BRITISH MEDICAL JOURNAL

LONDON SATURDAY JUNE 11 1960

GEOGRAPHICAL VARIATION IN LEUKAEMIA MORTALITY IN RELATION TO BACKGROUND RADIATION AND OTHER FACTORS

BY

W. M. COURT BROWN, M.B., B.Sc., F.F.R.
Director of the Medical Research Council's Clinical Effects of Radiation Research Unit, Western General Hospital, Edinburgh

R. DOLL, M.D., D.Sc., F.R.C.P.
Deputy Director of the Medical Research Council's Statistical Research Unit, London School of Hygiene and Tropical Medicine

F. W. SPIERS, D.Sc.
Professor of Medical Physics, Department of Medical Physics, University of Leeds

B. J. DUFFY, M.D.
Professor of Preventive Medicine, Seton Hall College of Medicine, Jersey City, New Jersey, U.S.A.

AND

M. J. McHUGH, M.Sc.
Medical Research Council's Environmental Radiation Research Unit, Department of Medical Physics, University of Leeds

There is no doubt that the risk of developing leukaemia can be increased by exposure to ionizing radiations, but it is not clear whether this effect is produced by all types of exposure or whether it is limited to certain levels of dose and of dose-rate. Cases have been produced by exposure of the whole body to doses of γ rays of the order of 100 to 500 rads given within a few seconds as a result of the explosion of atomic bombs (Folley, Borges, and Yamawaki, 1952; Lange, Maloney, and Yamawaki, 1954; Medical Research Council, 1956; Wald, 1958) and by partial body-exposure to x rays given at rates of 10 to 50 rads per minute in the course of radiotherapy (Court Brown and Doll, 1957; Simpson and Hempelmann, 1957). In most of the latter cases substantial amounts of active marrow may be presumed to have received total doses of at least 100 rads. The evidence to implicate smaller doses, such as are used in diagnostic radiography, is less complete (March, 1950; Stewart, Webb, and Hewitt, 1958; Faber, 1958); but if these doses are leukaemogenic, it may be because the rates at which they are given are similar to those used in radiotherapy. It does not necessarily follow that a similar effect would be produced by ionizing radiations given at much lower rates. Even if a dose of 1 rad given in 1 second or 1 minute carries some leukaemogenic risk, there may not be any risk from exposure to the same dose spread over about 10 years—that is, given at the average dose-rate of natural background radiation.

Doses given at very low dose-rates may, however, be presumed to produce mutations in marrow cells comparable to the gene mutations in germ cells, and if such mutations are capable of playing any part in the development of cancer the possibility would have to be considered that the natural background radiation might also be responsible for some cases of leukaemia. Lewis (1957) has argued that the present evidence of the relationship between dose and incidence implies that background radiation may produce about 10 to 20% of the cases of leukaemia that occur in the U.S.A. Others (Brues, 1958; Lamerton, 1958; Mole, 1958) disagree, and some think that the evidence from animal experiments weighs heavily against the possibility that any cases could be produced by irradiation of such low intensity.

It is difficult to make direct observations of the effect of background radiation, because any effect is likely to be small in comparison with that due to other causes. Populations of the order of hundreds of thousands would have to be studied, and it is difficult to maintain the same standards of diagnosis throughout such large populations. The present study was therefore undertaken with some misgiving; but it was thought that an attempt to measure the effect should be made—if only to demonstrate its impracticability. Scotland seemed to be a favourable area to study because: (1) it contains two contrasting cities, each of approximately 180,000 inhabitants, with similar geographical situations and each containing a medical school, but built out of different material and likely to provide a substantial difference in background radiation; (2) the population is fairly stable and many people reside in the same town throughout their life; (3) the Registrar-General for Scotland had provided us with copies of all death entries relating to leukaemia for the years 1939–56, inclusive, in the course of another investigation.

Method

The country was divided into 10 areas: the two cities referred to previously (Aberdeen and Dundee) and the two surrounding rural areas (Aberdeenshire and Angus and Kincardine); two other large cities (Edinburgh and Glasgow); three largely rural areas covering the remainder of the northern, western, and central regions; and one large area—the rest of Scotland—comprising the whole region south of Perthshire less Edinburgh and Glasgow. Accurate counts of the population by sex and age had been made for each of the 10 areas on two occasions during the period studied—in September, 1939, when the population was required to register for the purposes of identification, and at the 1951 census. Estimates of the populations in 10-year age-groups were obtained from the Registrar-General for 1956 and estimates for intervening years were made by simple arithmetical interpolation. In view of the distortion of the population by military service during the war, the estimates for this period are certainly inaccurate, and the results have therefore been analysed separately for 1939–46 and 1947–56. By 1947 the great majority of men in the armed Forces had been demobilized, and the population estimates for the second period are believed to be reasonably accurate. The inaccuracy in the earlier period is unlikely to be important as it must have affected all the 10 areas and is unlikely to have created a significant bias in favour of one.

The deaths were classified according to the area of usual residence; persons in the armed Forces or normally resident abroad were excluded. The causes of death were initially classified in nine groups—acute, chronic, and unspecified lymphatic leukaemia; acute, chronic, and unspecified myeloid leukaemia; other and unspecified acute leukaemia; chronic unspecified leukaemia; and leukaemia without other specification. Estimates of the total numbers of deaths likely to have been due to acute leukaemia, chronic myeloid leukaemia, and chronic lymphatic leukaemia were then obtained by allocating the unspecified cases to one or other of these three groups by assuming that for each sex and in each 10-year age-group the proportions of the various types were the same as those recorded when the types were specified. A detailed account of the method is given in a report on the changes in leukaemia mortality in England and Wales (Court Brown and Doll, 1959).

Sex and age-specific mortality rates for each of the three main types of leukaemia and for all leukaemia were calculated for all Scotland for the two periods 1939–46 and 1947–56. The expected numbers of deaths in each of the 10 areas from each type of leukaemia were then calculated by multiplying the observed rates for all Scotland by the estimated populations in each sex and 10-year group in each area. Finally, the observed deaths in each area were classified in the nine original diagnostic groups and the numbers attributed to acute leukaemia, chronic myeloid leukaemia, and chronic lymphatic leukaemia were estimated by assuming that the proportions of the various types among the unspecified cases were the same, in each age and sex group, as the proportions recorded in the same area when the types were specified.

Estimates of the expected numbers of deaths and of the observed numbers attributable to the three main types of leukaemia were confined to persons aged 15 years and over as it was thought that this age-group would be the most likely to show any effect due to background radiation. Adults would have had opportunity of accumulating a greater dose from background sources, and there are reasons for thinking that much childhood leukaemia, which has a peak mortality at age 3 years, is due to environmental factors that have become common only in the past 30 years.

Measurements of the natural background radiation were made in four areas. The surveys covered two predominantly granite districts—Aberdeen City and Aberdeen County—and two districts of sedimentary rocks—Edinburgh and Dundee. In all four areas most of the houses and buildings are made of local stone, so that a sufficient homogeneity exists to give significance to a mean population dose-rate.

Measurements of gamma-ray dose-rate were made out-of-doors and in houses. The houses, found by private inquiry, numbered 155 in Edinburgh, 103 in Aberdeen, and 71 in Dundee. They were distributed in reasonably representative patterns over the built-up areas of the cities and included the various types of building material in proportions closely following the statistics provided by the city surveyors. Approximately the same numbers of measurements were made on roads and pavements.

In Aberdeenshire the distribution of the 172 houses in which measurements were made had to be arranged to take into account the variations in population density and local geology. The survey included all the 10 parishes or boroughs with populations of 3,000 or more; 4 out of the 10 parishes with populations between 2,000 and 2,999; 5 out of the 23 parishes with populations between 1,000 and 1,999; and 8 out of 39 parishes having populations less than 1,000. A procedure of random selection, with some stratification as to region, was adopted for parishes of less than 3,000 population, and in all groups the numbers of houses selected lay between 10 and 14 per 1,000 inhabitants.

The measurements were made with a portable high-pressure ionization chamber, having the required sensitivity and long-term stability (Spiers, 1959); a single observation, with an ion-collection time of about three minutes, carried a standard error of $\pm 1.5\%$. At each out-of-door site two measurements were made, and in houses two measurements were made at each of three selected points—in the living-room, kitchen, and one upstairs bedroom. The mean of the six indoor measurements was taken as typical of the house dose-rate. In single-floor flats only two rooms were measured. The cosmic-ray response of the instrument, corrected to allow for overhead shielding, was subtracted from the reading at each site before applying an appropriate gamma-ray calibration factor to derive the local gamma-ray dose-rate.

Results

Leukaemia Mortality

The numbers of deaths attributed to leukaemia among adults in each of the 10 areas studied and the numbers expected on the basis of the leukaemia mortality for all Scotland are shown in Table I; they are shown separately for men and for women and for each of the periods 1939–46 and 1947–56. The differences between the numbers of deaths observed and expected in each area are statistically highly significant ($\chi^2=51.94$; $n=9$; $P<0.001$). In two of the areas—Aberdeen and Edinburgh—the differences are large and are likely to

TABLE I.—*Number of Deaths Attributed to Leukaemia in Various Parts of Scotland (1939–56) Compared with the Number Expected on the Basis of the Scottish National Mortality (Persons Aged 15 Years and Over)*

Area	No. of Deaths Among Men				No. of Deaths Among Women				Total No. of Deaths	
	1939–46		1947–56		1939–46		1947–56			
	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
Aberdeen	18	16·0	45	31·2	22	15·3	49	29·5	134	92·0
Dundee	11	15·7	38	29·8	12	15·2	33	29·1	94	89·8
Edinburgh	59	43·6	100	83·9	61	40·5	85	78·2	305	246·3
Glasgow	85	103·9	162	187·3	74	81·9	142	156·6	463	529·7
Aberdeenshire	18	14·3	21	26·6	15	11·5	27	21·5	81	73·9
Angus and Kincardine	15	12·6	24	23·8	9	11·5	19	20·8	67	68·7
Banff, Inverness, Moray, and Nairn	11	19·2	50	35·9	14	16·0	34	28·9	109	100·0
North Scotland	14	15·6	27	27·7	12	13·3	19	22·2	72	78·8
Perthshire	16	13·0	26	24·9	14	12·1	34	21·8	90	71·8
Rest of Scotland	241	234·0	422	444·0	172	187·6	327	360·5	1,162	1,226·1
All Scotland	488	487·9	915	915·1	405	404·9	769	769·1	2,577	2,577·0

TABLE II.—*Standardized Mortality Ratios for Leukaemia in Various Parts of Scotland, for Men and for Women and for the Periods* 1939–46 *and* 1947–56 *(Persons Aged* 15 *Years and Over)*

Area	Standardized Mortality Ratio for:				
	Men	Women	1939–46	1947–56	All Persons 1939–56
Aberdeen	133	158	128	155	146
Dundee	103	102	74	121	105
Edinburgh	125	123	143	114	124
Glasgow	85	91	86	88	87
Aberdeenshire	95	127	128	100	110
Angus and Kincardine	107	87	100	96	98
Banff, Inverness, Moray, and Nairn	111	107	71	130	109
North Scotland	95	87	90	92	91
Perthshire	111	142	120	128	125
Rest of Scotland	98	91	97	93	95
All Scotland	100	100	100	100	100

be attributable to chance.* In Table II, standardized mortality ratios—that is, the observed numbers of deaths expressed as percentages of the numbers expected—are given for men and for women and for all persons for each period. The data show that in Aberdeen the ratio was the highest recorded both for men and for women, it was the highest recorded in the period 1947–56 and was the second highest (equal to that in Aberdeenshire) in the period 1939–46. In Edinburgh, the mortality ratio was the second highest recorded for men and the fourth highest for women; it was the highest recorded in the period 1939–46, but was only slightly above average in 1947–56.

*The contributions to χ^2 are respectively 19.17 and 14.06. In Perthshire the proportionate excess is slightly greater than in Edinburgh, but the expected number of deaths is much smaller and the difference may be regarded as a chance finding (contribution to χ^2, 4.64).

In Table III the results are shown separately for acute leukaemia, chronic myeloid leukaemia, and chronic lymphatic leukaemia; because of paucity of numbers in some of the groups the data are shown only for all persons and for the whole period 1939–57. Standardized mortality ratios are shown in Table IV. The data show that the excess mortality in Aberdeen has been principally due to an excess of acute leukaemia and of chronic myeloid leukaemia, while the excess mortality in Edinburgh has been due principally to an excess of chronic lymphatic leukaemia.

The total leukaemia mortality in Aberdeen and in Edinburgh is shown for three separate age-groups in Table V. The observed mortality is seen to have been greater than expected at all adult ages in Aberdeen, but in Edinburgh the excess is limited to ages 35 years and over.

TABLE IV.—*Standardized Mortality Ratios for Acute, Chronic Myeloid, and Chronic Lymphatic Leukaemia in Various Parts of Scotland,* 1939–56 *(Persons Aged* 15 *Years and Over)*

Area	Standardized Mortality Ratios for:			
	Acute Leukaemia	Chronic Myeloid Leukaemia	Chronic Lymphatic Leukaemia	All Leukaemia
Aberdeen	161	142	117	146
Dundee	95	103	125	105
Edinburgh	113	113	154	124
Glasgow	94	80	80	87
Aberdeenshire	121	94	100	110
Angus and Kincardine	89	84	124	98
Banff, Inverness, Moray, and Nairn	117	87	112	109
North Scotland	84	132	72	91
Perthshire	142	96	121	125
Rest of Scotland	92	103	92	95
All Scotland	100	100	100	100

TABLE III.—*Numbers of Deaths Attributable to Acute, Chronic Myeloid, and Chronic Lymphatic Leukaemia in Various Parts of Scotland (1939–56) Compared with the Numbers Expected (Persons Aged 15 Years and Over)*

Area	No. of Deaths from Acute Leukaemia		No. of Deaths from Chronic Myeloid Leukaemia		No. of Deaths from Chronic Lymphatic Leukaemia		Total No. of Deaths	
	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected
Aberdeen	77·5	48·0	29·2	20·6	27·3	23·3	134	92·0
Dundee	44·5	46·6	20·8	20·2	28·7	23·0	94	89·8
Edinburgh	143·5	126·6	62·7	55·5	98·8	64·1	305	246·2
Glasgow	264·8	281·9	93·0	116·7	105·3	131·0	463	529·7
Aberdeenshire	46·0	37·9	15·3	16·3	18·7	19·7	81	73·9
Angus and Kincardine	31·0	34·7	13·0	15·4	23·0	18·6	67	68·7
Banff, Inverness, Moray, and Nairn	60·1	51·2	19·2	22·1	29·8	26·7	109	100·0
North Scotland	32·8	38·9	23·2	17·6	16·1	22·3	72	78·8
Perthshire	51·1	36·1	15·4	16·1	23·5	19·5	90	71·8
Rest of Scotland	592·6	641·8	279·7	270·9	289·6	313·4	1,162	1,226·1
All Scotland	1,343·9	1,343·7	571·5	571·4	661·8	661·6	2,577	2,577·0

TABLE V.—*Comparison Between the Numbers of Deaths from Leukaemia Observed and Expected in Aberdeen and Edinburgh, by Age (Persons Aged 15 Years and Over)*

Age (Years)	Aberdeen			Edinburgh		
	No. of Deaths		Observed Deaths as % of Expected	No. of Deaths		Observed Deaths as % of Expected
	Observed	Expected		Observed	Expected	
15–34	23	16·6	139	36	40·7	88
35–54	38	27·0	141	92	70·6	130
55+	73	48·4	151	177	134·9	131
All ages	134	92·0	146	305	246·2	124

Background Radiation

The dose-rates out-of-doors in Edinburgh, Dundee, and Aberdeen are shown in Fig. 1. The mean dose-rate of 104 m.rad per year in Aberdeen is more than twice the mean of 48.5 m.rad per year in Edinburgh. Fig. 2 shows that the dose-rates in the stone houses in the three cities are also different, the mean dose-rate in the Aberdeen granite houses being 87 m.rad per year compared with 48.5 m.rad per year in sandstone houses in Edinburgh. Though no exact analysis has been made, the difference in dose-rate between the Dundee (Old Red) and the Edinburgh (Lower Carboniferous) sandstone houses is in keeping with the higher potash content of the Dundee stone (C. F. Davidson, 1959, personal communication).

The results of the out-door measurements in Aberdeen show the interesting feature that the mean dose-rates over half-mile annular zones increase steadily from 75 m.rad per year in the peripheral zone (2½ to 3 miles radius) to 115 m.rad per year in the central zone.

The dose-rates measured in the survey of the county of Aberdeen are shown in Figs. 3 and 4. Each histogram shows a greater spread of dose-rates than is seen in the results for the cities because much greater variation exists in surface geology and in the materials used for constructing roads and houses.

In each of the four areas the average dose-rate out-of-doors is taken as the mean of all the outdoor observations. In the three cities a mean indoor dose-rate is obtained by weighting, according to the proportions of houses of different types. In Aberdeen County mean dose-rates are derived for each population group surveyed, and a final average dose-rate for the whole population is obtained by weighting the mean dose-rate for each group by the proportion of the total population it represents.

The dose-rates in this report have so far related to measurements in air. In order to determine mean dose-rates to the bone-marrow, it is necessary to introduce (1) attenuation factors for overlying tissues, (2) a time factor to allow for the length of time exposed to indoor and outdoor radiation, and (3) the additional dose-rate from cosmic rays and internal sources.

The attenuation factor for bone-marrow has been derived from measurements in a water-filled model irradiated by a nearly omnidirectional array of radioactive sources. These measurements were made at several points on the surface and within the model, and covered a range of gamma-ray energies (Spiers and Overton, 1960). With the use of data on the distribution of red marrow in the body (R. E. Ellis, 1958, personal communication) a mean attenuation factor was derived at a gamma-ray energy approximating to that of background radiation. The value of 0.64 for this mean attenuation factor corresponds to a mean marrow depth of about 4 cm. from the body surface.

The time factor has been assumed to be 0.25 for outdoor radiation and 0.75 for indoor radiation—that is,

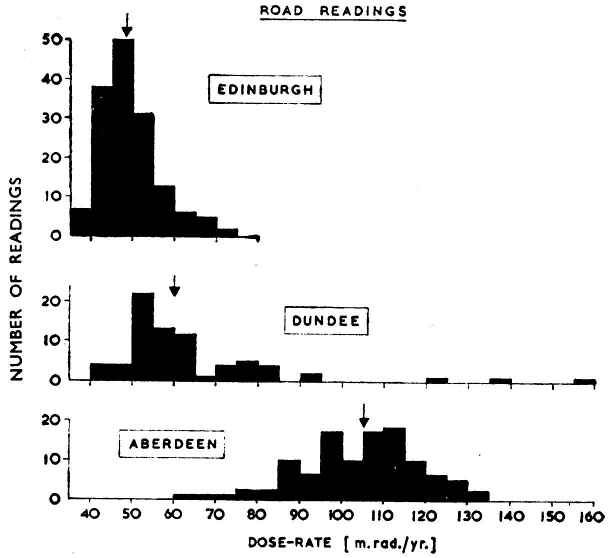

FIG. 1.—Background radiation out-of-doors in Aberdeen, Dundee, and Edinburgh.

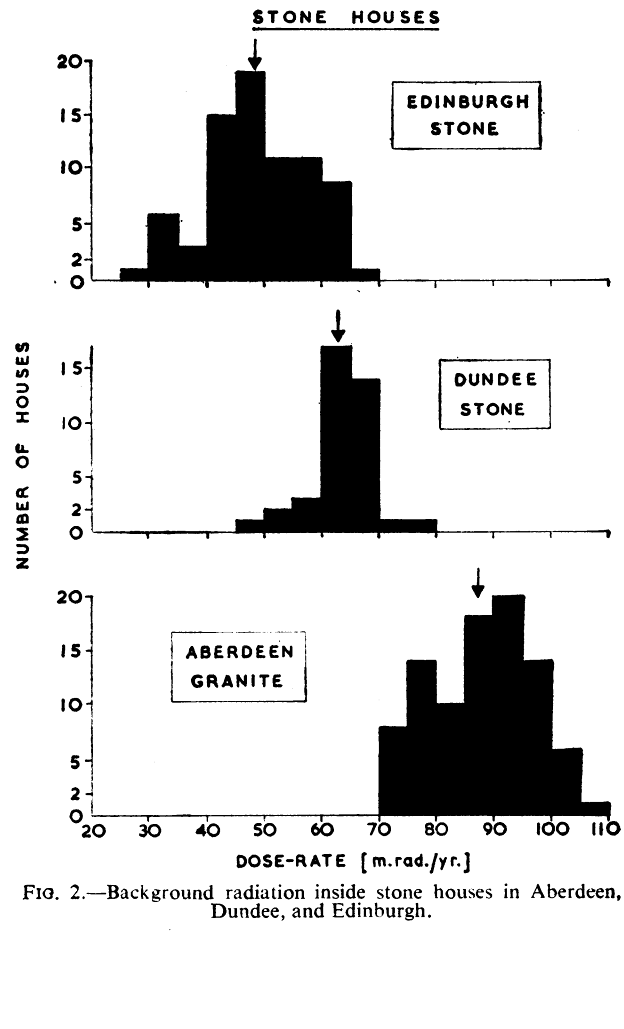

FIG. 2.—Background radiation inside stone houses in Aberdeen, Dundee, and Edinburgh.

it has been assumed that on average six hours a day are spent outdoors.

Cosmic rays and potassium-40 contribute most of the dose-rate from natural sources, additional to the local gamma radiation. The cosmic-ray dose-rate averaged for time spent indoors and out-of-doors amounts to approximately 24 m.rad per year to the bone-marrow. In trabecular bone the average potassium content may be expected to lie between 0.05% for mineral bone and a value near to 0.2% for the marrow; a mean dose-rate of 15 m.rad per year may be taken as sufficiently representative. Small additional dose-rates from carbon-14 and radon bring the total internal dose-rates to 43 m.rem per year.

The data in Table VI show the contributions made by these various factors and the total annual doses to the bone-marrow for populations in the four areas investigated. The mean dose-rates for the four areas have standard errors of approximately 1% and the difference in the mean bone-marrow dose-rates to the populations

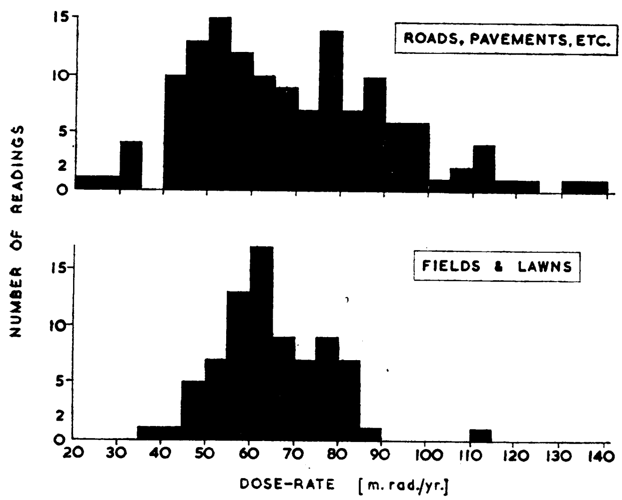

FIG. 3.—Background radiation out-of-doors in Aberdeenshire (excluding Aberdeen City).

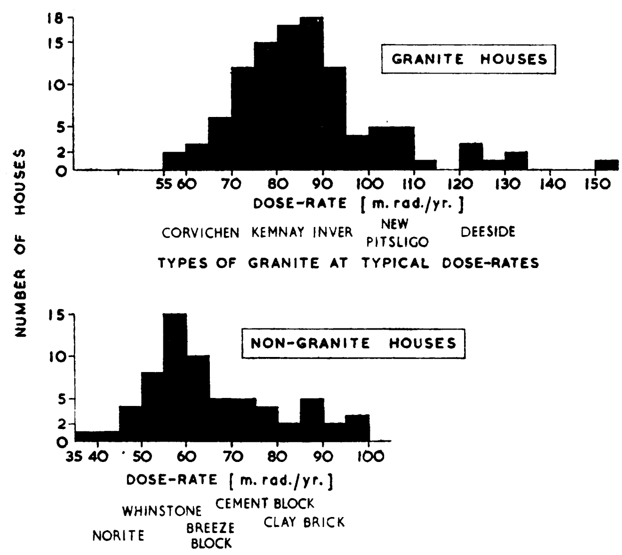

FIG. 4.—Background radiation indoors in Aberdeenshire (excluding Aberdeen City).

TABLE VI.—*Mean Bone-marrow Dose-rates from* [redacted] *Internal Radiation in Four Parts of S*[redacted]

Type of Radiation	Mean Dose-rate in m.ra[redacted]		
	Edinburgh	Dundee	Ab[redacted]
Local gamma radiation, measured in air:			
Out-of-doors	48·5	63·0	[redacted]
In houses	60·0	67·2	[redacted]
24-hour average ..	57·1	66·2	[redacted]
Total radiation to bone-marrow:			
Local gamma radiation	37	43	[redacted]
Other background and internal sources ..	43	43	[redacted]
Total dose ..	80	86	[redacted]

of Aberdeen and Edinburgh is 21 ± 0.6 [redacted] r. If a shorter period of three hours is [redacted] be spent out-of-doors per day the difference in the population dose-rates in Aberdeen and Edinburgh is reduced to 18.5 m.rad per year. Certain systematic errors in instrument calibration, attenuation factor, allowance for cosmic rays, etc., are common to the measurements in all four areas: the values of the dose-rates in absolute units have a limiting error of about ±3.5%.

The differences will have been underestimated slightly as a result of the increase during the survey of local gamma radiation due to fall-out. The measurements were made in Aberdeen in August, 1958; in Dundee in October, 1958; in Edinburgh in February 1959; and in Aberdeenshire in August, 1959. Between the surveys in Aberdeen and Edinburgh the dose-rate over undisturbed grassland in Leeds rose by about 3 m.rad a year (Spiers, 1959). It is, however, improbable that the dose-rates over tilled land, hard surfaces of roads and pavements, and in houses have increased to the same extent. Measurements made at 12 road points in the 1958 road survey were repeated in 1959, and the difference between the mean dose-rate on the two occasions was less than its standard error, which—for this small number of measurements—was 2 m.rad per year.

A more detailed account of the results of the survey will be published elsewhere (Spiers and McHugh, 1960).

Comparison Between Mortality and Background Radiation

Estimates of the average marrow-dose received per annum from all natural sources are shown in Table VII in comparison with the standardized mortality ratios for acute leukaemia and chronic myeloid leukaemia combined—that is, for the two types of leukaemia that are known to be capable of being produced by ionizing radiations. The Table shows that the ranking order is the

TABLE VII.—*Comparison Between Average Radiation Dose to Bone-marrow and Mortality from Acute Leukaemia and Chronic Myeloid Leukaemia in Four Parts of Scotland (Persons Aged* 15 *Years and Over)*

Area	Average Dose to Bone-marrow (m.rad/Year)	Acute Leukaemia and Chronic Myeloid Leukaemia	
		Standardized Mortality Ratio	Standardized Death Rate per Million Persons per Year
Aberdeen	101	155	46
Aberdeenshire ..	94	113	33
Dundee	86	98	29
Edinburgh ..	80	113	33

same fo[illegible] measurements in three of the four areas ; [illegible]a the mortality ratio is the second highest, [illegible]one-marrow dose is the lowest. The Table [illegible] that the difference in mortality is [illegible] greater than the difference in the estimated [illegible]e. The best comparison is perhaps between [illegible]d Dundee, since these towns are similar in [illegible] apart from the features associated with [illegible]ckground radiation. Comparison of the [illegible]owns shows that the recorded mortality is [illegible] in Aberdeen, whereas the marrow dose i[illegible]gher.

Discussion

[illegible] of leukaemia mortality in Scotland s[illegible]ubstantial differences are recorded in d[illegible]s. Some of these differences are p[illegible]e to random fluctuation ; but other factors are needed to account for the high mortality in Aberdeen and Edinburgh. Present knowledge suggests that these may include (1) the completeness of case-finding, (2) economic status, and (3) exposure to ionizing radiations.

The diagnosis of leukaemia is relatively sophisticated and many cases are likely to be missed unless pathological services are readily available. Much of the increase in leukaemia mortality in Britain over the past 30 years has been attributed to improved case-finding, and it has been suggested that this is particularly important as an explanation of the very great increase in the mortality from chronic lymphatic leukaemia that has occurred in the older age-groups (Court Brown and Doll, 1959). It may therefore be thought that the excess mortality in Edinburgh, which is mostly attributable to chronic lymphatic leukaemia and is limited to ages 35 years and over, is principally due to this factor. Since Edinburgh is a capital city with a high standard of living and a large and world-famous medical school this is not unreasonable. The same factor may also account to some extent for the excess mortality recorded in Aberdeen. The last two professors of medicine have had a special interest in haematology, and it is possible that their precept and example have resulted in a greater awareness of the possibility of the diagnosis. It should, however, be noted that the first of them subsequently became professor of medicine in Edinburgh in 1938 and that in 1947–8 the Aberdeen mortality was much higher that that recorded in Edinburgh. Moreover, in contrast to the experience in Edinburgh, the Aberdeen mortality was higher than expected at all adult ages, and the excess was primarily due to a high incidence of acute leukaemia and chronic myeloid leukaemia.

High economic status has been found to be associated with a high leukaemia mortality in several studies in Britain (Registrar-General of England and Wales, 1938, 1958) and in the U.S.A. (MacMahon, 1957). In the period 1930–2 the standardized mortality ratio for leukaemia (combined at that time with Hodgkin's disease) was 153 in social class I (business executives and higher professions) and 85 in social class V (unskilled labourers). In 1949–53 the ratios for leukaemia alone were respectively 123 and 89. The reason for the high mortality in the wealthier strata is unknown ; it may be no more than a reflection of the effect of better case-finding and, perhaps, a greater exposure to ionizing radiations ; but, whatever the explanation, the factors responsible for it may be presumed to have contributed to the excess in Edinburgh—a capital city with a high proportion of professional, administrative, and clerical workers—and to account for some of the deficiency in the crowded industrial city of Glasgow. There is, however, no reason to suppose that social class factors *per se* should have contributed to an abnormal incidence of leukaemia in Aberdeen.

The effect of differences in exposure to ionizing radiation is difficult to assess. Published estimates of the risk associated with low doses have been obtained by extrapolation from data for patients given radiotherapy for ankylosing spondylitis and for persons exposed to the atomic explosions in Hiroshima and Nagasaki. Whether it is justifiable to extrapolate over so large a range of total dose and of dose-rate is open to doubt, but there is no reason to suppose that the leukaemogenic effect of small doses on a normally susceptible population could be much more than proportional to the total dose, and the estimates may be used to provide an upper limit to the number of cases which are likely to be produced.

According to Lewis (1957) the risk per rad is likely to be of the order of 2 cases per million persons per year (with upper and lower limits of 0.7 and 6.0 cases per million per year.) Court Brown and Doll (1957) suggested that the risk per rad might lie within the range of 1.0 to 1.6 cases per million persons per year, and the United Nations Scientific Committee (United Nations, 1958) estimated the risk on the assumption that 1 rem would produce approximately 1.5 cases per million persons per year. In all these studies it was assumed that the risk would persist for the rest of the lives of the exposed persons. On this basis the figure used by the United Nations Scientific Committee leads to the conclusion that the observed geographical differences in the average marrow dose from background radiation—of the order of 10 to 20 m.rad per year—would be unlikely to have produced much more than 5 to 10 cases per million persons in a 10-year period.

Further experience, however, has shown that the risk of developing leukaemia after irradiation is likely to diminish sharply after about five to eight years, though it has not yet been shown to disappear entirely. It therefore seems likely that a more realistic estimate would be that a dose of 1 rad to the bone-marrow might result in the production of about one case of leukaemia per million man-years for perhaps 10 years from the date of exposure (Court Brown and Doll, 1960). On this basis the observed differences in bone-marrow dose would be unlikely to produce more than 1 or 2 cases per million persons in 10 years. In contrast, the difference between Aberdeen and Dundee in the mortality from acute leukaemia and chronic myeloid leukaemia in a similar period is calculated to have been of the order of 170 cases per million persons and the difference between Aberdeen and Edinburgh to have been of the order of 130 cases per million persons. In our opinion, therefore, the finding of an excess mortality in Aberdeen from the two types of leukaemia that are known to be produced by radiation cannot be attributed to the high level of the background radiation. Knowledge of the mechanism of carcinogenesis is, however, incomplete, and the possibility that the effect of low doses of radiation has been underestimated should be borne in mind until more data are obtained.

Another source of radiation exposure is in the use of radiotherapy for medical diagnosis. Data collected by the Medical Research Council (1956) suggested that the average dose to the gonads from this source might be about 20–25% of that received from background radiation. Data for the average marrow dose and for its variation between different parts of the country are now being collected by the Committee on Radiological Hazards to Patients appointed by the Ministry of Health and the Department of Health for Scotland. No data are yet available, but it would not be surprising if the average marrow dose proved to be of the same order as that received from background radiation (United Nations, 1958). Since the dose-rate for diagnostic radiography is of the same order as that used in radiotherapy, there is less difficulty in attributing to it a leukaemogenic effect. Regional differences are, however, unlikely to be great, and it would be unreasonable to suppose that they could account for much more than the maximum effect estimated for the differences in background radiation.

Summary and Conclusions

Estimates have been made of the mortality from leukaemia for 10 parts of Scotland over the years 1939 to 1956. The highest mortality (146% of the expected) was recorded in Aberdeen, the second highest (124% of the expected) in Edinburgh, and the lowest (87% of the expected) in Glasgow. The mortality in Aberdeen was the highest recorded among men and among women; it was the highest recorded in the period 1947–56, but in the period 1939–46 (when the estimates are less reliable because of wartime movements of population) it was the second highest.

Estimates of the mortality attributed to acute leukaemia, chronic myeloid leukaemia, and chronic lymphatic leukaemia show that the excess mortality in Aberdeen was principally due to a high mortality from the two former types, while the excess in Edinburgh was principally due to a high mortality from chronic lymphatic leukaemia.

The excess in Aberdeen and Edinburgh cannot reasonably be attributed to random fluctuation. Possible explanations include (1) better case-finding, (2) high economic status, and (3) exposure to ionizing radiations.

It is suggested that better case-finding and a high economic status could account for the excess in Edinburgh and that better case-finding could account for some of the excess in Aberdeen. There are, however, reasons for thinking that this is not the sole explanation.

Measurement of the amount of radiation received from background sources were made in four areas—Aberdeen, Aberdeenshire, Dundee and Edinburgh. Estimates of the average marrow dose received from these sources indicate that the highest dose (101 m.rad/year, is received in Aberdeen and the lowest (80 m.rad/year) is received in Edinburgh. Extrapolation from the effects of large doses given at very much greater intensities suggests that differences of this order are unlikely to account for much more than 1% of the observed differences in mortality—if they are capable of being leukaemogenic at all.

Local differences in the average exposure to diagnostic radiography may be greater than the differences in background radiation. They may contribute to the variation in leukaemia mortality, but are unlikely to be a major factor in its production.

Whether the assumptions made in the present study are justified will not be apparent until further data are available. It is, however, clear that it is insufficient to study leukaemia mortality only in relation to background radiations. The proper interpretation of geographical variations can be made only when the effect of social and economic factors can also be assessed.

We are grateful to the Registrar-General of Scotland for the detailed data relating to leukaemia deaths and for the estimates of population by area in 1956; and to Dr. G. G. Dickie, Dr. I. A. G. MacQueen, Dr. H. E. Seiler, and Dr. I. B. L. Weir, Medical Officers of Health for Aberdeenshire, Aberdeen, Edinburgh, and Dundee, and to their staffs for facilities for making the radiation measurements and for their invaluable practical assistance. We are grateful to Dr. J. R. Greening, of the Department of Medical Physics, Edinburgh University, to Dr. C. A. Murison, Physicist to the Western General Hospital, Edinburgh, to Mrs. H. D. Griffith, Dr. D. Lindsay, and Mr. Low, of the Department of Medical Physics, Aberdeen University, and to Mr. McKie and Mr. Ritchie, of the Physics Department, Dundee Royal Infirmary, for assistance in making the radiation measurements; and to the Civil Defence Authorities in the areas studied for assistance in the selection of houses for examination. We are indebted also to Miss F. Callaby and Miss A. Fotheringham, of the Medical Research Council's Clinical Effects of Radiation Research Unit, for help in the collection of the data and in the analysis of the results.

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