Measurement of background radiation for epidemiologic purposes involves the use of technics capable of detecting geographic variation in exposure to external and internal natural sources of radioactivity at low levels. Methods for determining dose over a period of time are necessary and instruments are being developed. The methodology of this problem is analyzed.

MEASUREMENT OF BACKGROUND RADIATION FOR EPIDEMIOLOGIC STUDIES

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MEASUREMENT of background radiation for epidemiologic purposes implies the characterization of geographic areas according to the ionizing radiation of natural origin received by the residents. The dosimetric problems involved in estimating the average population exposure are relevant to both the planning of epidemiologic studies and the interpretation of results. This area of investigation poses the following problems:

1. The term "background radiation" incorporates a variety of independent and semi-independent natural sources of radioactivity which do not necessarily vary concomitantly from place to place or from time to time. The existence of multiple sources of irradiation complicates the search for geographic areas of widely differing dose levels, since any one source must be markedly elevated before appreciably raising the total dose.

2. Each of the various sources raises measurement problems of its own. Methods that are capable of detecting environmental variation of the order of that encountered in this country and that are at the same time suitable for the large-scale use required in epidemiologic studies are only now becoming available.

3. Estimates of geographic variation in the dose rate from natural internal emitters are currently based primarily on measurement of sources in the environment. Technics for determining the extent to which such estimates accurately reflect differences in the body burden are still in the process of development.

4. The optimal demographic unit for epidemiologic investigation is itself subject to geographic variation. It will depend on the magnitude of interareal variation and intraareal homogeneity in exposure levels. In addition, choice of boundaries will be affected by the size of the resident population, its geographic distribution, and mobility patterns.

5. Of the total radiation dose received by the human population, only a part originates from natural sources. A second component results from exposure to man-made medical, industrial, and military sources. These may also vary geographically. Epidemiologic evaluation of the effects of exposure to back-

Table 1—Dose Rates from Cosmic Rays, United States of America

Altitude (Feet)	Excluding the Neutron Dose Rate* mr/yr	Neutron Dose Rate† mrem/yr
0	33.29	25.0
5,000	69.20	73.0
10,000	129.65	195.0

* Based on data from Solon, et al., 1960.[6]
† Based on data from Patterson, et al., 1959.[18]

ground radiation must, therefore, take into account the relative contribution to the total dose from man-made sources.

Sources of Exposure

Natural sources of radioactivity may be either external or internal with respect to the human organism. The external sources consist of cosmic rays and terrestrial gamma radiation. The internal emitters comprise those radioisotopes which are present in the human body either as necessary constituents of living matter such as potassium 40 and carbon 14, or as nonessential elements such as radium and its daughter products.

The term "cosmic radiation" is used to designate a complex mixture of naturally occurring radiations of extraterrestrial origin. At the surface of the earth, it is made up essentially of secondary mesons, electrons, and gamma rays. The magnitude of the cosmic ray dose increases with both increasing altitude and increasing geomagnetic latitude. Variation in the components of cosmic radiation, as a function of altitude, is shown in Table 1.

Terrestrial radiation arises from the radioactive elements in rocks and soil. These are present either because their half-lives are comparable to the age of the earth or because they are continually being produced by the decay of unstable parent nuclei or nuclear reactions from cosmic rays. The three major sets of gamma-emitting isotopes are the uranium 238 series, the thorium 232 series, and potassium 40. Among the igneous rocks of the earth's crust, these three elements show roughly parallel variations with each other and with acidity which, in turn, is correlated with density and consequently with average depth of occurrence. The acidic rocks, which are the lightest and occur close to the surface, have the highest radioisotope concentration; whereas the more basic and heavier rocks, which occur mainly at great depth, have a lower content of these elements. In sedimentary rocks and their metamorphic derivatives, the over-all content of radioactive elements is lower than in igneous rocks.[1,2] Certain of the less abundant types, such as the black shales and schists, may, however, exhibit a relatively high uranium content. The approximate range of known geographic variation in human exposure to external terrestrial radiation is shown in Table 2.

Retention of uranium 238 and thorium 232 in human tissues is small. However, radium 226 and lead 210 of the uranium series and radium 228 of the thorium series can gain access to waters and be taken up by plants, thus entering the food chain cycle to man.

Table 2—Mean Dose of Irradiation to Bones from Sources of External Terrestrial Radiation

Region	Population in Millions	Aggregate Mean Dose (mrad/yr)
1. Normal regions	2,500	75
2. Granitic regions in France	7	190
3. Monazite region, Kerala in India	0.1	830
4. Monazite region, Brazil	0.05	315

Adapted from WHO, 1959.[26]

Table 3—Range of Radium 226 Content in Water Supplies Found in Survey of Midwest, United States of America

Range ($\mu\mu$g/liter)	Number of Cities	Total Population (1950 Census)
0.0-0.9	207	1,544,880
1.0-3.9	105	595,108
4.0-9.9	53	440,964
≥ 10	21	37,322

Adapted from Lucas, 1961.[20]

Once inside the body, they act as internal emitters and continue to irradiate the tissues until they are eliminated by physiological means or become inactive by decay. Since these isotopes tend to localize in bone, their contribution to the gonadal dose is negligible. The skeletal dose is difficult to estimate as it depends on their distribution within the skeleton.

Potassium 40 has a physiological role and may be expected to exhibit little geographic variation.[2] An example of geographic variation in the radium 226 content of water supplies in the midwestern region of the United States of America is shown in Table 3. Variability in the intake of radium 226 in foodstuffs is indicated by the range of from 556 to 913 $\mu\mu$g intake per year found during a preliminary study in New York City, Chicago, and San Francisco.[3]

The average annual dose to the human skeleton from all sources of natural radiation is estimated at 0.085 rad in the New England region. The contributions from external and internal sources are shown in Table 4. All values are expressed in rads in view of existing uncertainties concerning the relative biological effectiveness of alpha rays. One of the purposes of epidemiologic studies is to help resolve these uncertainties.

Radiogeological Analysis

In 1959, the Department of Epidemiology, Harvard School of Public Health, initiated a survey of cancer and background radiation in northern New England. During the course of this investigation, various methods of ascertaining geographic differences in human exposure to external and internal natural emitters were studied.

The first phase of the study consisted of determining the feasibility of using radiogeological data to identify zones of increased terrestrial radiation. The method applied by Dr. Marland Billings of the Department of Geological Sciences, Harvard University, was based on the assumption that the level of human exposure to terrestrial gamma radiation depends, to a major degree, on the concentration of radioisotopes in underlying bedrock formations. It required suitable maps showing the distribution of geological formations and the boundaries of the areal units under study. In addition, the concentration of

Table 4—Estimated Average Skeletal Dose Rates from Natural Sources of Background Radiation, New England Region

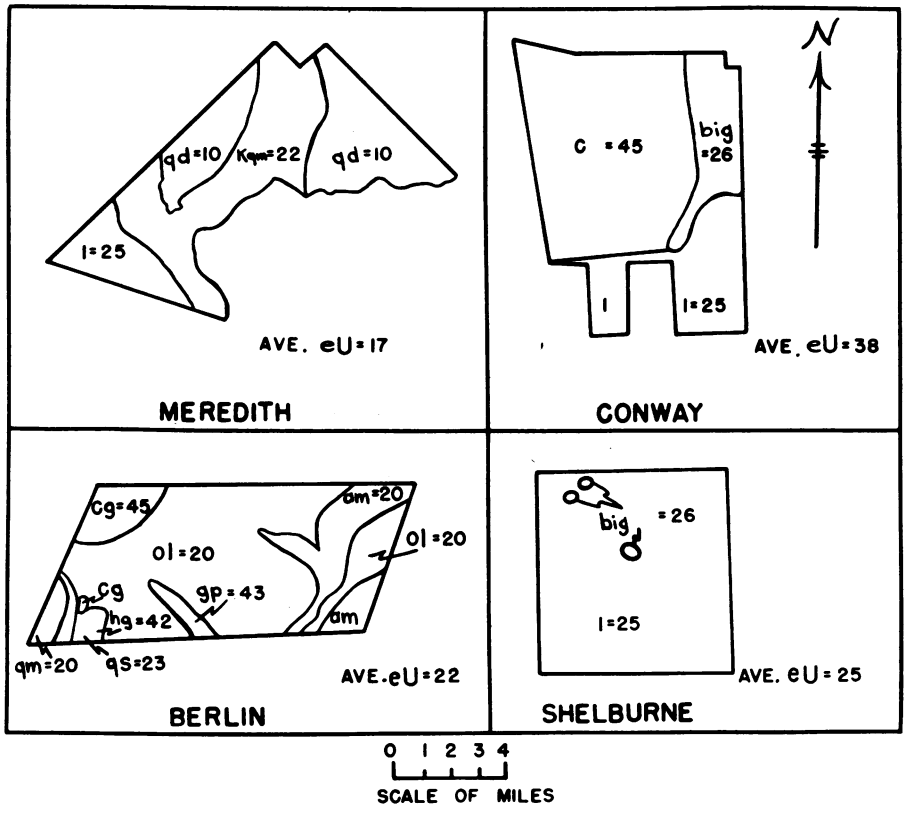
Source of Radiation	Average Annual Skeletal Dose Rates (mrads)
External Emitters*	
Cosmic rays†	33
Terrestrial gamma rays‡	35
Internal Emitters	
K_{40}	10
C_{14}	1
Ra_{226} series**	2
Ra_{228} series**	2
Pb_{210} series**	2
Total	85

* Assuming indoor exposure equal to outdoor exposure.
† Not corrected for neutron component.
‡ Assuming a shielding factor of 0.65.
** Personal communication from E. P. Radford, Jr.

relevant isotopes in each of the geological types had to be estimated.[4]

For comparative purposes, the radioactivity of bedrock may be expressed in terms of equivalent uranium in parts per million. This is the amount of uranium which, by itself, would yield the same quantity of gamma radiation in roentgens as the uranium, thorium, and potassium 40 in the particular rock. The equivalent uranium content was calculated for 58 geological formations in New Hampshire, 5 in Maine, and 24 in Vermont. Determinations were made from available data on the different types of rock. These varied in respect to both quantity and quality within the tri-state study area. The method of analysis was therefore adapted in each instance to the nature

Figure 1—Radiogeological Variability Within Selected Minor Civil Divisions in New Hampshire



Numeral after each formation symbol is average equivalent uranium in parts per million for that formation.

Average equivalent uranium for entire township is given in lower right hand corner of each map.

l=Littleton formation
cg=Conway granite
big=binary granite
ol=Oliverian series
qm=quartz monzonite
hg=hastingsite granite
gp=granite porphyry
qd=quartz diorite
kqm=Kinsman quartz monzonite
qs=quartz syenite

of the basic data which were available. Five principal sources were used: chemical analysis of rock specimens, alpha counts of rock specimens, direct measurements of outcrops in auto traverses, calculations based on counts obtained in air-borne surveys, and lithological similarity to rocks for which data were available in the literature.[4]

The basic geographic units used in the study were minor civil divisions. These are the primary political divisions into which counties are divided and are the smallest administrative units for which vital statistics are routinely tabulated. The boundaries of approximately one thousand minor civil divisions were plotted on state geological maps and the percentage area overlying each specific geological formation was calculated. An average equivalent uranium value for the minor civil division, weighted by the proportion overlying each geological formation, was thus obtained.

The radioactivity of bedrock underlying a single minor civil division may exhibit a wide range of variability. This is illustrated by the maps in Figure 1 which show the distribution of geological formations and their respective equivalent uranium concentrations in four minor civil divisions of New Hampshire. It will be noted that while the weighted average equivalent uranium concentrations for Berlin and Shelburne are similar, the two areas differ considerably with respect to the homogeneity of the underlying bedrock. Considerable intraareal variation in bedrock radioactivity is also exhibited within Conway and Meredith.[5] These findings suggest that even within as small an areal unit as the minor civil division there may be marked differences in terrestrial radiation. In assessing the average equivalent uranium levels for epidemiologic studies, it is therefore necessary to take into consideration the geographic distribution of the population resident within the minor civil division.

The value of radiogeological analysis for epidemiologic purposes will depend on the extent to which differences in the equivalent uranium concentration of geological formations reflect differences in human exposure to external and possibly internal emitters of terrestrial origin. Several environmental factors are known to affect the availability of gamma emitters originating in bedrock as potential sources of human exposure.

Of major significance is the attenuation effect due to the layer of unconsolidated material or soil overlying the particular rock formation. This will vary with the thickness of the soil and its relative richness in gamma emitters as compared to the underlying bedrock. Evidence suggesting that the gamma radiation from unconsolidated deposits and soil in parts of northern New England is closely related to that of the underlying bedrock was obtained by Billings from data recorded in automobile and air-borne surveys. We presume, therefore, that this is not a serious source of error in our study.

Among the principal gamma emitters in the uranium and thorium series are the progeny of the gaseous isotopes, radon (radon 222) and thoron (radon 220). The relative contribution of these elements to the total background gamma activity is influenced by factors which govern the distribution and behavior of the atmospheric and soil gases. These include ambient temperature, humidity and pressure, as well as soil conditions such as moisture and porosity. Temperature inversion may, for example, increase the atmospheric radon concentration by a factor of about ten. Snow absorbs gamma radiation from the ground with a reduction in intensity which is dependent on its depth and density. The effective gamma ray flux due to terrestrial radiation is thus a

function of meteorological patterns as well as the equivalent uranium content of the earth's material.[1]

Several investigators have measured alterations in the dose rate from local gamma emitters in buildings as compared with its value outdoors. Construction materials may have a twofold effect. Radiation from outside the building may be absorbed by the structural elements. On the other hand, building materials may themselves constitute a source of radioactivity. In the case of brick, concrete, and shale, increased indoor dose rates were observed. For wood-frame houses a slight reduction was noted.[1] Contrary to other studies, a recent survey by Solon, et al., in the New York metropolitan area, demonstrated that the radiation level inside houses in this area, essentially irrespective of construction material, was not very different from, although generally somewhat lower than, the outdoor level in the same location.[6] The net effect on the total human exposure dose rate will depend on the composition of the structural elements and a time factor to allow for the duration of exposure to indoor and outdoor radiation.

Measurement of External Emitters

From these considerations, it is clear that the radiogeological method of estimating human exposure to sources of terrestrial radiation requires validation by direct dosimetry. For this purpose, a survey of external gamma radiation levels in certain areas of northern New England is planned in cooperation with the Health and Safety Laboratory of the U. S. Atomic Energy Commission. This group has undertaken a similar study during the past two years in New York State, in cooperation with the State Department of Health, using 20-liter air-filled ionization chambers and portable scintillation detectors.[7] New high-pressure ionization chambers, more sensitive and more reliable for field measurements than the air chambers, have recently been developed for use in the completion of the New York study and in the New England survey. These are steel-walled chambers, filled with argon or nitrogen gas to about 30 atmospheres pressure, and utilizing portable vibrating reed electrometers for current measurement.[8]

Unexpected complications in the proposed survey have, however, been introduced by the latest series of atomic bomb tests. Recent data have pointed to the magnitude of gamma activity from radioactive fallout, mainly zirconium 95 and possibly other fission products of comparably short half-lives. Investigators in this country and elsewhere have recently suggested that in the months following the moratorium on nuclear testing in 1958, the infinite-plane gamma dose rate from fallout reached a significant proportion of the total background.[9-11] The quantitative effect of resumed atmospheric testing cannot, as yet, be predicted. Measurement of true background dose rates may, however, be difficult until the end of 1962, at which time the dose rate from fallout, provided no further testing occurs, is expected to drop to negligible levels.

A major limitation of this type of survey is that a single measurement represents only one point in an intensity range and may be unreliable as an index of the dose rate integrated over a period of time. This difficulty may be overcome by making repeated measurements to correct for diurnal and seasonal variations.

Another approach is the use of the film-badge dosimeter. Such an instrument is advantageous in that it provides a permanent record of the total dose over a period of several weeks. Since the unit can be worn without inconvenience, it also permits monitoring of the

total external background to which a single individual is exposed. However, the film used in dosimeters which are currently available commercially is not sufficiently sensitive to differentiate with reliability the low dose levels which are of concern in the study of background radiation. Encouraging results have been obtained at the Health and Safety Laboratory of the Atomic Energy Commission in the development of a sensitive scintillation-film dosimeter. Thallium activated sodium iodide is used as the scintillation material in conjunction with dental type x-ray film.[12] The use of such a dosimeter for large-scale studies is, however, rendered impractical by the high cost of the sodium iodide component. Attempts to substitute a less expensive plastic scintillation material have been reported by Sax and Spiers and were conducted by Fitzgerald in connection with the northern New England survey. Scintillation crystals of various shapes, sizes, and composition coupled with x-ray type and personnel monitoring type film were tested. The dependency of the film density on crystal dimensions, dose, dose rate, and energy were examined. Units capable of detecting an exposure of less than one mr were developed. While this provides sufficient sensitivity for the measurement of background gamma radiation levels, major problems with respect to dose rate and temperature dependency are encountered. These technical problems require resolution before this type of dosimeter becomes of practical value in epidemiologic investigations.[11,13,14]

A system capable of detecting a 20 per cent increase in background over a period of approximately four days has been reported by Roesch, et al.[15] The method consists of reading a condenser chamber "pencil" after exposure by recharging it to its initial voltage through a resistor. At the instant of recharging, a voltage pulse is produced across the resistor which is proportional to the dose. The pulse height is measured by any of several methods. The advantages of this method are that it is differential, hence more sensitive, and it is a pulse measurement rather than a direct current measurement. In addition, the condenser chamber is recharged, ready for use at the same time and the method readily lends itself to automation. By this method at the Hanford Laboratories Operation, a standard Victoreen No. 362 pencil could measure 1 ± 0.2 mr at the 95 per cent confidence level. The method has been used extensively at Hanford but no other use of it is known.[16]

Aerial measurements have been used to make rapid radiation surveys of large areas. The equipment usually consists of scintillators that are used to scan the countryside from an airplane flying at about 500 feet above the ground. The dose rate information is plotted automatically by the survey instrument on a moving chart that moves in synchronism with a map upon which the navigator marks the flight paths. This information has been used to provide rough estimates of geographic variation in the surface dose rate, taking into account differences in the geometry of aerial and surface measurements.[27,28]

Measurement of cosmic radiation has in the past generally excluded the neutron dose since the type of ion chambers and scintillation detectors used for this purpose were relatively insensitive to the neutron flux. The magnitude of the latter component may be assessed by using different neutron detectors to determine the cosmic neutron energy spectrum. These include the bismuth fission ionization chamber, the proton-recoil proportional counter, and the moderated and bare BF_3 proportional counters. Results obtained by Patterson (see Table 1) suggest that the relative contribution from neutrons may be sufficiently high to warrant its inclusion in any estimate of the total cosmic dose.[17,18]

Measurement of Internal Emitters

Of the radioisotopes originally present in rock-type formations, some may become internal emitters through natural processes. They may be leached or dissolved into ground and surface waters, thus gaining access to man's water and food supply. For either physical or biological reasons, only a few of the naturally radioactive heavy atoms are important sources of internal radiation exposure. The three most important are believed to be radium 226, the most abundant natural isotope of radium; lead 210, a daughter of radium 226 and of radon 222, and radium 228, a daughter of natural thorium.

Food is generally considered to be a more important vehicle for the ingestion of radium than is water. To date, no differences in the ability of the human body to retain radium 226 and its daughters present in soluble form in drinking water as compared to the same elements, possibly in different chemical form, ingested in food have been observed.[19]

In certain areas of the United States and Great Britain geographic variation in the body content of radium has been found to correlate with levels of radium in water supplies.[19,20] These levels, in turn, have been found to be associated with specific geological strata. Water derived from surface sources such as rivers, lakes, or wells penetrating unconsolidated sand or gravel deposits were, in general, found to contain considerably lower concentrations of radium 226 than wells penetrating deep sandstone formations of Cambrian or pre-Cambrian ages. It should be noted that the activity of the water consumed depends both on the aquifer from which it is drawn and the methods used for its treatment prior to consumption.

The validity with which the equivalent uranium content of underlying bedrock may be used as an index of the radium body burden acquired by the resident population may therefore be expected to vary from one locality to another.

Progress of epidemiologic studies in this area will depend on developments in the technics of measuring radium body burdens. The basic methods currently available were originally designed for use in populations characterized by a relatively high occupational exposure. The whole-body counting technic, which is advantageous in that it requires no chemistry or special preparation of the individual, is at present considered not suitable for counting individuals whose bodies contain less than 10^{-9} curies.[21] Similarly, the application of radon breath measurement and metabolic balance determination to the field of background dosimetry is considerably limited by the problem of achieving adequate sensitivity.[22] On the other hand, development of new procedures for radiometric analysis of biological specimens, such as bone and teeth, may provide a valuable tool for epidemiologic investigations. In a large-scale population study, teeth are obtainable with relative ease and recent bovine and human studies suggest that they may serve to accurately indicate the body burden of radium 226, if acquired by chronic exposure.[23]

A method of determining the concentration of radium 226, radium 224, radium 223, and polonium 210 in a single tooth has recently been developed by Dr. E. P. Radford, Jr., of the Department of Physiology, Harvard School of Public Health.[24] Samples weighing from one to two grams are dissolved in HCl and polonium 210 is plated onto silver. The solution is then treated by a modification of the coprecipitation procedure of Goldin.[25] Radium 224 and radium 223 are separated from radium 226 by statistical analysis of the nonrandom decay of their daughters using

a low background proportional counter. Studies of the variation in the amount of these isotopes in teeth extracted from persons living in areas of differing geological radioactivity will shortly be reported.

Summary

The measurement of background radiation for epidemiologic purposes involves the application of technics capable of detecting geographic variation in human exposure to both external and internal natural sources of radioactivity at very low levels. While radiogeological analysis may be useful in identifying areas of different potential exposure, direct measurement of the dose received by the human population is desirable. Spot measurements of external gamma radiation may currently be made with portable high pressure ionization chambers. Instruments suitable for recording the dose accumulated over a period of time are still in the process of development. Radiometric analysis of small amounts of biological material, such as individual teeth, is now possible and may be used to estimate the body burden of radium and other emitters in large-scale population studies.

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