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AEROSOL STUDIES

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- USSR -

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AEROSOL STUDIES

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Theoretical Basis of Operation of the Aerosol IVK-1 Chamber for the Study of Experimental Respiratory Infections

Report I

Operational Dynamics of the Aerosol Chamber

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The IVK-1 chamber was created (1) for the study of virus infections produced by aerosols of the pathogens of respiratory infections.

In the use of the aerosol chambers a number of questions of a physical nature arise without an answer to which work with infectious aerosols may be incomplete. Among these questions is that of the time an equilibrium (maximum) aerosol concentration is reached in the chamber, the time needed for removal of the aerosol from the chamber after performing the experiment, the time for which the aerosol is preserved in the chamber, the quantity of sprayed virus-containing material by weight, the quantity of this material absorbed by animals, and many others. In addition, knowledge of the physical characteristics of operation of the chamber is necessary for making up rules of safety technique, without which work with the aerosol apparatus would be impossible.

In the present report the fundamentals of the theory of operation of the IVK-1 aerosol chamber are presented, which can be used for work with any similar chamber.

Let us consider a chamber with a volume V, in which a sprayer has been set which has an output of the virus-containing aerosol suspension of fr per unit time. The value of f can change during the experiment. This is explained by the fact that the quantity of virus-containing suspension during the period of operation of the sprayer is decreasing constantly, while the air pressure remains constant. Let us designate with the letter "L" the quantity of air fed to the chamber per unit time. The chamber communicates with the atmosphere; therefore, no excess pressure, above atmospheric, occurs in the chamber from the entrance of the aerosol into it. Naturally, the air coming from the chamber is disinfected, but this is not significant for the problems being analyzed.

The figure f is measured in grams per minute; V, in liters; L, in liters per minute. Henceforth, for estimation purposes we shall use the following figures for the IVK-1 chamber: V=100; L=42 liters/min; f=0.11 gram/min (on the average for the time of operation of the sprayer in the experiment).

Let us imagine the chamber before starting the spraying. At some

moment the sprayer begins to work. The aerosol content in the chamber will increase until air not containing aerosol is displaced from it. Roughly, this is the time it takes for the sprayed material to fill the chamber. Because the chamber volume equals V liters and the sprayer supplies L liters of aerosol per minute, then t_0, roughly equal to V/L, (1) minutes after the beginning of spraying the entire air which does not contain aerosol will be displaced, and the chamber will be filled with sprayed infectious material. The time t_0 will be called the time needed for "scavenging" the chamber.

Evidently, the final quantity of suspension in the chamber cannot exceed a figure of f equal to V/L (2), because with further influx of the suspension into the chamber the same quantity of suspension will be carried away by air leaving the chamber. Here we are not considering the settling of the aerosol on the walls and floor of the chamber. If the time needed for settling or coagulation of the aerosol particles (their "lifespans") is greater than the "scavenging" time, the lifespan of the particles may be overlooked, because these particles will be carried away by the air current (they do not manage to settle). However, if the lifespan of the aerosol particles is less than the "scavenging" time, these particles will settle out on the walls and floor of the chamber, and the time needed for the occurrence of an equilibrium concentration is equal to their lifespan. In view of the fact that the aerosol consists of particles of different sizes, the time needed to reach an equilibrium concentration for the small aerosol particles is the "scavenging" time; for the large ones, "their lifespan".

Having described the main qualitative features, let us analyze the work equation of the chamber. Let us try to find out the time relationships of the entire aerosol mass in the chamber, that is, of the mass included in drops of a certain radius. Let us designate the entire mass of drops of radius r in the chamber by the letter "x". Then x should satisfy the following differential equation:

$$\frac{dx}{dt} = f(t) - \lambda x - \frac{Lx}{v}, \qquad (3)$$

where λ is the probability of death of the particles per unit time; $1/\lambda$ is the characteristic of the "lifespan" of particles with radius r in the chamber, a value which is the reciprocal of the probability of their death; f is the number of grams of virus-containing suspension supplied per unit time by the sprayer in the form of particles with the same radius. In working with aerosols of any other degree of dispersion the corresponding value of λ is used, which is proportional to the square of the particle radius.

The physical significance of the separate terms in equation (3) is the following. On the left, the change in the aerosol mass is indicated per unit time. It is a function of the mass f(t) being fed to the chamber per unit time (the first term on the right side), the mass of the aerosol which precipitates and settles out on the walls and floor of the chamber by virtue of processes which will be analyzed in the next report, and of the aerosol carried out of the chamber with the

particles air (the third term on the right). The last two terms have a minus sign, because they cause a decrease in the number of particles.

Problems of the dynamics of the aerosol chamber have been analyzed by Rosebury [2] [because numbers are given for references and for various equations in this article the former will be put in brackets; the latter, within parentheses]. Our equation (3) is different from that obtained by Rosebury in two respects. In Rosebury's work neither the relationship of the consumption of the fluid to time nor the lifespans of the aerosol particles, as determined by the figure λ, are taken into consideration. In equation (3) they are. Therefore, equation (3) is a more general one, and it becomes the same as that obtained by Rosebury when $\lambda=0$ and $df/dt=0$.

As a point of fact, λ is certainly not equal to 0. Therefore, use of Rosebury's equation can lead to incorrect results. After the completion of the spraying, when the supply of air, L, and the supply of the suspension, f, become equal to zero, Rosebury's equation has the following form:

$$\frac{dx}{dt}=0, \tag{4}$$

the solution of which is that x=constant, that is, the quantity of suspension sprayed into the chamber does not change. As a matter of fact, after the conclusion of the spraying the aerosol settles out in the chamber, and this phenomenon is described by our equation, which under these conditions assumes the following form:

$$\frac{dx}{dt}=-\lambda x \tag{5}$$

The solution of this is as follows:

$$x=x_0\cdot e^{-\lambda t}=x_0\cdot 10^{\frac{-\lambda t}{2,3}}, \tag{6}$$

where x_0 is the quantity of aerosol in the chamber at the time of completion of the spraying.

From the last formula it follows that with $t=2.3/\lambda$ $x=0.1x_0$, that is, the aerosol concentration in the chamber decreases 10 times. From this the relationship of λ to the lifespan of the aerosol is seen.

The solution of equation (3) looks like this:

$$x(t)=S_0^t\, e^{-\left(\lambda+\frac{L}{v}\right)(t-a)}\cdot f(a)\cdot da, \tag{7}$$

where a is the variable of integration, e=2.72, the base of natural logarithms; the limits of integration are chosen so that t=0 (start of spraying), x(t)=0.

In a number of cases equation (7) for the quantity of aerosol in the chamber can be simplified.

Let us assume that f does not depend on the time (stabilized feed of the suspension); then from equation (7) we obtain:

$$x = \frac{f}{\lambda + \frac{L}{v}} \left[1 - 10^{-\left(\lambda + \frac{L}{v}\right)\frac{t}{2,3}} \right]. \qquad (8)$$

Let us analyze two cases:

a) $\lambda \ll L/V$; Rosebury's equation belongs to this case also (the lifespan of the aerosol is much longer than the "scavenging" time, that is, the time in which the air in the chamber is completely replaced; it is equal to V/L). Then:

$$x = f\frac{v}{L}\left[1 - 10^{\frac{-Lt}{2,3 \cdot v}} \right]. \qquad (9)$$

With increase in t this figure approaches its maximum value: $x_0 = f \cdot V/L$ (10), whereby with $t = 2.3 \cdot V/L$ (11) x reaches 90 percent of the equilibrium value, x_0.

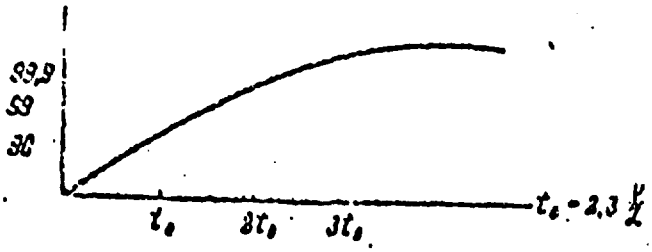
While equation (1) roughly defined the time needed for saturation of the chamber with aerosol, equation (11) which we have obtained permits a determination of this time with somewhat greater accuracy. After substituting the parameters of our chamber into this equation we obtain that the time needed for saturation is equal to $t_0 = 2.3 \cdot 100/42 \sim 5.4$ minutes.

Therefore, as early as after about five minutes the equilibrium concentration is reached, and from this time on the aerosol concentration changes very little. Thus, it follows from the equation that if the aerosol concentration in the chamber after t_0 minutes is equal to 90 percent, then after $2t_0$ it will reach 99 percent, and after $3t_0$, 99.9 percent. It should be taken into account that the time t_0 is determined by the volume of the chamber and the expenditure of air. Under the condition which we have analyzed the relationship of the aerosol concentrations to the time can be represented graphically by means of the following graph (see Figure).

b) $\lambda \gg L/V$ (the lifespan of the aerosol particles is much less than the "scavenging" time). In this case solution of equation (8) assumes the following form:

$$x = \frac{f}{\lambda}\left(1 - 10^{\frac{-\lambda t}{2,3}}\right). \qquad (12)$$

This solution differs from solution (9) only in the replacement of V/L by $1/\lambda$, that is, in the case being analyzed the time needed for reaching the equilibrium concentration is not equal to the "scavenging" time but rather to the lifespan of the particles in the chamber.



Aerosol Concentration in Percentages of the Equilibrium Concentration $\left(\frac{x}{x_0}\right)$

Saturation of the chamber under this condition occurs when $t_1 = 2.3/\lambda$. Graphically, this relationship will have the same form as on the Figure presented but t_0 being replaced by t_1.

The time in which the aerosol is removed from the chamber is equal to the time the equilibrium concentration is reached, $t = 2.3V/L = 5.4$ minutes. Thereby, after the time t the chamber will contain 10 percent of the aerosol; after 2t, one percent; after 3t, 0.1 percent of the aerosol. Therefore, we can with definite accuracy ascertain the time needed for removal of the aerosol from the chamber, which is very important for work with virulent pathogens. Precise calculation of this time and strict observance of it in working with the chamber make it possible to be completely safe in taking experimental animals out of the chamber after the performance of the experiment. The quantity of aerosol remaining in the chamber is easily disinfected by means of spraying in appropriate disinfectants.

Conclusions

1. The operational dynamics of the IVK-1 aerosol chamber were analyzed, and a mathematical equation has been given for its operation.

2. In the experimental study of various aerosols containing virus or bacterial material spraying must be accomplished with consideration of the time at which the equilibrium (maximum) concentration occurs.

3. On completion of the work in the aerosol chamber with infectious material the length of time spent in scavenging the chamber should correspond to the time of maximum possible (99.9 percent) removal of the infectious material (that is, three times the "scavenging time").

4. The data presented permit us to calculate the time needed for reaching the equilibrium concentration of the aerosol and the "scavenging" time of the chamber.

5. The fundamentals of operation of the IVK-1 aerosol chamber presented can be used for work with any aerosol chambers.

In conclusion, I should like to express my sincere appreciation

to I. P. Mazin and B. M. Bolotovskiy for their great assistance in the discussion of problems touched on here.

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