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Effect of respiratory airflow rate on removal of soluble vapors by the nose

E. F. AHARONSON, H. MENKES, G. GURTNER, D. L. SWIFT, AND D. F. PROCTOR
Department of Environmental Medicine and Department of Medicine, The Johns Hopkins University, Baltimore, Maryland 21205

AHARONSON, E. F., H. MENKES, G. GURTNER, D. L. SWIFT, AND D. F. PROCTOR. *Effect of respiratory airflow rate on removal of soluble vapors by the nose.* J. Appl. Physiol. 37(5): 654–657. 1974.—The effect of respiratory airflow rate on the uptake of acetone by the nose was measured. The uptake coefficient (*R*), which describes the average flux of soluble vapor into the nasal walls per unit partial pressure in the gas stream, rose more than 50% when the flow of air containing acetone increased from 2 to 5 liters/min. The uptake of ether was also measured, and calculations from data reported in the literature were made, which showed that *R*'s for ether, ozone, and SO_2 also increase with airflow rate. The increased *R* at higher airflow rates markedly reduces the amount of soluble air pollutant reaching the lungs at these flow rates.

air pollution; defense mechanism; nasal breathing; soluble gas

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FOR THE DEFENSE OF THE LUNG against polluted air, the upper respiratory tract can remove and retain foreign materials. It effectiveness for the removal of various vapors and particles when concentration and ventilation rates are varied has been studied and reported in the literature (1, 2, 4–6, 8, 10). In most cases the role of the nose has been looked at indirectly, i.e., by the comparison of retentions during nasal or mouth breathing. In the present study the effect of of airflow rate on the uptake of soluble vapors by the nose was examined with the nose isolated from the rest of the respiratory system. A theoretical approach to the problem served in analyzing both the data reported here and those available from the literature and demonstrated that the nose increases its efficacy in removing contamination when airflow increases.

THEORY

The theoretical approach is based on a simplified unidimensional model of the nose, which is shown schematically in Fig. 1. The *x* axis represents the center of an inspired air stream passing through the nose. Some of the foreign vapors contained in that air are lost to the surrounding mucus and may go to the bloodstream if they diffuse through the mucus and mucosal tissue. For simplicity only the quasisteady state achieved when the flow of air is maintained in one direction will be considered. The tendency of a specific substance to be lost in such a process can be estimated by a local uptake coefficient, *r*, defined as the flux (amount of material flowing per unit area and unit time) through the walls per unit partial pressure difference between air and blood ($\Delta P = P_A - P_{BL}$). *r* depends not only upon the properties of the foreign material, but also upon the type of flow in the airstream, the local geometry, the amount of mucus secreted to that area, and the perfusion of the surrounding tissues; hence *r* may be a function of distance along the *x* axis (*x*). The area of contact between mucus-lined tissue and air, along the segment from x_0 (a point along the airstream) to $x_0 + dx$, can be expressed as $l \cdot dx$, where *l* is the perimeter of the air passage, which is also a function of *x*. Using these definitions one can express the local flux out of the air stream by $r \cdot \Delta P \cdot l \cdot dx$. Since the flux must affect the partial pressure of the substance in the main stream, the rate of removal can be expressed as $\dot{V} \cdot dP_A/P_B$, where $\dot{V}$ is the volume flow rate of the airstream, P_B is the barometric pressure, and dP_A the change in partial pressure along the above-mentioned distance, d*x*. A major assumption is made—that the nose is not a single-unit mixing chamber—so that P_A decreases along *x* as the vapor is removed.

When a steady state is achieved, and if the driving pressure for flux is assumed to be the pressure in the airstream, i.e., the back pressure in the blood is neglected

$$\frac{-\dot{V} \cdot dP_A}{P_B} = r \cdot P_A \cdot l \cdot dx \tag{1}$$

Rearranging

$$\frac{dP_A}{P_A} = \frac{-P_B}{\dot{V}} \cdot r(x) \cdot l(x)\, dx \tag{2}$$

Integrating

$$\ln \frac{P_A^{out}}{P_A^{in}} = \frac{-P_B}{\dot{V}} \int_{x^{in}}^{x^{out}} r \cdot l \cdot dx \tag{3}$$

The unsolved integral in the right-hand term of *Eq. 3* is, by definition, an overall uptake coefficient (*R*) resulting from summation of local coefficients along the whole nasal path. Ideally speaking, if the local coefficients were the same r^* throughout the nose, the derivation of *Eq. 3* could have been pursued to give

$$P_A^{out} = P_A^{in} \cdot e^{-\left(\frac{r^*}{\dot{V}} \cdot A \cdot P_B\right)} \tag{4}$$

where *A* is the surface area of contact. Furthermore, if the shape under consideration were cylindrical, the gradient seen when going downstream would be exponential. Un-

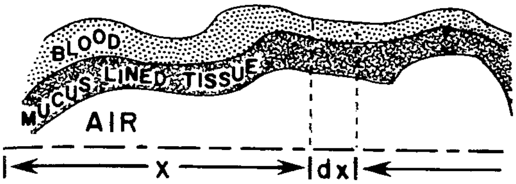

FIG. 1. Model of the nose. Air containing a soluble vapor flows along the x axis.

fortunately, the local r and l cannot be estimated as functions of x. Still, the value of the integral (R) can be derived from *Eq. 3* if the necessary partial pressures and airflow rate are known.

In this analysis there are no assumptions regarding factors affecting local uptake other than zero back pressure. Whether the rate of uptake is limited by diffusion through the gas phase, diffusion through the tissue, chemical reactions in the tissue, or local blood flow in the tissues, the analysis holds so long as the rate of uptake is proportional to the pressure of the vapor in the gas phase.

METHODS

Mongrel dogs weighing approximately 20 kg were anesthetized. The nasal passage was isolated in a manner similar to that reported by others (2, 3, 11) (Fig. 2). The dog's trachea was cannulated so that it breathed spontaneously during the experiments. A one-way stream of air containing an inert tracer gas, argon, along with a soluble gas, either ether or acetone, could then be passed through the nasal passage. Each exposure was preceded by a relatively long wash with uncontaminated air. The partial pressures of the added gases were measured by a mass spectrometer (Bendix, MA-1, time of flight). The mass spectrometer sampled continuously at a very slow rate from two locations: the entrance to the nose (in) and near the outlet from the trachea (out). The same probe was moved back and forth between the two sampling positions throughout the experiment. To avoid condensation of water vapor inside the capillary tube connecting to the mass spectrometer, continuous flow through the tube was maintained, and a fluido-dynamic resistance was applied to the tip (7). The 90 % response time of this system was better than 0.5 s for the gases used. At a fixed composition the ratio of the reading of soluble vapor to that of argon did not change when the mixture was heated by 15°C, although the absolute readings did change. Absolute concentrations of argon and acetone were not measured. The volume flow rates were estimated by a spirometer attached to a bag in box.

RESULTS

An experimental record is shown in Fig. 3. It shows the buildup of both argon and acetone at the outlet after the onset of exposure. The probe was then alternated between the inlet and outlet. The last portion of the record shows outlet readings at the end of the exposure, namely after the gas supply had been switched to clean air. During the switch to clean air acetone in the nose continued to be absorbed, while argon was not. This may account for the apparent early onset of acetone washout.

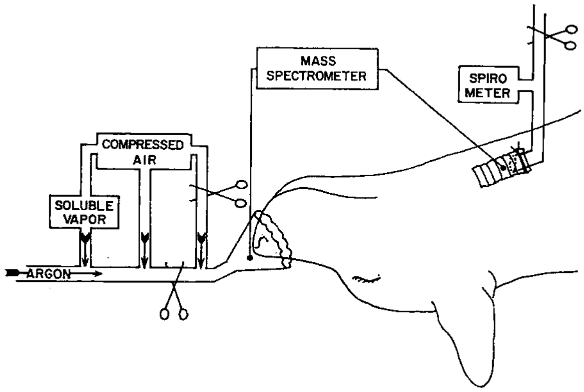

FIG. 2. Isolated nose of a dog. A constant flow of air containing argon and a soluble vapor is passed through the nose. A mass spectrometer measures contaminant gases, and a spirometer measures airflow rates.

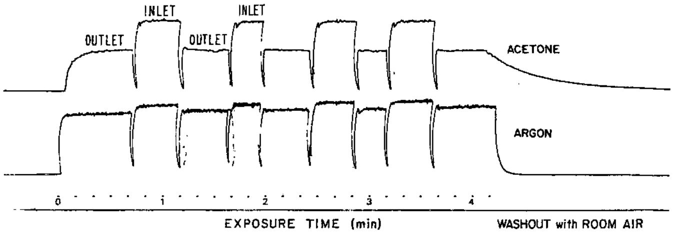

FIG. 3. Record of mass spectrometer readings of acetone and argon at the inlet and outlet of the nose.

Argon, which is relatively insoluble in the nose, served as a tracer for changes in the sampling rate related to temperature effects and dilutions with water vapor. Therefore, the acetone reading (Ac) was expressed relative to that of argon (Ar) at the same time. No correction for possible differences in the rate of saturation of the inspired gas with water vapor was made. Figure 4 shows that a few minutes after beginning the exposure, a quasi-steady state was achieved in which Ac at the output was appreciably lower than that at the input, and the ratio of the two remained constant for relatively long periods of time.

For evaluation of R and the effect on it of airflow rate, the back pressure of acetone was neglected (its partial pressure in blood was assumed to be zero). In Fig. 5 the steady-state values of $(\mathrm{Ac}^{\mathrm{out}})/(\mathrm{Ac}^{\mathrm{in}})$ vs. $1/\dot{V}$ on a semilogarithmic scale are given. The point of the origin should be added to the measured data since the absorption capability of the system is limited, i.e., as flow rates approach infinity, $\mathrm{Ac}^{\mathrm{out}}$ approaches $\mathrm{Ac}^{\mathrm{in}}$. The slope of a line extending from the origin to a point on the curve represents R for the $\dot{V}$ corresponding to that point. It can be seen that R rises as $\dot{V}$ increases, i.e., as the mean transit time decreases. In this case R more than doubled when flow rose from 0.75 l/min to 7.5 l/min. Figure 6 shows results obtained with acetone and, for comparison, results from a single experiment with ether. R for ether is much lower than for acetone, but it also increases as flow goes up. Also shown are curves constructed from data on ozone and SO_2 uptake reported in the literature. The increase in R as $\dot{V}$ increases is again obvious.

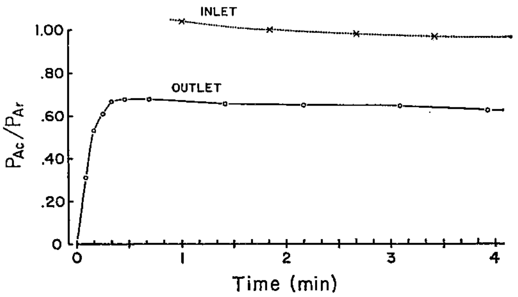

FIG. 4. Buildup of outlet concentration of acetone to quasi-steady state. P_{Ac} = partial pressure of acetone; P_{Ar} = partial pressure of argon.

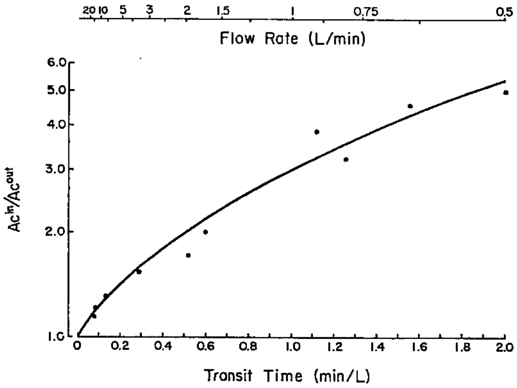

FIG. 5. Effect of airflow rate on removal of acetone by the nose in one experiment. The line was drawn by eye to fit the points. Ac^{in} = pressure of acetone entering the nose (relative to argon); Ac^{out} = pressure of acetone leaving the nose (relative to argon).

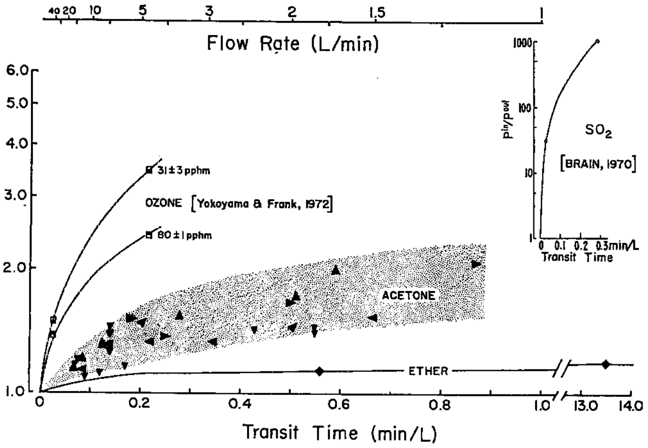

FIG. 6. Effect of airflow rate on acetone, ether, ozone, and SO_2 removal by the nose. Data for ozone were taken from (11) and data for SO_2 were taken from (1). P^{in}/P^{out} = pressure entering the nose relative to pressure leaving the nose. Shaded area includes experimental points for acetone; different symbols refer to results in different dogs.

DISCUSSION

The model makes use of the definition of the local uptake coefficient, r, stating that after the system has reached its steady state, the local rate of removal at each point is linearly proportional to the driving force (partial pressure difference) and to the area of contact. It does not hypothesize any relation with regard to x or to factors that might affect the efficiency of removal, e.g., concentration or airflow rate. The overall uptake coefficient, R, results from integration of the local coefficients with respect to the contact area, thus describing the flux into the nasal walls per unit driving pressure. If R is independent of airflow rate and of the partial pressure in the airstream, there will be a linear relation between the logarithm of the ratio of outlet to inlet partial pressures and the average transit time, i.e., reciprocal of flow rate. (For example, in a case where 10% of the inhaled soluble vapor passes through the nose at a given flow if the $\dot{V}$ is doubled, the level at the outlet should rise to 32%.)

Since it was not possible to measure back pressure in the nasal tissue or blood, we assumed it to be zero. This assumption might be justified for materials highly soluble in fat or water on the basis of the big dilution taking place in various parts of the body. However, it is not at all certain that back pressure is not exerted locally at the nose even with as soluble a substance as acetone. Still, assuming zero back pressure, we tended to underestimate R more at higher flow rates when the larger uptake will result in a significant back pressure sooner.

A major assumption in the analysis is that the partial pressure of the soluble gas falls progressively as it passes through the nose. This is preferred to an alternative assumption, that the uptake of soluble materials in the nose is analogous to exchange of gas in an alveolus. It is unlikely that perfect mixing takes place in the nose resulting in a common driving pressure for uptake, i.e., the outlet pressure. For this reason the former assumption has been used and forms the basis for the analysis.

R differed from dog to dog but always increased with increasing airflow rate. The increased coefficient means that at a higher flow rate, the retention is increased by more than can be accounted for by the higher partial pressure difference created. Figure 6 shows this to be true for ozone and SO_2 as well as for acetone and ether. The fact that this interpretation of available data has been largely overlooked must be attributed to the yardstick used in measurements of retention. For example, when Yokoyama and Frank (11) stated that "the uptake of O_3 was inversely related to flow," they were examining the effect of an 8-fold increase in flow rate and found the retention to decrease from approximately 71% to 33%. But if R did not improve at higher flows, they should have observed a decrease to 15%. Frank et al. (8) and Brain (1) described results for SO_2 in which penetration went up from 0.1% to 3.2% with a 10-fold increase in airflow rate. As emphasized by Brain, this represents a 32-fold increase in the amount of SO_2 presented to the trachea. However, had R not changed with flow rate, the level in the trachea would have reached 50% rather than 3.2%, i.e., the penetration would have been increased 500-fold.

We considered four explanations for the improved uptake coefficient with increased airflows:

1) If the uptake coefficients are concentration dependent such that R is greater at higher values of P_A, the effect of increasing airflow rate would be to increase uptake due to the higher levels of contaminant present along the x axis for the same input levels. In fact, Brain pointed out that SO_2 retention increased at higher concentrations. On the other hand, Yokoyama and Frank measured ozone uptake in two ranges of airflow rate and showed that *R* decreased when concentration went up (Fig. 6). Egle (5, 6), measuring the uptake of acetaldehyde, found no effect of changes in concentration. In our experiments since absolute concentrations were not measured, the possible effects of an increased P_A are difficult to assess. However, in one experiment where the output concentration at a low airflow rate was fortuitously equal to the input concentration at a higher flow rate, *R* was still much greater at the high flow rate.

2) If a substantial part of the resistance to mass transfer is due to a boundary layer near the walls in the gaseous phase, then since the resistance of this layer may decrease with increasing airflow, uptake may improve at higher flows.

3) Perfusion of the nasal tissues, which are erectile in nature, presumably plays an important role in the uptake mechanism. Accordingly, if the increased demand for water vapor and heating associated with the higher airflow rate induces an increased blood supply to the area, the improved coefficient may have resulted from better perfusion. This might be significant for the removal of acetone or ether, but it is likely that ozone reacts chemically in the tissues before it can be removed by blood. In fact, Yokoyama and Frank (11) found no effect of locally applied phenylephrine hydrochloride or histamine on retention, suggesting that blood supply to the system does not constitute a significant rate-limiting step in the process.

4) The effective area for uptake of soluble gases in the nose may change with the rate of airflow. This may occur because the airstream passes over a larger surface area, thus tending to equalize the P_A in all parts of the nose where uptake can occur.

Factors other than total inspiratory flow can also affect *R*. Since body position affects the pattern of nasal flow, presumably through some reflex mechanism (9), it is possible that other reflexes can change the local geometry of the nose. If, for example, otherwise unventilated portions of the nose can be exposed to inspired air without decreasing the transit time, a potent mechanism for protecting the lung might exist. Brain (1) suggested that increased mucus production in the nose might account for an increased uptake with higher concentration of SO_2. However, until further experimental evidence is available, we can only speculate about other mechanisms for changing *R*.

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Present address of E. F. Aharonson: Israeli Institute for Biological Research, P.O. Box 19, Ness Ziona, Israel.

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