U.S. Department of Commerce · National Bureau of Standards

RESEARCH PAPER RP736

Part of Journal of Research of the National Bureau of Standards, Volume 13, November 1934

A NOTE ON BACTERICIDAL EFFECTS OF X-RAYS

By Fred L. Mohler and Lauriston S. Taylor

ABSTRACT

The effects of X-rays in liquids are localized in columns of ionization along the path of each high-speed electron. It is assumed that biological effects are produced in these columns and experimental results of Wyckoff and Rivers on killing of colon bacilli by cathode rays and X-rays are expressed in terms of the effective collision area of the column and bacillus for killing. Cathode rays of 155 kv give an area of 0.68×10^{-10} cm². X-rays of wave lengths ranging from 0.56 to 4 A give values between 0.72×10^{-10} and 2.6×10^{-10} cm². As the area of the bacillus is about 10^{-8} cm² passage of a column through the bacillus is in general not fatal. The column must pass through a particular point to cause death.

When an X-ray is absorbed by matter the entire energy of the X-ray quantum is given to a single electron. This high-speed secondary electron traverses the medium and produces a dense path of ion pairs. The energy of the secondary electron is related to the wave length of the X-rays by the quantum relation.

$$V \text{ (electron volts)} = 12340/\lambda \text{ (angstroms)} \qquad (1)$$

The number of ion pairs in air is about $V/35$. The length x of the electron path depends on the density of the medium and is given with fair approximation by the relation

$$x\rho = v^4/.505\times10^{43} \qquad (2)$$

where ρ is the density and v the electron velocity.[1] The path is crooked and the average distance the electron goes is less than x. These general relations should be applicable to liquids and solids as well as gases. In a medium of density one the electron path will be reduced to about one eight-hundredth of its value in air and the ion density will be correspondingly greater. Experiments [2] on the ionization of liquid carbon disulphide by X-rays (effective wave length 0.27 A) have given roughly quantitative information concerning these columns of ionization. The number of ions produced per quantum in the liquid is about the same as in the gaseous phase. The volume ionized by each quantum is equal to a cylinder of length equal to the electron path (3×10^{-3} cm) and of cross section 0.28×10^{-10} cm². This dense column of ionization disappears by recombination in less than a millionth of a second and only a small fraction of the ions diffuse into the surrounding medium.

[1] A. H. Compton, *X-rays and Electrons*, p. 256(1928).
[2] Mohler and Taylor, J. Research NBS 13,659(1934);RP733.

It is attractive to assume that biological effects of X-rays are produced exclusively in these columns of ionization and that the chance of producing a given effect on a cell depends on the chance of a column passing either through the cell or through a particular part of the cell. This view is not new. Wyckoff [3] has discussed his experimental results on destruction of bacteria by X-rays in these terms. His computations are however made on a somewhat different basis. In the following we will treat his results from a purely columnar viewpoint.

Experiments on the destruction of bacteria by cathode rays of 155 kv were made by Wyckoff and Rivers.[4] Separate bacteria spread on a surface of agar were exposed to a beam of cathode rays of measured intensity and the fraction surviving after a time t was determined by counting the clusters developed after an incubation period. They show that this survival ratio is given by the relation

$$A(t)/A_0 = e^{-at} = e^{-bnt} \tag{3}$$

where n is the number of cathode rays per cm^2 per sec and b gives the fraction of bacteria killed per cathode ray and a the fraction per sec. As they point out this exponential relation is consistent with the view that killing depends simply on the cathode ray striking a given area in the bacillus. Consider this area, σ, associated with the cathode ray. Then an area $n\sigma$ is sterilized when n rays pass through the surface and we see that σ is to be identified with the constant b. In their experiments with colon bacilli a current of 1.65×10^9 electrons per sec gave a value of a of 0.112 per sec. Hence $\sigma=0.68\times10^{-10}$ cm^2. Their experiments with *Bacillus aertryke* gave an identical effective area. *Staphylococcus aureus* gave an area half as great. The colon bacillus is a rod about 2×10^{-4} cm long and 0.5×10^{-4} cm in diameter and hence has a cross section of about 10^{-8} cm^2 in any direction. The fatal area is very much smaller than the area of the bacillus.

Wyckoff [5] carried out comparable experiments on the destruction of colon bacilli by X-rays of different wave lengths. The X-rays were predominantly the characteristic radiations listed in table 1. The experimental data are the air ionization in roentgens per sec and the constant a of eq 3 determined from measurements of survival ratios. The energy of the secondary electrons in electron volts (eq 1) divided by 35 gives the number of ion pairs produced per quantum, and from the measured air ionization one derives the number of quanta absorbed in air per cm^3 per sec. The rate of absorption of quanta and production of columns, n, in the agar is taken to be 780 times this. The volume sterilized by each column is σx where x is given by eq 2 and $n\sigma x$ is the volume sterilized per sec which is equated to the constant a of eq 3. The last column of table 1 gives the computed values of σ for the different radiations. The physical basis for these computations becomes uncertain for the longest wave lengths since eq 2 giving the range x has not been tested in this range.

[3] Wyckoff, J. Exp. Med., 52,769(1930).
[4] Wyckoff and Rivers, J. Exp. Med., 51,921(1930).
[5] Wyckoff, J. Exp. Med., 52,435(1930).

TABLE 1.—*Killing of colon bacilli by X-rays*

Radiation	λ(A)	Energy of electrons	Range of electrons	Quanta absorbed in agar	Rate of killing (a)	Effective areea σ
		kv	*cm*	*Per sec per cm³*		*cm²*
AgK	0.564	22	1.2×10^{-3}	1.9×10^{11}	0.0174	0.76×10^{-10}
MoK	.710	17.4	$.75\times10^{-3}$	3.1×10^{11}	.0167	$.72\times10^{-10}$
CuK	1.537	8.0	1.6×10^{-4}	12.4×10^{11}	.0370	1.9×10^{-10}
CrK	2.29	5.4	$.72\times10^{-4}$	29×10^{11}	.0413	2.0×10^{-10}
AgL	3.98	3.1	2.4×10^{-5}	25×10^{11}	.0159	2.6×10^{-10}
Cathode rays		155	1.8×10^{-2}			$.68\times10^{-10}$

The important conclusion from these computations is that the effective area is nearly the same for cathode rays and secondary electrons produced by X-rays and that this area is very much smaller than the cross section of a bacillus. On the view that there is a sensitive spot in the bacillus through which the column of ionization must pass, the effective area may be expressed as

$$\sigma=\pi(a_1+a_2)^2$$

where a_1 is the radius of the column and a_2 the radius of the spot. The experimental values of σ are of the same magnitude as the cross section of the column of ionization computed for the particular case of carbon disulphide ionized by X-rays. If the columns in agar are of comparable size the area of the hypothetical spot may be indefinitely less than σ.

Wyckoff has expressed the effectiveness of both cathode rays and X-rays in terms of the fraction absorbed by a single bacillus. From a purely columnar viewpoint the absorption does not enter at all in evaluating the effectiveness of cathode rays; while in the case of X-rays it is the absorption coefficient of the bacillus and of the surrounding medium which is significant. It is to be emphasized that in the present state of knowledge there is little question of right or wrong in either viewpoint.

The density of ionization in a column decreases with increasing speed of the electron and is nearly 15 times as great for the AgL secondaries as for the 155 kv cathode rays. If the effectiveness of X-rays depended solely on the volume of the columns of ionization then σ would remain constant and the effect per roentgen would decrease with increasing wave lengths. For Wyckoff's experimental data the values of σ increase somewhat with increasing wave length and the effect per roentgen decreases but not as much as for a pure volume effect. It is doubtful whether this variation in σ is significant and it is certain that no general conclusion as to biological effectiveness of X-rays can be drawn from a single series of experiments.

Although σ may be expected to vary with the biological material and the quality of the radiation, nevertheless the columnar viewpoint seems to offer a logical starting point for theory. The known physical effects of X-rays in liquids and solids are limited to the columns of ionization produced by high-speed electrons. The numerical value of σ is a convenient expression for the bactericidal effectiveness of the columns whether or not one takes the view that killing depends on striking a certain spot in the cell.

WASHINGTON, September 13, 1934.