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32. The work reported here has been supported in part by grants from the Albert and Mary Lasker Foundation and by the American Cancer Society on recommendation of the committee of Growth of the National Research Council.
33. Since so many effects involving various tissues and organs have now been ascribed to the pituitary "growth hormone," it might be more appropriate to designate the hormone *somatotropin*, if, avoiding the restrictive distinctions between somatic tissue and the visceral or generative organs that have led to confusion in recent years, we understand the term in its broad sense as implying something that nourishes or affects the whole body (*soma*).
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Fallout Dosages at Washington, D.C.

Irving H. Blifford, Jr. and Herbert B. Rosenstock

The ground-level concentration of fission products in the air has been measured daily for several years. Fission product activity at Washington, D.C., although it is readily detectable, has generally remained less than the natural background due to radium and thorium products that are normally present in the atmosphere. However, even with low air concentrations of long-lived activities, material deposited on the ground may conceivably lead to appreciable dosages for long exposures.

In this report, a calculation of the radiation dosage received by an unshielded man for all biologically significant time (here referred to as the "infinity dose") is therefore attempted from the measured air concentration of fission products and the estimated rate of fallout (*1, 2*). Detailed calculations, to be sure, are not feasible on account of the many unknowns such as particle size, meteorological parameters, and so forth; but in view of the general lack of information on the subject, even a crude calculation based on experimental data is of interest.

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Data and Analysis

It will be assumed that the fission products are distributed in the lower atmosphere in the concentrations measured by our air filtration equipment (*2*). Our experimental data consisted of daily measurements of the atmospheric radioactivity collected by an efficient filter device. The collected radioactivity was measured with a thin-window Geiger counter, and the activity due to fission products was calculated from decay measurements. The estimated over-all accuracy of this determination is ± 20 percent. Figure 1 is an example of the raw filtration data obtained during 1953 and 1954. The earlier and most prominent responses observed during 1953 were due to United States tests in Nevada, while those later in the year followed tests in the Soviet Union. Subsequent to the Pacific thermonuclear tests of 1954, the atmospheric fission product concentration increased gradually from June to September, when much larger activities from Soviet tests appeared.

If $a(t)\ dt$ represents the number of fission product disintegrations at time t in time interval dt per unit volume, the total number $n(t)$ of disintegrations that take place per unit volume after a time t will be

$$n(t) = \int_t^\infty a(t_1)\,dt_1. \qquad (1)$$

(This is also the number of radioactive atoms contained in a unit volume at time t.) According to Way and Wigner (*3*), the time dependence after 1 day is given by

$$a(t_1) = ct_1^{-1.2} \qquad (2)$$

where c is a constant. One measurement at $t_1 = t$ suffices to determine the constant c. Evaluating Eq. 1 by means of Eq. 2, we obtain

$$n(t) = \int_t^\infty a(t)\,(t/t_1)^{1.2}dt_1 = 5a(t)t. \qquad (3)$$

If V_1 is the velocity of fallout, the total number of radioactive particles that will fall on a unit of area (and later disintegrate there) is then simply $5\ V_1 a(t)t$. The total number of radioactive atoms N that fall on a unit area due to deposition from the entire volume directly above is then

$$N = 5\int_0^\infty V_1 a(t)\,t\,dt. \qquad (4)$$

(This is also the total number of disintegrations that will occur per unit area for all time.)

Although Eq. 2 is not valid at $t = 0$, the lower limit of Eq. 4 causes no difficulty since, at some distance from the explosion, $a(t)$ usually remains zero for the first few days after detonation. Under the assumption that each measured beta disintegration corresponds to one gamma

ray of about 1 Mev (*4*), the infinity dosage R in roentgens can be calculated in a straightforward way to be

$$R = \frac{N}{2.7 \times 10^{12}} \qquad (5)$$

when N is given in disintegrations per square foot.

If the rates of fission product disintegrations $a(t)$, the time t that has elapsed since the explosion, and the velocity of fallout V_1 are known, the infinity dose due to any one explosion can be calculated from Eqs. 4 and 5. The calculation may then be repeated for all other explosions to give the total infinity dose due to all past explosions.

Of these three required quantities, the first has been measured with adequate precision (*2*). For the second, one is faced with the difficulty that only the total activity can be measured on any one day, and not the separate activities due to separate past explosions. Therefore, it has been necessary in several instances to assign certain fractions of a given disintegration rate to different explosions in what appeared to be a reasonable, but somewhat arbitrary manner. The final results, fortunately, are not very sensitive to fairly large mistakes in this assignment. For the third quantity, V_1, the situation is less satisfactory.

No daily record of V_1 is available. The quantity must therefore be taken outside the integral sign in Eq. 4 and an average value used. This will lead to a good approximation only if V_1 is reasonably constant, a condition that, in fact, is not satisfied. The measured values ranged all the way from 700 to 500,000 feet per day with an average of 40,000 feet per day (*2*). The high values are quite rare and, incidentally, are correlated with rainfall. It follows that if a day with very large V_1 occurred soon after an explosion (that is, at a time when $a(t)$ was high) our results for this explosion would be too low, whereas if no such day occurred until $a(t)$ due to one explosion has decayed to a small fraction of its original value, our results for that explosion would be much too high. The possibility that such errors occurred in individual cases cannot be excluded. However, the main interest of the present article is not in the dosage due to individual explosions, but in the total dosage accumulated over several years. In so long a time, the errors will largely compensate.

The measurements of V_1 from which the average of 40,000 feet per day was obtained were made by comparing air-filter measurements of atmospheric radioactivity with simultaneous measurements of fission products deposited on the ground over a period of 6 months (*2*). Earlier measurements on naturally radioactive substances have given lower figures (*5*). Furthermore, the entire "lower atmosphere" would be exhausted in 1 day if the fallout velocity were as high as 40,000 feet per day. It is felt, therefore, that the average velocity that has been used here, if not correct, must be high. Since V_1 is by far the least certain of the required data, the calculated infinity dos-

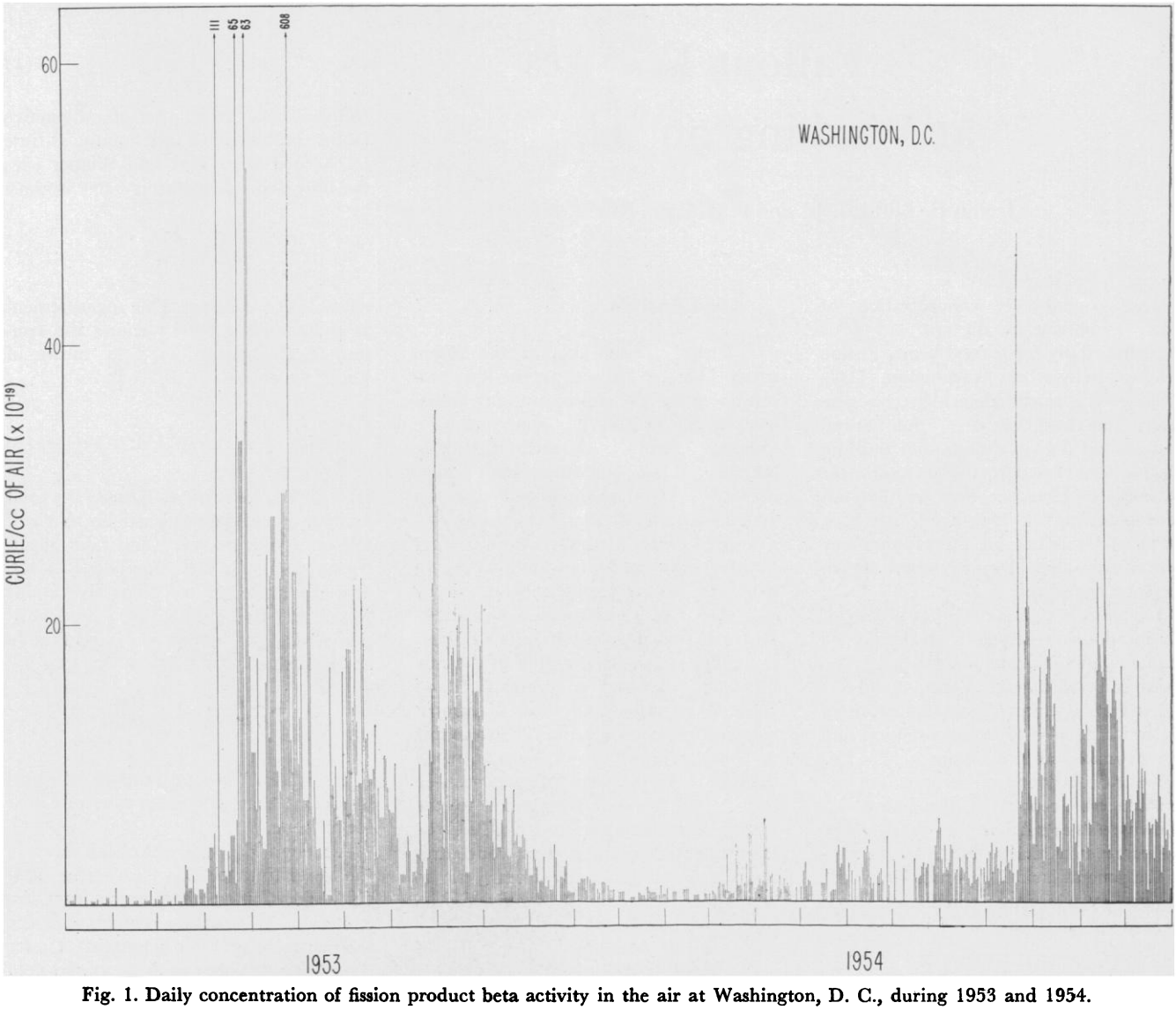

Fig. 1. Daily concentration of fission product beta activity in the air at Washington, D. C., during 1953 and 1954.

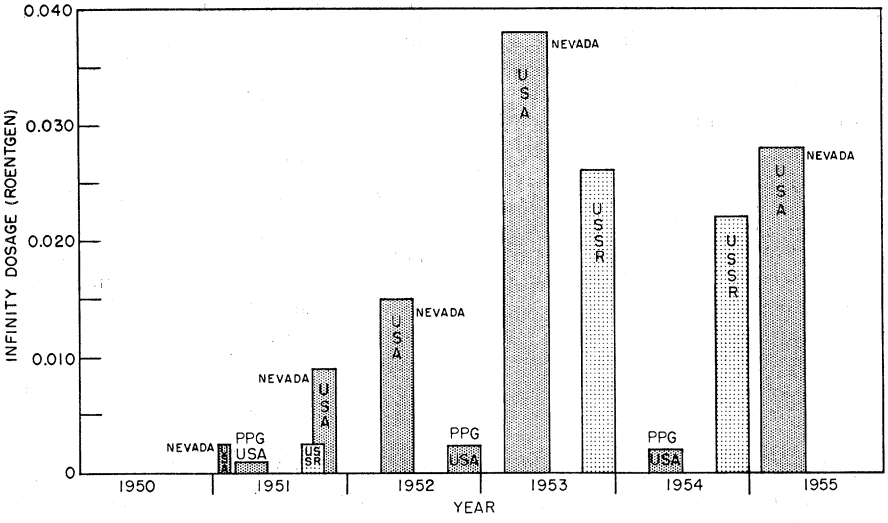

Fig. 2. Infinity dosages due to fallout from the United States and Soviet test series.

ages are probably also too high rather than too low.

Figure 2 shows the infinity dosage at Washington, D.C., for the known tests from January 1951 through May 1955. The dosages were obtained from the described direct measurements and numerical integration of Eq. 4 together with Eq. 5. The highest calculated dosage due to any one test was 0.038 roentgen (Nevada tests of the spring of 1953), and the lowest was about 0.001 roentgen (Pacific tests of the spring of 1951). The width of the bars corresponds only roughly to the actual periods of the tests.

Table 1 gives the calculated infinity dosages in Washington, D.C., from both the United States and the Soviet tests as less than 0.2 roentgen. For the aforementioned reasons, this result claims order-of-magnitude accuracy only, but it is almost certain to be an upper limit. About 60 percent of the total dosage is seen to come from the Nevada tests, about 33 percent from the Soviet tests. Owing to likely cancellation of any systematic errors in the collection or interpretation of data, these percentages should be somewhat more reliable.

The Pacific tests contributed only about 7 percent of the total fallout dosage at Washington, D.C. This result may be regarded as somewhat surprising since the total energy released and therefore the quantity of fission debris undoubtedly far exceeded the combined total of all other tests. The fallout outside the immediate area of detonation is thus observed to be a much stronger function of distance than of energy release.

Table 1. Infinity dosages due to fallout at Washington, D.C.

Test	Total infinity dosage (roentgens)
U.S. Nevada	0.093
U.S. Pacific	0.012
U.S.S.R.	0.051
Total	0.156

In this calculation, the possibility that some of the fission particulates remain suspended in the stratosphere for long times has been ignored. Ordinarily, the fission products appear to be removed from the lower atmosphere relatively quickly. The primary agency seems to be rainfall; Stokes' law fallout probably plays a secondary role. However, it is known that the clouds of radioactivity from thermonuclear weapons rise to heights far above the level of precipitation. In this case, it is possible that a reservoir of radioactive debris could be formed in the upper atmosphere. The rate of fall into the precipitation level is very likely slow compared with the rate of wash-out by rain. If this is the case, measurements of the concentration of fission products in the air after a thermonuclear explosion should show the fairly rapid initial decrease with time that is usually observed after pure fission explosions, followed by a subsequent rise due to the penetration of high-altitude activity into the troposphere.

There does, indeed, seem to be experimental evidence for this effect from ground-level measurements of air activity. Figures 3 and 4 show the normalized fission activity per unit volume of air at several locations for the period of approximately 50 to 140 days after the thermonuclear tests of the spring of 1954. The curves were obtained by correcting the measured daily air concentrations for decay using the $t^{-1.2}$ law. In Fig. 3 it will be observed that all four locations gave somewhat similar responses. Generally, there seemed to be a minimum in the vicinity of 100 days and a rise thereafter to a more or less constant value. The initial decrease was more pronounced at Subic Bay, probably because of high residual activity from low-level clouds of fission products.

At San Francisco and Honolulu (Fig. 4), the relative fission activity concentration still appeared to be increasing at 140 days. The Soviet tests of the fall of 1954 and the United States tests in Nevada in the spring of 1955 have prevented continuation of these particular measurements. These phenomena were not observed (at least in such a marked manner) after any of the atomic explosions prior to the thermonuclear tests of 1954.

On the basis of these measurements, a simple mathematical model is proposed to estimate the additional fallout that is not included in the previous calculation. The distribution of radioactivity in the lower atmosphere is assumed to be irregular below the level of precipitation h_1, (approximately 40,000 feet) and more or less uniform above it, to an upper limit h_{max} of about 120,000 feet (estimated height of original cloud). The velocity of fallout V_2 in the upper atmosphere is assumed to be much smaller than V_1. The activity in the lower atmosphere is assumed to be exhausted at time T. Radioactivity from the upper level will appear at some later time at ground level

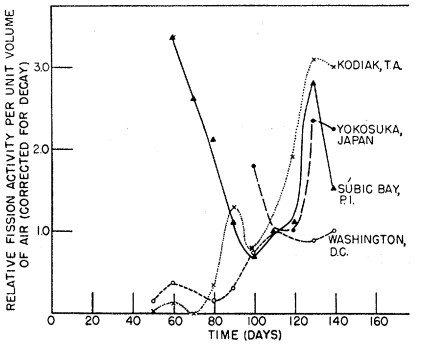

Fig. 3. Relative fission product activity per unit volume of air at Kodiak, Alaska; Yokosuka, Japan; Subic Bay, Philippines; and Washington, D.C.

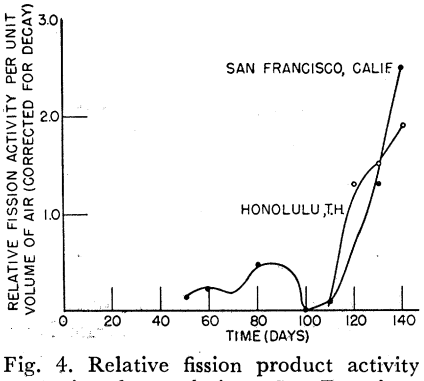

Fig. 4. Relative fission product activity per unit volume of air at San Francisco, Calif., and Honolulu, Hawaii.

and will remain substantially constant (except for radioactive decay) until at t_{max} the upper level activity is also exhausted. Therefore, Eq. 4 may be split into two parts:

$$N = N_1 + N_2 \quad (6a)$$

$$N_1 = 5V_1 \int_0^T a(t)\, t\, dt \quad (6b)$$

$$N_2 = 5V_2 \int_T^{t_{max}} a(t)\, t\, dt \quad (6c)$$

The dosage R resulting from N_1 alone is that given in Fig. 2. For $t > T$, the relationship of Eq. 1 holds in the form

$$a(t)\ t^{1.2} = a(T)\, T^{1.2}$$

and Eq. 6c becomes

$$N_2 = (50/8)\, V_2 a(T)\, T^2 \left[(t_{max}/T)^{0.8} - 1\right] \quad (7)$$

The time it takes to clear the lower atmosphere is given by $T = h_1/V_1$. The time required to exhaust both the upper and lower regions is

$$t_{max} = \frac{h_{max} - h_1}{V_2} + \frac{h_1}{V_1}$$

or, if $V_2 << V_1$ and $h_{max} = 3h_1$, then

$$t_{max} = 2h_1/V_2.$$

Using these relationships, Eq. 7 may be written

$$N^2 = (50/8)\, a(T)\, T\, h_1 \left\{\frac{V_2}{V_1}\left[\left(2\frac{V_1}{V_2}\right)^{0.8} - 1\right]\right\}. \quad (8)$$

The quantity between the braces in Eq. 8 differs from unity by a factor of less than 3 for all V_1/V_2 between 1 and 10,000. It may therefore be neglected for the purposes of this calculation.

Figures 3 and 4 suggest that the experimental value for T was about 100 days, and the average observed air concentration $a(T)$ was 21 disintegrations per cubic foot, per day. With h_1 as 40,000 feet, the number of disintegrations per square foot for all time then becomes

$$N_2 = 5.3 \times 10^8.$$

Therefore from Eq. 5, the total infinity dosage at Washington, D.C., due to fallout from the upper level would be about 2×10^{-4} roentgen. This is, of course, a very small addition to the dosages given in Table 1.

Summary and Discussion

It has been assumed that the fission product conglomerate emits one gamma ray per beta particle throughout its lifetime. The fallout velocities are not accurately known, and in some cases the detonation and response times have been approximated. For these reasons, the dosages reported in this paper can be accurate in order of magnitude only. With these reservations, an infinity dose of 0.2 roentgen or less due to all explosions between January 1951 and May 1955 is reported for Washington, D.C. Therefore, it is probable that the total fallout from all weapons tests that have so far been conducted will produce only a fraction of the lifetime dosage due to natural radioactivity and cosmic radiation (*6*).

Most of the dosage comes from the Nevada tests, and only a small part from the Pacific thermonuclear tests (*7*). Fission products contained in that part of the cloud of a thermonuclear explosion which extends above the level of precipitation is found to contribute only very slightly to the dosage at great distances. No analysis was carried out for air activity data taken at other locations, but their qualitative similarity to those taken in Washington suggests that infinity doses in most other locations in the northern hemisphere will not be greatly different.

Present results are in essential agreement with two other measurements that have been reported. Eisenbud and Harley (*8*) have measured fallout deposited on gummed papers (*9*) at various locations in the United States and have found an average dose of 0.001 roentgen per year. Stewart, Crooks, and Fisher (*10*) have measured the activity of air, rainwater, and ground deposits in England and report an infinity dose of 0.055 roentgen. This somewhat lower figure may result from their greater distance from Nevada, which appears to be the source of most of the fallout in the United States.

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R. C. Archibald and Mathematics Libraries

Raymond Clare Archibald was born in Colchester County, Nova Scotia, on 7 October 1875, the son of Abram Newcomb and Mary Mellish Archibald. When he was a small boy, his father died, and Raymond was brought up by his mother. During his youth she held a position as teacher in the Mount Allison Ladies College at Sackville, New Brunswick, and Archibald was himself graduated from Mount Allison University when still but 18 years old. At this time he received an A.B. degree with first class honors in mathematics and a teacher's diploma in violin. Presently he continued his studies at Harvard University, where he was awarded a second bachelor's degree in 1896 and a master's degree in 1897. After one more year of graduate study there, he went to Germany for 2 years. The first was spent at the University of Berlin and the second at the University of Strasbourg, from which he received his doctor's degree in 1900. Later on (1909–10) he studied for a year at the Sorbonne and still later (1922) for a short time at the University of Rome.

During the years 1894–95 and 1900–07 he taught in the Mount Allison Ladies College. Some of his duties were in mathematics, but in later years he used