *Heat and Mass Transfer*, McGraw-Hill, NY.
[329] Garimella, S. V., 1996, "Enhanced Air Cooling of Electronic equipment," in *Air Cooling Technology for Electronic Equipment*, S. J. Kim and S. W. Lee, eds., CRC, Boca Raton, FL, pp. 173–202.
[330] Settles, G. S., 2006, "Fluid Mechanics and Homeland Security," submitted to Annu. Rev. Fluid Mech., 38.
[331] Carranza, J. E., Fisher, B. T., Yoder, G. D., and Hahn, D. W., 2001, "On-Line Analysis of Ambient Air Aerosols Using Laser-Induced Breakdown Spectroscopy," Spectrochim. Acta, Part B, **56**(6), pp. 851–864.
[332] Myers, L. J., 1992, "The Dog-Handler Team as a Detection System for Explosives: A Tail to be Told," *Proceedings of the Conference on the Aviation Security Problem and Related Technologies*, W. H. Makky, ed., SPIE CR42, San Diego, pp. 93–103.
[333] Furton, K. G., and Myers, L. J., 2001, "The Scientific Foundation and Efficacy of the Use of Canines As Chemical Detectors for Explosives," Talanta, **54**(3), pp. 487–500.
[334] Gazit, I., and Terkel, J., 2003, "Explosives Detection by Sniffer Dogs Following Strenuous Physical Activity," App. Animal Behav. Sci., 81(2), pp. 149–161.
[335] Gazit, I., Lavner, Y., Bloch, G., Azulai, O., Goldblatt, A., and Terkel, J., 2003, "A Simple System for the Remote Detection and Analysis of Sniffing in Explosives Detection Dogs," Behav. Res. Methods Instrum. Comput., **35**(1), pp. 82–89.
[336] Rooney, N. J., Bradshaw, J. W. S., and Almey, H. E., 2004, "Attributes of Specialist Search Dogs-A Questionnaire Survey of UK Dog Handlers and Trainers," J. Forensic Sci., **49**(2), pp. 300–306.
[337] Ternes, J. W., and Prestrude, A. M., 1992, "Integration of the Human, Canine, Machine Interface for Explosives Detection," *Proceedings of the 1st International Symposium on Explosive Detection Technology*, S. M. Khan, ed., Report DOT/FAA/CT-92/11 U. S. Federal Aviation Administration, Atlantic City, NJ, pp. 891–902.
[338] Settles, G. S., 1999, "Schlieren and Shadowgraph Imaging in the Great Outdoors," *Proceedings of the 2nd Pacific Symposium on Flow Visualization and Image Processing*, S. Mochizuki, ed., Honolulu, Pacific Center of Thermal-Fluids Engineering, Tokyo.
[339] Fine, D. H., Fraim, F. W., MacDonald, S. J., and Thrash, K. M., Dec. 27, 1994, "Method and System for Sampling and Determining the Presence of Compounds in Containers," U.S. Patent 5,376,550.
[340] Davidson, W. R., Stott, W. R., Akery, A. K., and Sleeman, R., 1992, "The Role of Mass Spectrometry in the Detection of Explosives," *Proceedings of the 1st International Symposium on Explosive Detection Technology*, S. M. Khan, ed., Report DOT/FAA/CT-92/11, U. S. Federal Aviation Administration, Atlantic City, NJ, pp. 663–667.
[341] Cartwright, P. A., Alcock, N. J., Groves, D. M., Almey, H. E., and Brookes, M. D., 2001, "Development of Performance Evaluation Tubes for Remote Air Sampling for Canine Olfaction (RASCO)," in *Proceedings of the 3rd FAA International Symposium on Explosives Detection and Aviation Security Technologies*, U. S. Federal Aviation Administration, Atlantic City, NJ.
[342] Lord, D., 2004, "RASCO: A New Cargo Screening Methodology Comes of Age," Aviation Security International, **9**(4), p. 34.
[343] Jenkins, A., Mar. 9, 1976, "Inspection Apparatus," U.S. Patent 3,942,357.
[344] Ornath, F., and Beuchler, S. S., Aug. 24, 1999, "Method and Apparatus for Sampling Contaminants," U.S. Patent 5,942,699.
[345] Smith, D. J., 2005, "The Internal Airflow in Cargo Containers and Methods to Sample it for Chemical Trace Detection," M.S. Thesis, Pennsylvania State University, State College PA.
[346] Anonymous, 1996, "Airline Passenger Security Screening—New Technologies and Implementation Issues," US National Research Council Report NMAB-482-1, U. S. National Academy of Science, Washington, DC.
[347] Anonymous, 2002, "People Screening Weapon & Explosives Detection," Market Report 2003–2010, Homeland Security Research Corp., San Jose, CA.
[348] Hallowell, S. F., 2001, "Screening People for Illicit Substances: a Survey of Current Portal Technology," Talanta, **54**(3), pp. 447–458.
[349] Dravnieks, A., 1975, "Evaluation of Human Body Odor: Methods and Interpretations," J. Soc. Cosmet. Chem., **26**(11), pp. 551–571.
[350] Bethune, D. W., Blowers, R., Parker, M., and Pask, E. A., 1965, "Dispersal of *Staphylococcus Aureus* by Patients and Surgical Staff," Lancet, **318**, pp. 480–483.
[351] Whyte, W., Vesley, D., and Hodgson, R., 1976, "Particle Dispersion in Relation to Operating Room Clothing," J. Hyg. (Lond), **76**, pp. 367–378.
[352] Whyte, W., 2001, *Cleanroom Technology: Fundamentals of Design, Testing, and Operation*, Wiley, New York.
[353] Settles, G. S., Gowadia, H. A., Strine, S. B., and Johnson, T. E., 1996, "The Natural Aerodynamic Sampling of Trace Explosives From the Human Body," *Proceedings of the 2nd FAA Conference on the Aviation Security Problem and Related Technologies*, W. H. Makky, ed., SPIE CR42, Atlantic City, NJ, pp. 65–70.
[354] Settles, G. S., Ferree, H. C., Tronosky, M. D., Moyer, Z. M., and McGann, W. J., 2001, "Natural Aerodynamic Portal Sampling of Trace Explosives From the Human Body," in *Proceedings 3rd FAA International Symposium on Explosive Detection and Aviation Security*, U. S. Federal Aviation Administration, Atlantic City, NJ.
[355] Achter, E. K., Burke, E. J., Miskolczy, G., and Sonin, A. A., Mar. 20, 1990, "Walk-in Inspection Apparatus for Producing Air Samples," U.S. Patent 4,909,089.
[356] Linker, K. L., Hannum, D. W., and Conrad, F. J., June 22, 1999, "Vertical Flow Chemical Detection Portal," U.S. Patent 5,915,268.
[357] Settles, G. S., June 13, 2000, "Chemical Trace Detection Portal Based on the Natural Airflow and Heat Transfer of the Human Body," U.S. Patent 6,073,499.
[358] Davies, J. H., Apr. 23, 2002, "Apparatus and Method for Screening People and Articles to Detect and/or to Decontaminate with Respect to Certain Substances," U.S. Patent 6,375,697.
[359] Phares, D. J., Holt, J. K., Smedley, G. T., and Flagan, R. C., 2000, "Method for Characterization of Adhesion Properties of Trace Explosives in Fingerprints and Fingerprint Simulations," J. Forensic Sci., **45**(4), pp. 774–784.
[360] Neudorfl, P., McCooeye, M. A., and Elias, L., 1993, "Testing Protocol for Surface-Sampling Detectors," *Proceedings of the 4th International Symposium on the Analysis and Detection of Explosives*, J. Yinon, ed., Kluwer Academic, New York, pp. 373–384.
[361] Sorensen, D. N., and Voight, L. K., 2003, "Modelling Flow and Heat Transfer Around a Seated Human Body by Computational Fluid Dynamics," Build. Environ., **38**(6), pp. 753–762.
[362] Murakami, S., Kato, S., and Zeng, J., 2000, "Combined Simulation of Airflow, Radiation and Moisture Transport for Heat Release From a Human Body," Build. Environ., **35**(6), pp. 489–500.
[363] Craven, B. A., and Settles, G. S., 2005, "A Computational and Experimental Investigation of the Human Thermal Plume," submitted to J. Biomech. Eng.
[364] Schellenbaum, R. L., 1987, "Air Flow Studies for Personnel Explosives Screening Portals," *Proceedings of the 1987 Carnahan Conference on Security Technology: Electronic Crime Countermeasures*, Lexington, KY, IEEE, New York, pp. 101–105.
[365] Hobbs, J. R., and Conde, E. P., 1993, "Analysis of Airflows in Personnel Screening Booths," *Proceedings of the Fourth International Symposium on the Analysis and Detection of Explosives*, J. Yinon, ed., Kluwer Academic, New York, pp. 437–453.
[366] Daws, L. F., 1970, "Movement of Airstreams Indoors," J. Inst. Heat. Vent. Eng., 37(2), pp. 241–253.
[367] Parmeter, J. E., Linker, K. L., Rhykerd, C. L., Hannum, D. W., and Bouchier, F. A., 1998, "Explosives Detection Portal for High-Volume Personnel Screening," in *Enforcement and Security Technologies*, Proc. SPIE, **3575**, pp. 384–391.

[368] Linker, K. L., and Brusseau, C. A., Jan. 1, 2002, "Target Detection Portal," U.S. Patent 6,334,365.
[369] Whyte, W., and McGeorge, D., 1994, "Evaluating the Effects of a Cleanroom Air Shower on Particle Dispersion," Microcontamination, **12**(9), pp. 39–41, 69.
[370] Batill, S. M., and Hoffman, J. J., 1986, "Aerodynamic Design of Three-Dimensional Subsonic Wind Tunnel Inlets," AIAA J., **24**(2), pp. 268–269.
[371] Settles, G. S., and McGann, W. J., 2001, "Potential for Portal Detection of Human Chemical and Biological Contamination," in *Aerosense 2001: Sensor Technology and Application*, SPIE-International Society for Optical Engineering **4378**, Paper 01.
[372] Edge, B. A., Paterson, E. G., and Settles, G. S., 2005, "Computational Study of the Wake and Contaminant Transport of a Walking Human," submitted to ASME J. Fluids Eng.
[373] Rodes, C. E., Kamens, R. M., and Wiener, R. W., 1995, "Experimental Considerations for the Study of Contaminant Dispersion Near the Body," Am. Ind. Hyg. Assoc. J., **56**(6), pp. 535–545.
[374] Kim, T., and Flynn, M. R., 1991, "Airflow Pattern Around a Worker in a Uniform Freestream," Am. Ind. Hyg. Assoc. J., **52**(7), pp. 287–296.
[375] Flynn, M. R., and Miller, C. T., 1991, "Discrete Vortex Methods for the Simulation of Boundary-Layer Separation Effects on Worker Exposure," Ann. Occup. Hyg., **35**(1), pp. 35–50.
[376] Flynn, M. R., and Ljungqvist, B., 1995, "A Review of Wake Effects on Worker Exposure," Ann. Occup. Hyg., **39**(2), pp. 211–221.
[377] Murakami, S., Zeng, J., and Hayashi, T., 1999, "CFD Analysis of Wind Environment Around a Human Body," J. Wind. Eng. Ind. Aerodyn., **83**, pp. 393–408.
[378] Moyer, Z. M., 2003, "The Human Aerodynamic Wake and the Design of a Portal to Sample It," M.S. thesis, Pennsylvania State University, University Park, PA.
[379] Craven, B. A., and Settles, G. S., 2005, "The Design of a Chemical Trace Detection Portal That Samples the Aerodynamic Wake of a Walking Person," in preparation.
[380] Anonymous, 1998, *Hidden Killers: The Global Landmine Crisis*, U.S. Dept. of State Publication 10575.
[381] Andersson, N., Dasousa, C. P., and Paredes, S., 1995, "Social Cost of Land Mines in 4 Countries—Afghanistan, Bosnia, Cambodia, and Mozambique," Br. Med. J., **311**(7007), pp. 718–721.
[382] Ashley, S., 1996, "Searching for Land Mines," Mech. Eng. (Am. Soc. Mech. Eng.), **118**(4), pp. 62–67.
[383] Strada, G., 1996, "The Horror of Land Mines," Sci. Am., **278**(5), pp. 40–45.
[384] Pamula, V. K., 2003, "Detection of Explosives," in *Handbook of Machine Olfaction*, T. C. Pearce et al., eds., Wiley, New York, pp. 547–580.
[385] Phelan, J., and Webb, S. W., 1998, "Simulation of the Environmental Fate and Transport of Chemical Signatures From Buried Landmines," *Proceedings of the 1999 Detection and Remediation Technologies for Mines and Minelike Targets III*, Proc. SPIE, **3392**(1), pp. 509–520.
[386] George, V., Jenkins, T. F., Leggett, D. C., Cragin, J. H., Phelan, J., Oxley, J., and Pennington, J., 1999, "Progress on Determining the Vapor Signature of a Buried Land Mine," *Proceedings of the SPIE Aerosense Conference*, Orlando, FL, Proc. SPIE, **3710**, pp. 258–269.
[387] Jenkins, T. F., Leggett, D. C., Miyares, P. H., Walsh, M. E., Ranney, T. A., Cragin, J. H., and George, V., 2001, "Chemical Signatures of TNT-Filled Land Mines," Talanta, **54**(3), pp. 501–513.
[388] Morgan, J. S., Bryden, W. A., Miragliotta, J. A., and Aamodt, L. C., 1999, "Improved Detection of Explosive Residues by Laser Thermal Desorption," Johns Hopkins APL Tech. Dig., **20**(3), pp. 389–395.
[389] Fair, R. B., Pollack, M., and Pamula, V. K., 1998, "MEMS Devices for Detecting the Presence of Explosive Material Residues in Mine Fields," in *Proceedings of the 1999 Detection and Remediation Technologies for Mines and Minelike Targets III*, Proc. SPIE, **3392**(1), pp. 409–417.
[390] Fisher, M., Cumming, C., IaGrone, M., and Taylor, R., 1998, "An Electrostatic Particle Sampler and Chemical Sensor System for Landmine Detection by Chemical Signature," *Proceedings of the 1998 Detection and Remediation Technologies for Mines and Minelike Targets III*, Proc. SPIE, **3392**(1), pp. 565–574.
[391] Morrocco, J. D., 2000, "Field Trials in Kosovo Test Mine Detection," Aviat. Week Space Technol., **156**, p. 38.
[392] Turner, A. P. F., 2000, "Biosensors—Sense and Sensitivity," Science, **290**(5495), pp. 1315–1317.
[393] Cole, L. A., 2003, *The Anthrax Letters: A Medical Detective Story*, Joseph Henry Press, Washington DC.
[394] Pope, C., 1928, "The Diagnostic Art of Smelling," Am. J. Med., **34**, pp. 651–653.
[395] Hayden, G. F., 1980, "Olfactory Diagnosis in Medicine," Postgrad Med. J., **67**(4), pp. 110–118.
[396] Tassopoulos, C. N., Barnett, D., and Fraser, T. R., 1969, "Breath-Acetone and Blood-Sugar Measurements in Diabetes," Lancet, **1**(1282), pp. 1286.
[397] McSherry, J., 1986, "Sniffing Out the Diagnosis," Can. Med. Assoc. J., **135**(10), pp. 1070.
[398] Smith, K., Thompson, G. F., and Koster, H. D., 1969, "Sweat in Schizophrenic Patients: Identification of the Odorous Substance," Science, **166**, pp. 398–399.
[399] Distelheim, I. H., and Dravnieks, A., 1973, "A Method for Separating Characteristics of Odors in Detection of Disease Processes 1," Int. J. Dermatol., **12**(4), pp. 241–244.
[400] Di Natale, C., and D'Amico, A., 2001, "The Electronic Nose Analysis of Breath As Potential Diagnostic Tool: the Case of Lung Cancer," *Proceedings of the Eighth International Symposium on Olfaction and the Electronic Nose*, J. R. Stetter and W. R. Penrose, eds., The Electrochemical Society, Washington DC, pp. 48–53.
[401] Krüger, U., Körber, R., Ziegler, K.-H., Koronczi, I., Nachnani, S., and Goschnick, J., 2001, "Electronic Noses Towards Practical Application in Medical Diagnostics," *Proceedings of the Eighth International Symposium on Olfaction and the Electronic Nose*, J. R. Stetter and W. R. Penrose, eds., The Electrochemical Society, Washington DC, pp. 62–64.
[402] Lawrence, A. H., Nanji, A. A., and Taverner, J., 1988, "Skin-Sniffing Ion Mobility Spectrometric Analysis—A Potential Screening Method in Clinical Toxicology," J. Clin. Lab Anal, **2**(2), pp. 101–107.
[403] Batterman, S. A., Franzblau, A., and Zhou, N.-Z., 1996, "Airborne Emissions at Skin Surfaces: a Potential Biological Exposure Index," Int. Arch. Occup. Environ. Health, **68**, pp. 268–274.
[404] Stetter, J. R., Penrose, W. R., Kubba, S., Kocka, F., McEntegart, C. M., Roberts, R. R., and Iademarco, M. F., 2001, "Enhancement of the Sensitivity of the Electronic Nose for Bacterial Applications," *Proceedings of the Eighth International Symposium on Olfaction and the Electronic Nose*, J. R. Stetter and W. R. Penrose, eds., The Electrochemical Society, Washington DC, pp. 54–61.
[405] Roller, C., Namjou, K., Jeffers, J. D., Camp, M., Mock, M., McCann, P. J., and Grego, J., 2002, "Nitric Oxide Breath Testing by Tunable-Diode Laser Absorption Spectroscopy: Application in Monitoring Respiratory Inflammation," Appl. Opt., **41**(28), pp. 6018–6029.
[406] Pavlou, A. K., and Turner, A. P. F., 2000, "Sniffing Out the Truth: Clinical Diagnosis Using the Electronic Nose," Clin. Chem. Lab. Med., **38**(2), pp. 99–112.
[407] Persaud, K. C., Pisanelli, A. M., and Evans, P., 2003, "Medical Diagnostics and Health Monitoring," in *Handbook of Machine Olfaction*, T. C. Pearce et al., eds., Wiley, New York, pp. 445–460.
[408] Settles, G. S., 2004, "The Penn State Full-Scale Schlieren System," *Proceedings of the 11th International Symposium on Flow Visualization*, T. J. Mueller and I. Grant, eds., Notre Dame University, IN.
[409] Kaminski, R. K., 1980, "Leak Detection: A Route to Conservation and Safety," Proc., Am. Pet. Inst., Sect. 3, **59**, pp. 37–41.
[410] Peale, R. E., and Summers, P. L., 1996, "Zebra Schlieren Optics for Leak Detection," Appl. Opt., **35**(22), pp. 4518–4521.
[411] Settles, G. S., 1999, "Imaging Gas Leaks by Using Schlieren Optics," Pipeline and Gas Journal, **226**(9), pp. 28–30.
[412] Mcrae, T. G., and Kulp, T. J., 1993, "Backscatter Absorption Gas Imaging—A New Technique for Gas Visualization," Appl. Opt., **32**(21), pp. 4037–4050.
[413] Kher, U., 2000, "Electronic Noses Sniff Out a Market or Two," Time, **155**(11), pp. 64–65.
[414] Aston, C., 2001, "Biological Warfare Canaries," IEEE Spectrum, **38**(10), pp. 35ff.
[415] Olender, T., Fuchs, T., Linhart, C., Shamir, R., Adams, M., Kalush, F., Khen, M., and Lancet, D., 2004, "The Canine Olfactory Subgenome," Genomics, **83**(3), pp. 361–372.