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The Fate of Light Air Ions in the Respiratory Pathways

by
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Electric properties of the atmosphere are recognized as important factors in biometeorological processes. Air ionization especially has been studied thoroughly and the physiological basis of its influence upon man, animals and plants systematically elucidated. The question arises as to where the light air ions are retained in the respiratory tract of man.

In this paper consideration will be given only to light air ions with an electrical mobility

$$u = 2.0\ \mathrm{cm}^2 .\ \mathrm{v}^{-1}.\mathrm{s}^{-1},$$

with a mechanical mobility

$$B = 1.27.10^{12}\ \mathrm{s.g}^{-1},$$

with a single elementary charge

$$e = 4.8.10^{-10}\ \mathrm{abs.e.s.u.},$$

with a diffusion coefficient

$$D = 5.4.10^{-2}\ \mathrm{cm}^2.\mathrm{s}^{-1},$$

and a corresponding radius

$$r = 5.0.10^{-8}\mathrm{cm}.$$

If air ions of both signs in equal numbers are inhaled so that no spatial charge arises in the air, two ways of retention in the airways have to be evaluated:

(1) deposition due to induced mirror charge;
(2) thermic deposition.

Both pathways have to be examined separately as it is difficult to submit them to mathematical analysis simultaneously.

If we consider the mucosa of the airways as a conductive plane with zero potential, then a charged particle will induce a virtual mirror charge so that it will be attracted from the distance y toward the mucosa with a force

$$F = \frac{e^2}{4y^2} \tag{1}$$

and will approach the wall of the airways with a velocity

$$-\frac{dy}{dt} = \frac{e^2 B}{4y^2} \tag{2}$$

which yields by integration the equation of a cubic parabola

$$y^3 = \frac{3}{4}\, e^2 Bt. \tag{3}$$

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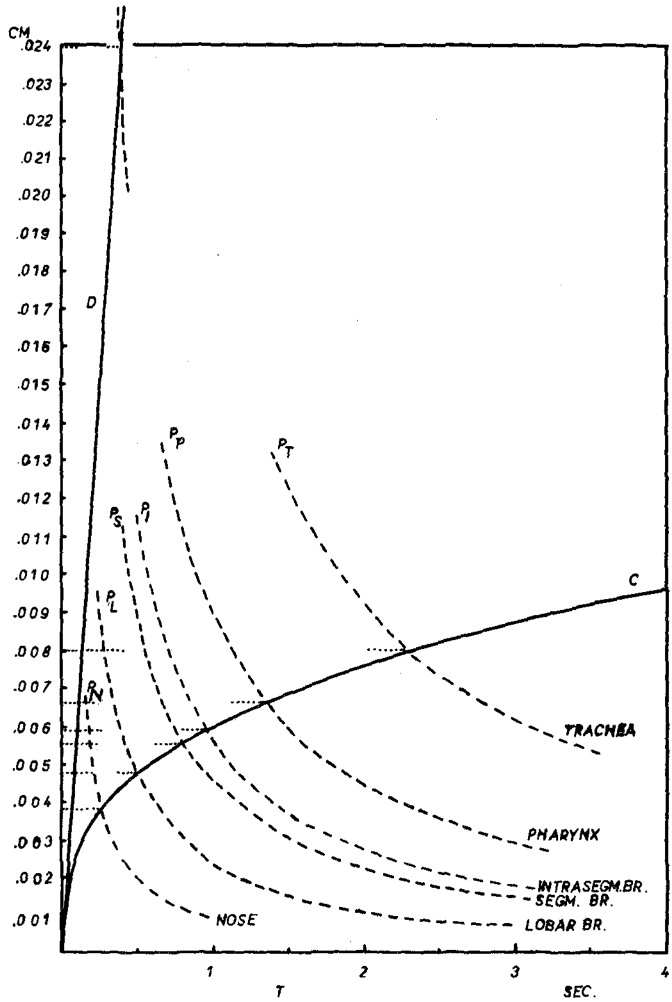

Fig. 1. Ion movement due to mirror charge (C) and in a homogeneous electric field of 0.03 v/cm intensity (D).The curves P represent the passage times at various levels (y) in the corresponding parts of the respiratory tract.

The ion passes the airways with a relatively high velocity since it is carried away by the streaming air (Fig. 1). There is no inertial effect on light ions which keep the stream lines of the laminar air moving even around bends.As the Reynolds number is nowhere exceeded in the respiratory pathways the streaming air may be considered as laminar.

In laminar streaming single layers are moving with different velocities v_x along x, parallel with the axis of the cylindric tubing or with the dividing median plane in plan-parallel planes. This axial velocity of a layer at a distance y from the wall follows the equation

$$v_{xc} = \frac{dx}{dt} = 2\bar{v}\left[1 - \left(1 - \frac{y}{R}\right)^2\right] \tag{4a}$$

in a cylinder with a radius R and

$$v_{xp} = \frac{dx}{dt} = \frac{3}{2}\,\bar{v}\left[1 - \left(1 - \frac{y}{a}\right)^2\right] \tag{4b}$$

between two plan-parallel planes running in a distance 2a. The symbol $\bar{v}$ means the mean linear velocity of streaming defined by $Q.\bar{v} = V$ where Q is the cross-section area of the tubing and V the volumic flow intensity.
Hence the trajectory of an ion will not be a cubic parabola, but a more complicated curve the equation of which can be obtained by combining the equations (2) and (4a,b). For a cylinder

$$5\left(\frac{y}{R}\right)^4 - 2\left(\frac{y}{R}\right)^5 = \frac{5e^2Bx}{4\ \bar{v}R^3} \tag{5a}$$

and for plan-parallel planes

$$5\left(\frac{y}{a}\right)^4 - 2\left(\frac{y}{a}\right)^5 = \frac{5}{3}\,\frac{e^2Bx}{\bar{v}\ a^3} \tag{5b}$$

Then, if the initial ion concentration be n_o and the ion concentration after passage through the tubing of the length x be n, the relation

$$\int_0^{y_o} \frac{2\pi(R-y)\ dy.v_{xc}}{\pi R^2.\ \bar{v}} \quad \text{and}$$

$$\int_0^{y_o} \frac{v_{xp}dy}{a.\bar{v}} \qquad \text{gives}$$

$$\frac{n}{n_o} = 1 - \left[4\left(\frac{y_o}{R}\right)^2 - 4\left(\frac{y_o}{R}\right)^3 + \left(\frac{y_o}{R}\right)^4\right] = 1 - p_{ic} \tag{6a}$$

or

$$\frac{n}{n_o} = 1 - \left[\frac{3}{2}\left(\frac{y_o}{a}\right)^2 - \frac{1}{2}\left(\frac{y_o}{a}\right)^3\right] = 1 - p_{ip} \tag{6b}$$

where y_o signifies the limit distance from which the ions still reach the wall (Fuks, 1961).

A graph shows the critical ratios $\frac{y_o}{R}$ or $\frac{y_o}{a}$ for the nose, pharynx, trachea, lobar, segmental, intrasegmental bronchi and bronchioli (Fig. 2). Assuming that the dimensional parameters and air flow velocities are as outlined in Table 1, the effectiveness of deposition in these parts of respiratory pathways can be calculated.

TABLE 1. Basal parameters according to (1) and (9), modified and the values of y_o and p_i for single segments of the airways

Segement	Radius r, half dist. a cm	Length x cm	$\bar{v}$ of the air flow cm/sec	y_o cm	p_i
Nose	a = 0.1	7.0	250	$4.08.10^{-3}$	$2.46.10^{-3}$
Pharynx	a = 0.4	4.0	60	$7.16.10^{-3}$	$4.72.10^{-4}$
Pharynx, with electrostatic filter	a = 0.4	4.0	60	$3.28.10^{-2}$	$4.90.10^{-3}$
Trachea	R = 0.8	12.0	131	$8.56.10^{-3}$	$4.53.10^{-4}$
Lobar bronchi	R = 0.4	2.8	120	$5.12.10^{-3}$	$6.47.10^{-4}$
Segmental bronchi	R = 0.25	6.0	85	$6.00.10^{-3}$	$2.25.10^{-3}$
Intrasegmental bronchi	R = 0.15	2.5	16,9	$6.38.10^{-3}$	$6.92.10^{-3}$
Bronchioles	R = 0.10	2.0	18,9	$5.61.10^{-3}$	$1.19.10^{-2}$

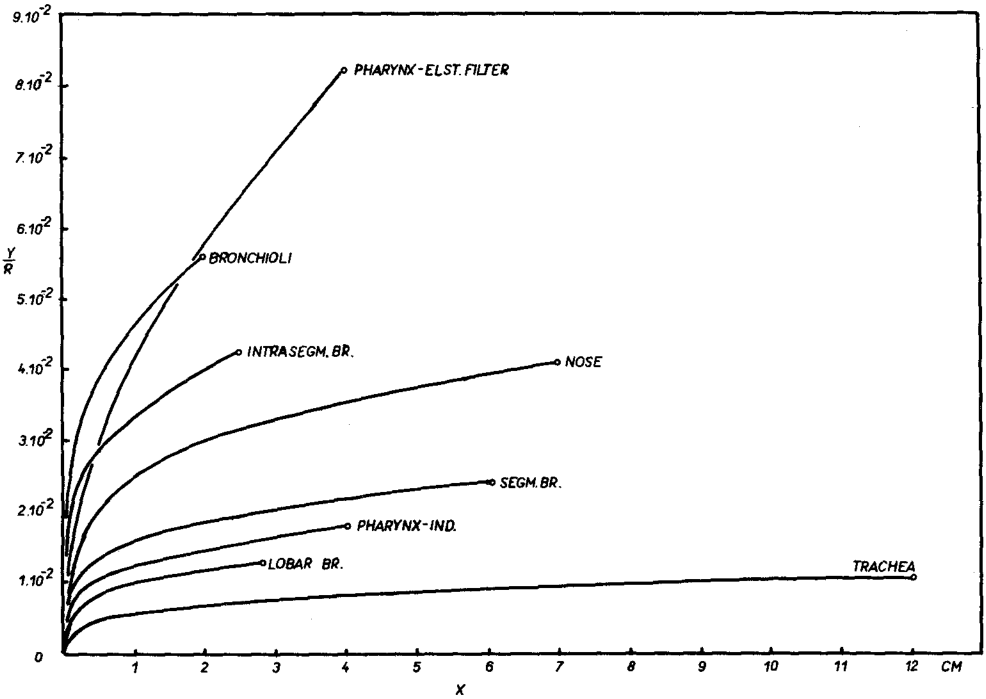

Fig. 2. Graphical representation of equations (5a, b). Small circles designate the critical values $\frac{y_o}{R}$ ev. $\frac{y_o}{a}$ for the corresponding part of the respiratory tract

It is apparent that the deposition due to this mechanism is negligible in the parts of respiratory pathways under consideration. In the deeper parts the relation $\frac{y_o}{R}$ increases, but the induced attractive force no longer diminishes the ion concentration because no light ions get there having been deposited by the other mechanism of thermic diffusion.

If particles with a diffusion coefficient D are suspended in air streaming through a cylindric tube, then in a time t their Brownian motion will carry to the wall all particles being at the time t = 0 at a shorter distance than

$$y_o = 2\sqrt{\frac{Dt}{\pi}}. \tag{7}$$

If m is substituted for $\frac{Dx}{R^2\,\bar{v}}$ or $\frac{Dx}{a^2\,\bar{v}}$, then

$$\frac{n}{n_o} = 1 - 2.56\ m^{2/3} + 1.2\ m + 0.177\ m^{4/3} = 1 - p_{t.c} \tag{8a}$$

for a cylinder and for plan-parallel planes (Fuks, 1961):

$$\frac{n}{n_o} = 0.9149\ e^{-1.885\ m} + 0.0592\ e^{-22.33\ m} + 0.0258\ e^{-151.8\ m} \tag{8b}$$

Calculation shows that total disappearance of light air ions begins in the intrasegmental bronchi and is finished in the bronchioles.

TABLE 2. The value of m and p_t for single segments of the airways

Segment	m	p_t
Nose	0.1512	0.3100
Pharynx	0.0113	0.0536
Trachea	0.0077	0.0903
Lobar bronchi	0.0079	0.0916
Segmental bronchi	0.0609	0.2389
Intrasegmental bronchi	0.3550	0.8129
Bronchioles	0.5710	0.9929

Quite remarkable is the high deposition rate in the nose. The per cent $100.p_t$ or the fraction relates, of course, to the entering and not to the initial concentration, as for this purpose another calculation would be necessary.

Hence all theories deriving the physiological action of air ions from their penetration into alveoli (Vasiljev, 1951) are not valid for light ions.

If unipolarly ionized air is inhaled, spontaneous dissipation of the ion mist due to spacial charge must occur. The concentration decreases according to Fuks (1955) as follows:

$$-\frac{1}{n}\frac{dn}{dt} = 4\pi\, ne^2B \tag{9}$$

and

$$\frac{1}{n} - \frac{1}{n_o} = 4\pi\, e^2Bt \tag{10}$$

or for the volume increase

$$V_t = 4\pi\, e^2Bt + V_o \tag{11}$$

which is evidently an equation of a straight line.
As the duration of the inspiration is approximately 2 seconds, the concentration of light air ions as high as $10^6/cm^3$ of air would decrease 8.4 times within this time (Fig. 3).

Lower concentrations, of course, will decrease much more slowly, a concentration of 10^3 ions per cm^3 will be still 99.2% of the initial one after 2 sec. Hence, thermic diffusion appears to be the most effective mechanism of deposition, retaining light air ions in the respiratory tract and preventing them from reaching the alveoli.

These calculations were based on the theory that the mucosa of the respiratory tract has a conductive surface of zero potential without its own electric field. However, all living matter produces bioelectric potentials at rest which are of no less importance than the action potentials of muscle and nerve cells (Kornblueh, 1955; Selye, 1950). Therefore, it can be assumed that the mucosa of the airways also has a bioelectric potential (Latmanizova, 1959). Even the existence of an electric field in the airways cannot be refuted with certainty.

Systematic investigations of the bioelectric potential (BEP) of the mucous membranes of the upper respiratory and digestive routes yielded very interesting results. Non-polarizing AgCl-electrodes filled with a physiological saline solution were used while the scarified skin of the volar side of the left wrist served as the reference potential (Pavlík, 1964). Measurements were made using the Poggendorf compensation method in a currentless state. In this manner 120 persons were investigated. Some were in good health, some were suffering from diseases of the respiratory tract. All tests were done during morning hours on fasting patients.

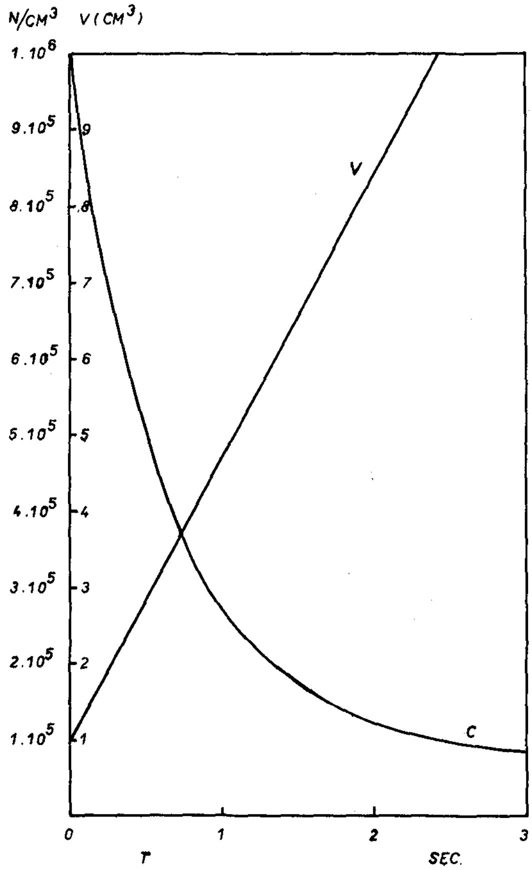

Fig. 3. Concentration decrease (C) and volume increase (V) of a cloud of unipolar ions with the mobility $1.27.10^{12}$ $s.g.^{-1}$ carrying one elementary charge

An absolute regularity in the value distribution of the BEP of the upper respiratory and digestive tracts was noted in all persons.

One can roughly sum up this regularity by determining that all values are negative, the negativity falling in the forward-backward direction. Some structures show nearly the same potential over the whole surface whereas others are characterized by a considerable variability. These observations form a base for an electrotopography of the mucous membranes of the upper respiratory and digestive tracts. The highest negative potential is found regularly on the upper surface of the tongue keeping its value nearly unchanged from the tip to the root. The lowest negative potential is formed on the tonsils followed immediately by the back wall of the pharynx and by the soft palate (Fig. 4).
Thus, very interesting relations occur in the isthmus faucium and in the pharynx where structures carrying the highest and the lowest BEP are situated in the closest proximity. It leads to the formation of an electric field with an intensity between the tongue and the tonsils of about 15 v/cm in the direction from the tonsil to the tongue surface.

The ability of this electric field to exert an influence upon electrically charged particles was established by investigation of the density of microbial flora over the surface of the mucosa.

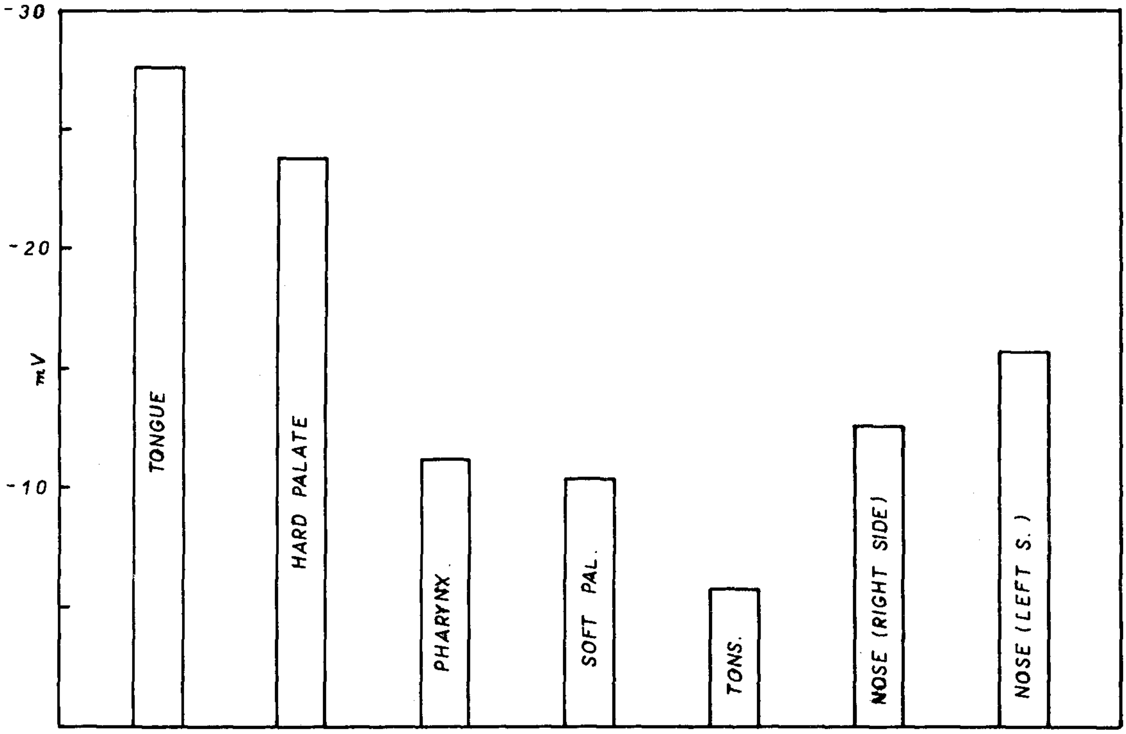

Fig. 4. Electrotopographic survey

Microorganisms are mostly endowed with a negative electrokinetic charge. The established electrophoretic mobility permits estimation of the charge in the saliva at about 60 mv (Pavlík, 1963, 1964).By substituting the proper values in the Helmholtz equation the value of 75 μ m/sec can be obtained for the electrophoretic velocity of the microorganisms in the area of the maximum field intensity. Therefore, it can be deducted that a microorganism appearing in the saliva on the tongue in the isthmus faucium can be attracted in a fraction of a second from this location to the surface of the tonsils or in the process of swallowing to the back wall of the pharynx. The permanent action of the electric field must also influence the distribution of microorganisms concentrating them at the positive pole of the system,i.e.on the tonsils, on the pharyngeal back wall and on the soft palate.

This theoretical approach was confirmed experimentally in 15 cases. By artificial inversion of the electric field for 4 min a corresponding shift in the distribution of the microflora was obtained. (Figs. 5 and 6).

When an light air ion enters such an existing electrostatic field in the process of breathing through the mouth it is forced toward one of the poles according to its own charge (Fig. 7). The intensity of the electric field may be estimated at about 30 mv/cm.This gives a light ion with an electric mobility of 2 $cm^2v^{-1}sec^{-1}$ a relatively high velocity of 0.06 cm/sec (see Figs. 1 and 2).The slope of the line D representing the movement of a light ion in this electric field indicates its velocity.It equals the velocity attained only in the final moments of movement along the cubic parabola. The movement of an ion in the laminar air streaming under the influence of a homogeneous electric field follows the equation

$$3\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right)^3 = \frac{2uEx}{a.\bar{v}} \qquad (12)$$

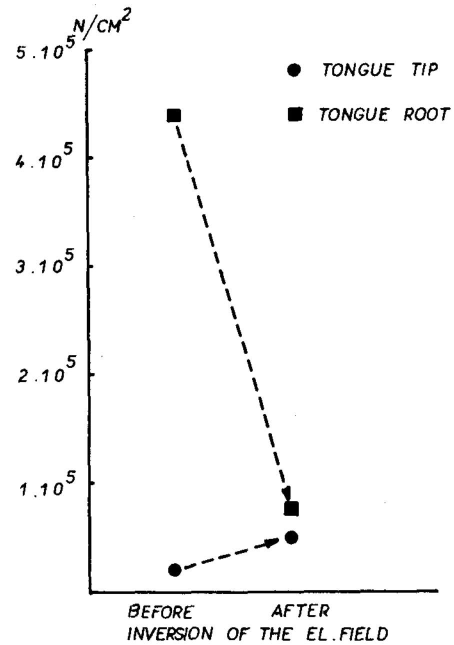

Fig. 5. The density of the microbial flora found on the tonsils, on the posterior wall of the pharynx, and on the tongue in correlation with the bioelectric potential; 15 cases

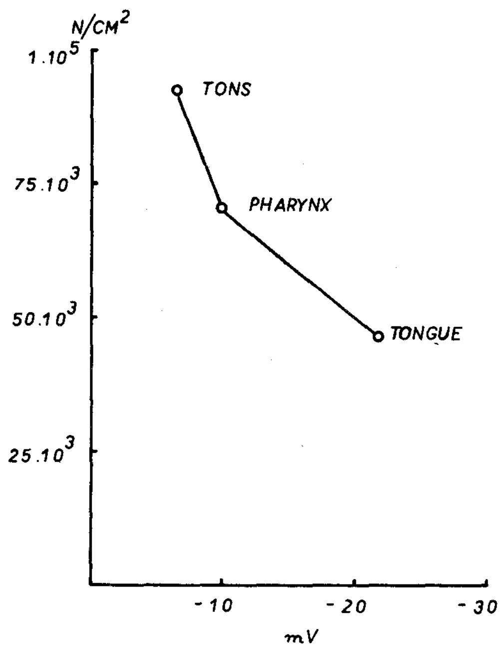

Fig. 6. The shift in the density of the microbial flora after an artificial inversion of the electric field in the oral cavity; 1 case

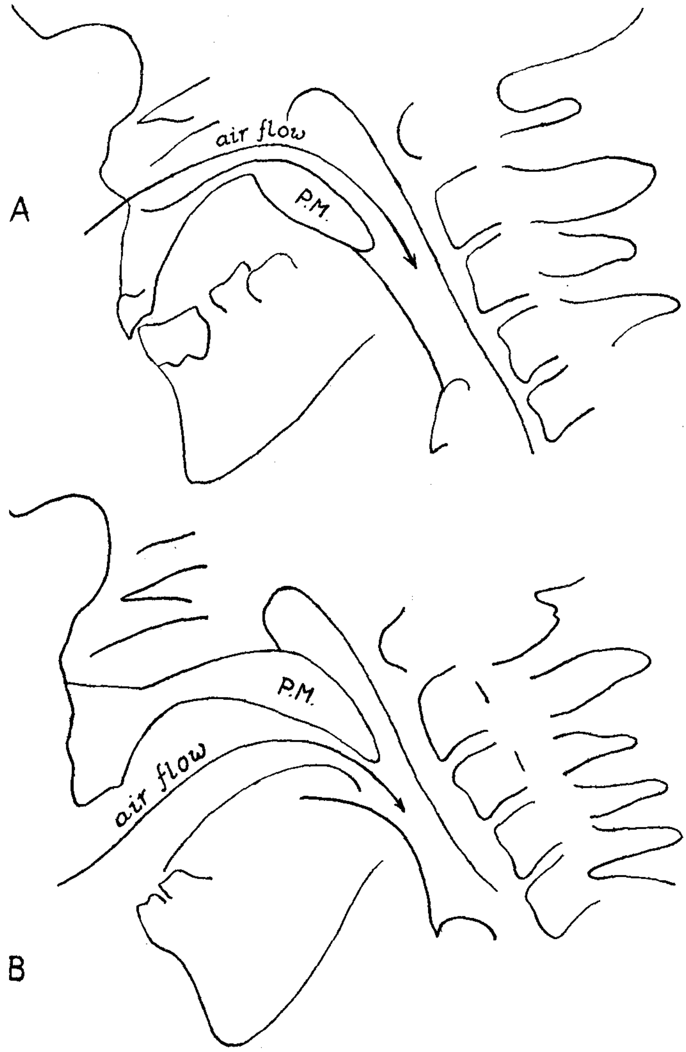

Fig. 7. Air flow during breathing through the nose (A) and through the mouth (B), established with the help of x-ray pictures using contrast material on the mucosal surface

which is obtained from the equation (4b) and from the equation for ion velocity in a homogeneous electrostatic field under stationary conditions:

$$-\frac{dy}{dt} = uE$$

where E signifies the intensity of the electrostatic field.
The loss of ions will be then

$$p_{fp} = \frac{3}{4}\left(\frac{y_o}{a}\right)^2 - \frac{1}{4}\left(\frac{y_o}{a}\right)^3 \qquad (13)$$

Assuming that all other parameters are the same as in the pharynx$(a,\bar{v},x)$, then the critical distance y_o is more than 4 times as great as without the electrostatic field and the effectiveness of retention about 10 times as high $4.9.10^{-3}$: $4.72.10^{-4}$. In reality the retained fraction remains very low and has no great importance in the whole deposition pattern. However, the fact that the ions distributed by the electrostatic field bring an opposite charge to the electrodes of the natural electrostatic filter may be of some importance to people breathing permanently through the mouth.

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ABSTRACT.- From an analysis of the fate of the light air ions it was concluded that the most effective mechanism of deposition is the diffusion depriving the inhaled air of light ions at the level of intrasegmental bronchi and bronchioles. A natural electrostatic filter exists in the isthmus faucium.This filter influences the retention of light air ions during mouth-breathing. The electrostatic filter acts on electrically charged particles such as microbes as shown by an investigation of the density of microflora. An increase of the ion retention rate,although quite high in comparison with the same condition in the absence of an electric field,does not radically change the whole deposition pattern. However, a permanent supply of the opposite charge to the electrodes of the natural electrostatic filter may be of some importance to mouth-breathers.

ZUSAMMENFASSUNG.- Es wurde das Schicksal der leichten Luftionen mit dem Ergebnis analysiert, dass der wirksamste Mechanismus der Ablagerung die Diffusion ist, durch die sich die inhalierte Luft mit leichten Ionen in der Höhe der Bronchien und Bronchiolen absetzt. Ein natürliches elektrostatisches Filter existiert in Form des isthmus faucium. Dieses Filter beeinflusst das Zurückhalten leichter Luftionen während der Mundatmung. Das elektrostatische Filter wirkt auf die elektrisch geladenen Teilchen wie Mikroben, wie man sie bei einer Untersuchung über die Dichte der Mikroflora beobachtet hat. Eine verstärkte Zurückhaltung der Ionen,obwohl sie im Vergleich zu denselben Bedingungen ohne elektrisches Feld recht hoch ist, ändert den ganzen Ablagerungsmechanismus nicht. Jedoch mag eine dauernde Zufuhr der den Elektoden des natürlichen elektrostatischen Filters entgegengesetzten Ladung von einiger Bedeutung für die Mundatmung sein.

RESUME.- On a analysé la destinée des ions légers de l'air.Il en découle que le mécanisme le plus efficace de déposition réside dans la diffusion qui prive l'air de ses ions légers au niveau des bronches et des bronchioles.Un filtre électrostatique naturel se trouve dans l'isthmus faucium. Ce filtre influence la rétention des ions légers de l'air durant la respiration par la bouche. Ce filtre électrostatique agit sur les particules chargées électriquement telles que les microbes,comme il découle de recherches effectuées sur la densité de la micro-flore. Un accroissement du taux de retenue des ions, même s il reste élevé en comparaison de ce qui se passe dans des conditions analogues mais en l'absence d'un champ électrique,ne modifie pas radicalement le mécanisme de sédimentation. Pourtant, un apport permanent de charges opposées aux électrodes du filtre électrostatique naturel peut avoir une certaine importance pour les individus respirant par la bouche.