85003501

DR-0759-5

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8/25/58
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CH--1347-A-1897

DE85 003501

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TOLERANCE CONCENTRATION OF RADIOACTIVE GASES IN AIR

By G. Failla

Report Prepared in November 1942

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Authorizing Official
Date: 8/1/93

Received: February 15, 1944
Issued: FEB 18 1944

MASTER

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TOLERANCE CONCENTRATION OF RADIOACTIVE GASES IN AIR

Report Prepared in November 1942

G. Failla

It is known that the incidence of cancer of the lung among radium ore miners in Europe is much higher than in the case of other miners in the same locality. While it has not been definitely established that radon in the air of the mines is solely responsible for the initiation of the cancerous process, it must be considered as at least a contributing factor and possibly as the most important factor. We shall assume, therefore, that cancer of the lung may be produced by breathing air containing low concentrations of a radioactive gas, over a period of years.

Experience in radiology has shown that exposure of the entire body to x- or gamma rays at the rate of 0.1 r/g hr. day for a number of years, causes no detectable changes in the blood counts of workers or in their general health. There is at present no indication whatever, that cancer of the lung may be produced by continued exposure of the body to this intensity of x- or gamma radiation. From this, we may conclude that ionization of lung tissue at the rate corresponding to 0.1 r/8 hr. day does not cause cancer, neglecting for the moment the fact that the intensity at the depth of the lungs is somewhat less than 0.1 r/8 hr. day when the whole body is exposed to this intensity of radiation as measured in air.

Cancer of the lung, as it occurs spontaneously in man, is practically always of the type that originates in epithelial tissue, and particularly in the lining of the bronchus. This is also true in the case of the lung cancers found in radium ore miners. Therefore, it would seem that radiation is most likely to produce cancer when the damage occurs in the epithelial lining of the air cavities in the lungs. It is readily apparent, also, that the lining

of the larger air cavities will be ionized to a greater degree than that of the smaller ones by short range radiation emitted by a radioactive gas uniformly distributed in the air within the cavities. Accordingly, the criterion of safety should be based on the ionization produced in the epithelial lining of the large air passages in the lung. For purposes of calculation let us take a cavity in the form of a cylinder 1.5 cm. in diameter and 3 cm. long, which corresponds roughly to the bronchus in man.

In such a cavity it may be assumed as a first approximation that the ionizing particles in the volume (having a range in air greater than the linear dimensions) will lose all their energy in a tissue layer on the walls of a closed cavity of thickness equal to the effective range of the particles in tissue. It may be assumed further that the ion density in the tissue layer is uniform with respect to both surface and depth. Under those conditions the rate of ion production in the tissue layer is given by the following expression:

$$N_1 = \frac{3.7 \times 10^{10} \text{ CVA}}{WAD} \quad \text{ion pairs/sec./gram}$$

Where C = Concentration of radioactive gas in air, in curies per cm³

V = Volume of cavity, in cm³

E = Average energy of ionizing particles, in e.v.

W = Energy lost by particle per ion pair produced in tissue, in e.v.

A = Area of cavity walls, in cm²

R = Effective range of ionizing particles in tissue, in cm

D = Density of tissue, in grams per cm³

The energy, W, lost by an ionizing particle in producing one ion pair in tissue is not known. However, this is immaterial in the present case and the numerical value for air will serve the purpose,

bearing in mind of course that the number N_1 will now be per gram of air and not of tissue. When the ionizing particle is an electron, the most probable value of w (in air) is 33 e.v. For alpha particles it is 35 e.v.

The range of the ionizing particles in tissue may be calculated from the value for air by assuming that it is inversely proportional to the density. In the case of alpha particles which travel in straight lines, the range is very definite. But even in this case, the effective range in the tissue lining the cavity is difficult to estimate. The particles strike the surface at different angles and many lose a considerable fraction of their energy in traversing the air in the cavity. In the case of electrons the path is tortuous but a smaller fraction of the energy is used up in ionizing the air in the cavity. These two factors, of course, depend a great deal on the initial kinetic energy of the electrons. At best, therefore, one can make only a rough estimate of the effective range of the ionizing particles in the tissues lining the cavity. The density D of lung tissue may be taken as one gram per cm^3 .

If the range of the ionizing particles is considerable (or soft x-rays are emitted by the radioactive gas) the ionization in the walls of the cavity will be augmented by any radiation which reaches the tissue in question from other air spaces in the vicinity. It is difficult to make a close estimate of this contribution but an upper limit for the tissue under consideration may be obtained by assuming that the energy liberated in all the air contained in the lungs (about 3000 cm^3) is absorbed uniformly by the lung tissue (weighing about 1200 grams). On this basis, the number N_2 of ion pairs produced per second per gram of lung is:

$$\begin{aligned}
 N_2 &= \frac{3.7 \times 10^{10} \times 3 \times 10^3 \text{ CE}}{1.2 \times 10^3 W} \\
 &= 9.2 \times 10^{10} \frac{\text{CE}}{W} \text{ ion pairs / sec. / gram}
 \end{aligned}$$

A third contribution to the tissue ionization is made by the radioactive gas which may dissolve in the lung tissue itself including the blood. When equilibrium is established one cm^3 of tissue will contain a fraction F of the amount of radioactive gas in one cm^3 of air in the lungs. Therefore:

$$N_3 = 3.7 \times 10^{10} \frac{C F E}{W}$$

The total ionization in the tissue layer will then be $N = N_1 + N_2 + N_3$

$$= 3.7 \times 10^{10} \frac{C E}{W} \left(\frac{V}{AR D} + 2.5 + F \right) \text{ ion pairs / sec. / gram}$$

In the accompanying table are given values of N_1 , N_2 , N_3 and N for electron energies from 30 to 1000 Kev. and a uniform concentration of radioactive gas in the air of the lungs of 10^{-9} curie/ cm^3 . The values used for the effective range R , are one-half the values ordinarily given for the range in water. This is a rough estimate and it should be borne in mind that the values of N_1 depend a great deal on this assumption.

It will be noted that the contribution to the ionization in the tissue layer lining the cavity due to radioactive gas dissolved in the tissue (N_3), is entirely negligible when $F = 0.1$; that is, when the concentration in the tissue is one-tenth that in the same volume of air. For low energy electrons the ionization in the tissue layer under consideration is very largely due to the electrons liberated in the air of the cavity (N_1). The contribution arising

Ionization Produced in Tissue Lining of a Cylindrical Cavity in the Lung, 1.5 cm. in Diameter and 3 cm. long, when Air in the Lung Contains 10^{-9} curie/cm³ of a Radioactive Gas That Emits Beta Particles.

E Kev	R cm	N ₁	R ₂	N ₃ (for F=0.1)	N ion pairs per sec. per gram	N ₈ ion pairs per gram per 8 hrs	N ₂₄ ion pairs per gram per hrs.
30	1.0×10^{-3}	1010×10^4	8.4×10^4	0.3×10^4	1020×10^4	2.9×10^{11}	8.8×10^{11}
40	1.5	900	11.2	0.5	910	2.6	7.9
50	2.3	735	14	0.6	750	2.2	6.5
60	3.0	680	17	0.7	700	2.0	6.1
80	4.8	560	22	0.9	580	1.7	5.0
100	6.8	500	28	1.1	530	1.5	4.6
125	9.5	440	35	1.4	480	1.4	4.2
150	12.0	420	42	1.7	460	1.3	4.0
200	19.0	355	56	2.2	415	1.2	3.6
300	40	260	84	3.4	350	1.0	3.0
400	65	208	112	4.5	325	0.9	2.8
500	90	188	139	5.6	330	0.9	2.9
600	113	180	167	6.6	350	1.0	3.0
800	170	160	223	9.0	390	1.1	3.4
1000	210	160	280	11.2	450	1.3	3.9

0.1 roentgen = 1.6×10^{11} ion pairs per gram

from the air distributed throughout the lungs (N_2) increases with the energy of the electrons and becomes equal to N_1 at about 600 Kev. Consequently the total ionization in the tissue layer (N) shows only a three fold variation in the range of 30 to 1000 Kev, with a minimum value at about 400 Kev. The fact that the contribution N_2 becomes really important when the effective range of the beta particle is of the order of 1 mm. of tissue, indicates that if very soft gamma radiation is present in amounts comparable to the electron emission, it should be taken into account.

The ionization resulting from exposure to 0.1 r of x- or gamma radiation is 1.6×10^{11} ion pairs per gram. To facilitate comparison, in the table are given values of N_8 and N_{24} representing the numbers of ion pairs per gram produced in the tissue lining of the cavity when a person remains in the radioactive atmosphere 8 or 24 hours, respectively. It will be seen that for beta particle energies over 80 Kev. the ionization resulting from an eight-hour exposure is approximately the same as that produced by 0.1 r. Therefore, 10^{-9} curie/cm³ may be taken as the tolerance concentration of a radioactive gas in the air in which a person remains not more than 8 hours a day, when the average energy of the emitted beta particles is between 80 and 1000 Kev. This concentration (10^{-9} curie/cm³) is too high when the beta particles have lower energies, or when a person stays in the radioactive atmosphere 24 hours a day.

It should be remembered that the figures given in the table are based on the assumption that there is in human lungs a cylindrical cavity 1.5 cm. in diameter and 3 cm. long. If the bronchus is smaller than this, the ionization in the epithelial lining will be correspondingly less, insofar as the contribution N_1 is concerned.

At this point it may be well to consider briefly certain steps in the process by which radiation produces cancer. The mechanism of the last step, that is, when a normal cell changes into a cancer cell, is not known, but the steps leading thereto have been found to be strikingly similar in many cases of cancer of the skin resulting from occupational or therapeutic over-exposure to radiation. Cancer of the skin may be produced by:

1. A large dose of radiation given within a relatively short time.

2. Irradiation at low intensities over a long period of time.

In either case the cancer does not appear for a period of at least many months and usually many years. In the case of the short exposure (a single treatment, or several in the course of a few weeks) the dose must be so high that marked tissue destruction occurs soon thereafter. The injured tissue either does not heal at all or does so very slowly over a period of many months, leaving a permanent scar. The cells in a refractory radiation wound show evidences of a losing struggle for existence. Circulation is very poor. Finally cancer becomes established. When the initial radiation wound heals - albeit with great difficulty - there may occur no cancerous degeneration for many years (even twenty or more). The process is usually set in motion by accidental injury of the devitalized tissue - circulation being very poor in this case, also. Then the sequence of events is essentially the same as in the case of the persistent radiation burn.

When cancer is produced by continuous or intermitted low intensity irradiation, tissue changes take place very gradually. For a time these changes are not even perceptible. Eventually, however, the tissue is permanently damaged. Circulation is interfered with and the conditions which favor the development of cancer become

established. Here again, it is usually an additional injury that precipitates the last step. If a generalization is permissible, one may say that cancer is apt to develop in a tissue which has been devitalized by radiation to such an extent that the existence of normal cells is very precarious. Deterioration of the cell environment by slowly progressing tissue changes, or a demand for greater activity to repair an additional local injury, sets off the spark.

In the usual treatment of cancer of the breast by radiation, the chest organs receive large doses, and numerous patients have developed fibrosis of the lung. Reasoning from analogy with the radiation cancers arising in the skin, fibrosis in the lung should favor the development of cancer in this organ. Yet there is no evidence of a high incidence of cancer in lungs showing marked radiation fibrosis. This, however, is inconclusive for at least two reasons. Patients who are treated with radiation for cancer of the breast as a rule do not live very long and there may not have been time for cancer to develop in a fibrotic lung. Then, cancer of the breast occurs mostly in women, who, on the other hand, are almost immune to cancer of the lung. Conceivably cancer might develop more readily in the lungs of men exhibiting the same degree of fibrosis. It is evident nevertheless that radiation damage in the lungs ranging from slight to very marked fibrosis does not lead to cancer of the lung within a few years. As a matter of fact, an informal inquiry among radiologists has failed to reveal any case of primary cancer of the lung arising in a region of radiation fibrosis. In this connection it should be noted that some patients with cancer of the breast treated by radiation do survive for ten or more years, although the proportion of such cases is very small.

quantitative data on the radiation dose required to produce lung fibrosis in humans under different conditions of treatment are not available. As a rough estimate one may take 3000 r of x-rays delivered to the lung over a period of a few months. It is obviously impossible to deliver this amount of radiation to the lungs of a person exposed to 0.1 r/day. Furthermore, this effect of radiation is not cumulative since it is definitely known that lung fibrosis, if not too marked, disappears within a few months or a few years. We must conclude, therefore, that even if lung fibrosis favors the development of cancer, long continued exposure to considerably more than 0.1 r/day is entirely safe, from this point of view.

Lung fibrosis has been discussed here for an additional reason. Is it one of the complications to be expected from a relatively short exposure to a high concentration of radioactive gas? This question cannot be answered categorically without considering many other factors. It is probable, however, that an atmosphere of radioactive gas which would cause lung fibrosis, would do more harm to a person in other ways and might prove lethal. The problem deserves further study. There is, however, one point that should be brought out here.

It will be recalled that in calculating the average ion density in the tissue lining the assumed lung cavity, the thickness of the lining was taken equal to the average range of the ionizing particles. It varies, therefore, with the speed of the particles. Accordingly, other conditions remaining constant, a larger volume of tissue is ionized the higher the energy of the beta rays. Furthermore, with high energy particles the contribution to the ionization due to the gas content of the whole lung becomes important, which means that all lung tissue is ionized to a degree comparable to that of the

cavity lining. While this may safely be taken as unimportant when the tissue ionization is that corresponding to 0.1 r/day, it must not be overlooked when the tissue dose approaches that which causes acute tissue changes. In other words, exposure to a high concentration of radioactive gas must be expected to produce more lung damage, the higher the energy of the beta particles emitted by the gas. The values of N given in the table, therefore, cannot be used for this purpose. The sum of N_2 and N_3 (or the value of E for that matter) gives a rough indication of the increasing lung damage to be expected as the energy of the beta particles increases, for the same concentration of radioactive gas expressed in curies per unit volume of air.

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