Radium in Drinking Water and the Incidence of Osteosarcoma

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Division of Epidemiology, Environmental and Occupational Health

James E. McGreevey
Governor

Clifton R. Lacy, M.D.
Commissioner

Radium in Drinking Water and the Incidence of Osteosarcoma

A Report to the
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Prepared By:

Perry Cohn[1], Ric Skinner[2], Stasia Burger[2], Jerald Fagliano[1] and Judith Klotz[2]

[1] Consumer and Environmental Health Services
[2] Cancer Epidemiology Services

Division of Epidemiology, Environmental and Occupational Health
New Jersey Department of Health and Senior Services

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SUMMARY

Radium has been found to be elevated in the shallow Kirkwood-Cohansey aquifer, a major drinking water supply source in parts of southern New Jersey, and the Englishtown, Old Bridge and Farrington aquifers in central New Jersey. Recent groundwater and drinking water surveys by the New Jersey Department of Environmental Protection and the U.S. Geological Survey provide a systematic basis for examining the potential public health implications of exposure to this naturally-occurring radium in water. High levels of exposure to radium isotopes have caused the bone cancer, osteosarcoma, among radium dial painters and patients receiving oral radium treatment for ankylosing spondylitis. Previous population-based studies of ingestion of the relatively lower levels of radium in drinking water have also shown associations with osteosarcoma mortality or incidence.

The New Jersey Department of Health and Senior Services conducted an exploratory study comparing rates of osteosarcoma in areas of southern and central New Jersey with varying amounts of radium in community drinking water supplies. Community water supplies were mapped using a geographic information system (GIS). Two measures of exposure were constructed. One measure classified water systems into those with radioactivity levels above either the U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) for combined radium-226 and radium-228 (5 picoCuries per liter (pCi/L)) or the gross alpha radioactivity MCL of 15 pCi/L. The second exposure measure was based on predicted cancer potency of the radium isotopes, and was expressed as equivalents of radium-228.

An association of osteosarcoma with radium exposure was observed among males, but not among females. For the sexes combined, the rate of osteosarcoma incidence in areas receiving drinking water above either the combined radium or gross alpha MCLs was 100% higher than in areas below either MCL. Among males, the osteosarcoma rate was more than three times higher (rate ratio = 3.3, 95 percent confidence interval 1.6, 6.0). When exposure estimates were categorized in terms of total radium cancer potency, expressed as equivalents of radium-228, the resulting incidence rate among those exposed at $\geq$ 4 pCi/L was 90% higher than those whose tap water had less than 0.5 pCi/L. The elevated incidence of osteosarcoma was entirely associated with exposed males. For males in areas receiving water with $\geq$ 4 pCi/L and 2.0-3.9 pCi/L, compared to those receiving <0.5 pCi/L, the rate ratios were 3.4 (95% CI 1.5, 6.7) and 3.1 (95% CI 1.3, 6.0), respectively. For males 25 and over, rate ratios were 6.2 (95% CI 2.0, 14) and 5.5 (95% CI 1.8, 13), respectively.

The results of this study, viewed in the context of previous studies of radium in drinking water, and biological knowledge of radiation effects, provide further evidence that exposure to radium at levels found in drinking water pose a measurable risk of this bone cancer. The findings are quantitatively consistent with risk estimates based on extrapolation from studies of higher level occupational and medical exposures, which have provided the basis for regulatory actions.

INTRODUCTION

In New Jersey, levels of radium in groundwater are elevated in many parts of the shallow Kirkwood-Cohansey and the Englishtown aquifers, as well as the Old Bridge and Farrington aquifers. This corresponds to an area extending from Cumberland County on the Delaware Bay to southeastern Middlesex County in the central part of the state. The elevated levels, which are naturally occurring, were recently documented by a recent survey of private domestic wells, monitoring wells and some community water system (CWS) wells by the U.S. Geologic Survey (USGS, 1998), and by a systematic survey of almost all CWSs by the New Jersey Department of Environmental Protection (NJDEP) (reported in part in Drinking Water Quality Institute, 2001).

The surveys were launched after the finding of gross alpha radioactivity in excess of the federal standard in a CWS previously thought to be in compliance (NJDHSS, NJDEP, and ATSDR, 2001). Because testing occurred within 48 hours of sampling, rather than the one year allowed by federal regulation, the gross alpha measurement captured the short-lived isotope, radium-224, in addition to the longer-lived isotopes, radium-226 and radium-228. The recent surveys also tested water within 48 hours of sampling and in general found that the amount of gross alpha radioactivity in many CWSs using the Kirkwood-Cohansey aquifer was greater than previously reported in regulatory testing. Since results of the gross alpha radioactivity measure is used to trigger radium testing, the higher gross alpha levels found in the recent surveys resulted in the characterization of many more systems for radium isotopes.

Relatively high levels of exposure to radium have been linked to an increased risk of the bone cancer, osteosarcoma. Incidence of this cancer was increased among radium dial painters following ingestion of radium (primarily radium-226 and radium-228), and among patients with ankylosing spondylitis who were exposed to radium-224 as a medical treatment (National Research Council, 1990). The potential for risk of bone cancers from ongoing exposure to the lower levels of exposure to radium in drinking water has been examined previously. In a study in Iowa and Illinois, Petersen et al. (1966) found that the bone cancer (including but not limited to osteosarcoma) mortality rate was 1.25 times higher in communities with $\geq$ 3 picoCuries per liter (pCi/L) of radium-226 compared to communities with < 1 pCi/L ($p = 0.08$). Two studies of osteosarcoma incidence among adolescent and post-adolescent youth have been conducted in Ontario (Finkelstein, 1994; Finkelstein and Kreiger, 1996). After combining the results of these studies, the odds ratio (OR) of those whose birthplace had radium-226 in water $\geq$ 30 milliBequerels (mBq/L), equivalent to $\geq$ 0.8 pCi/L, compared to those with levels < 7 mBq/L (0.2 pCi/L), was 2.0 (95 percent confidence interval (CI) 0.8, 5.1). A study in Wisconsin observed an overall OR for osteosarcoma of 1.5 (95% CI 0.8, 2.8) for those residing in counties with a CWS with $\geq$ 9 pCi/L compared to other areas (Moss et al. 1995). A second study in Wisconsin did not find an association between osteosarcoma incidence and residence in a zip code area with a CWS with combined radium-226 and radium-228 $\geq$ 2.5 or > 5 pCi/L (Guse et al. 2002).

Osteosarcoma is a rare cancer, occurring in approximately 3 persons per million per year. Incidence peaks in mid- to late-adolescence, when tumors are found at the zone of bone growth in the epiphyseal plate, and in the older adult. The etiologies may be different for the two age peaks. Established risk factors for osteosarcoma include radium, non-ionizing radiation (medical therapy and atomic weapons), the bone destruction caused by Paget's Disease and other bone defect syndromes, and exposure to alkylating chemotherapy agents. Osteosarcoma risk is also related to specific heritable conditions (retinoblastoma, Li-Fraumeni syndrome) (Miller et al., 1996). It is thought that genetic susceptibility contributes to 20-50% of primary osteosarcomas. Exposure to fluoride was linked to osteosarcoma in male rats, but epidemiologic studies have generally not supported this finding (Cantor et al., 1996).

Radium, as a divalent cation like calcium, is absorbed in the gastrointestinal tract and within a few days is incorporated into bone. There, the alpha, beta, and gamma radiation from radioactive decays may damage the DNA of osteocytes and osteoblasts, increasing the risk of osteosarcoma. Because of the time it takes to deposit in bone and cause an effect, the short half-life of radium-224 (3.5 days) reduces its cancer potency per unit of radioactivity compared to the other radium isotopes. Because of the high penetrating power of the electron ejected during its beta decay, radium-228 is accorded the highest potency and the alpha particle ejected by the decay of radium-226 has the next highest potency (USEPA, 1999).

The federal maximum contaminant level (MCL) for gross alpha radioactivity is 15 pCi/L, and the MCL for combined radium-226 and radium-228 is 5 pCi/L. Radium-224 is not included in the current federal standard. Based on extrapolation of risk from the highly exposed radium dial painters and medically treated cohorts, the U.S. Environmental Protection Agency (USEPA) estimates that the lifetime cancer mortality risk (predominantly due to bone cancer) at the MCL for combined radium is 0.7 per 10,000 to 2.0 per 10,000, depending on the relative proportion of radium-226 and radium-228. The USEPA (2000) has concluded that there is reasonable evidence that radioactivity acts linearly with dose down to zero. However, there has been considerable discussion of whether the cancer potency estimates of the radium isotopes can be applied to the much lower levels of exposure through drinking water supplies.

The availability of an improved characterization of gross alpha radioactivity and radium in drinking water prompted the present study in New Jersey. This epidemiologic study was conducted to determine if rates of osteosarcoma incidence were different in areas of the state with different levels of naturally occurring radioactivity due to radium in drinking water. In addition, the improved exposure characterization provides the opportunity to compare estimated risk differences to risk estimates extrapolated from higher exposures in occupationally or medically exposed cohorts.

METHODS

Study Area

The study area includes those parts of ten central and southern New Jersey counties south of the Raritan River (Atlantic, Burlington, Camden, Cumberland, Gloucester, Mercer, Middlesex, Monmouth, Ocean and Salem) that are served by a CWS with greater than 100 service connections. This area was selected because water from the Kirkwood-Cohansey and other affected aquifers is used extensively and was generally well characterized by the recent radium surveys. The area was limited to CWSs because areas served by private wells are not as well characterized. Within this area, CWS service areas were excluded for the following reasons: 1) insufficient data on gross alpha radioactivity and radium to characterize the CWS; 2) major changes in well use patterns such that recent surveys would be unrepresentative of past conditions; 3) use of surface water sources rather than groundwater; 4) service in a shoreline community with high seasonal residency; and 5) addition of fluoride, because of concerns about the potential for confounding. However, it should be noted that there are a small number of residences with private wells interspersed within the boundaries of some systems.

Mapping of Community Water Systems

Using ArcView 3.2 geographic information system (GIS) software, the boundaries of CWSs were mapped in the area of interest (Figure 1). A total of 100 CWSs (including portions of 5 CWSs) were included in the study area, after exclusions for the reasons cited above. For purposes of exposure characterization, 11 systems were divided into two or more subsystems (see below), for a combined total of 117 systems and subsystem units mapped. Two sets of maps were created. One set was used to locate cases with respect to system or subsystem boundaries. For this mapping, boundaries were street-based so that addresses could be accurately located outside or inside a system service area. A second set of maps was created to make estimates of population served by each CWS system or subsystem (see below).

Cases

Incidence cases of osteosarcoma (ICD-O morphology codes 9180/3 to 9190/3 and topography codes C40.0 to C41.9) in the study area from 1979 through 1998 were collected from the New Jersey State Cancer Registry. Using GIS, residence addresses of cases at the time of diagnosis were geocoded to the street level, using digital street center line data (Geographic Data Technology, Inc., Lebanon, NH) and, when needed, reference to commercial paper street maps. Based on the address mapping, cases were assigned using GIS to a CWS system or subsystem. Cases occurring as a second or third primary cancer diagnosis were included, but a separate analysis of single primaries was also conducted, since primaries diagnosed after cancer treatment may be caused by the treatment.

Population Data

Population estimates within CWS system and subsystem areas were made using GIS and data from the 1990 U.S. Census. The year 1990 is approximately midway in the time period of case ascertainment. The GIS was used to overlay boundaries of CWS systems and subsystems with boundaries of U.S. Census block groups, which are tied to age- and sex-specific population data. The population within each CWS system or subsystem was estimated using GIS by multiplying the 1990 population in each intersected block group by the proportion of the block group area lying within the CWS boundary, and summing the results for all intersected block groups.

Because this estimation method assumes that population is uniformly distributed within the block group, the second set of CWS boundary maps was used for this purpose. In these maps, boundaries were drawn to match block group boundaries rather than street-based service areas. Since population is often non-uniformly distributed, land-use maps were used to provide more accurate information on the distribution of the population within block groups, especially in rural-suburban areas, so that the map used for generating population estimates could be properly adjusted. Without this adjustment, populations would be underestimated in block groups where population is concentrated in a fraction of the area.

Exposure Characterization

In order to estimate past levels of radium exposure, data from the recent surveys (1997 to 2000) on gross alpha radioactivity, radium-226 and radium-228 in CWSs were obtained from the Bureau of Safe Drinking Water in the NJDEP and from the USGS. For these surveys, the gross alpha levels were tested about 48 hours after sampling to capture the short-lived isotopes, particularly radium-224. The sample type (untreated well, treated well, point of entry, or distribution), date and location was recorded for each sample. Since it is unlikely that there would be significant change in naturally occurring radioactivity levels over decades, the recent data were regarded as representative of past conditions, if well use patterns did not change significantly.

Radium-224 was characterized by USGS and NJDEP in a limited number of wells (approximately 40 wells in 20 systems). For the rest, levels of radium-224 were estimated based on the average isotopic proportions found in the Kirkwood-Cohansey aquifer: radium-224 activity was approximately 1.6 times the average of radium-226 and radium-228.

The amount of data for each well and system varied, depending in part on re-sampling based on level of contamination and similarity of well depths. For example, the most complete information (multiple point of entry samples from each well or wellfield) was available for CWSs having the highest level of radioactivity. In contrast, if all wells in a system had a similar depth and little radioactivity was found, sampling was often limited to a fraction of the wells. There were also instances in which a system had wells in the low radioactivity Potomac-Raritan-Magothy aquifer (located deeper than the affected aquifers) and only one or two distribution samples were taken. In some CWSs, radioactivity levels in wells currently in use were assumed to be representative of wells no longer in use, but of similar depth. Distribution samples were not used when influenced by new wells.

Each system or subsystem was assigned a value for gross alpha radioactivity, radium-224, radium-226 and radium-228. Assessments were based on the average of point of entry data, supplemented by distribution and raw water data. In systems where measured levels of radioactivity in wells were similar (within 20%) of one another, levels in the wells were averaged. When levels among wells were more divergent, and where well water was blended within a short distance of the wells (such as within a water tank), averages were weighted by volume output of the wells. Where radioactivity measures among wells indicated that areas of a CWS were distinct, a system may have been divided into subsystem areas of relatively homogeneous exposure. Subsystem areas were defined based on system architecture (mains and storage tanks) and relative well pumping volumes, as described previously by Cohn et al. (1999). Subsystem boundaries were intended to represent a reasonable historical approximation for use in studies of diseases thought to arise from long-term exposure.

Analysis

Exposure levels in CWSs were categorized in two ways. First, systems or subsystems were classified as being above either the gross alpha radioactivity MCL of 15 pCi/L or the combined radium-226 and radium-228 MCL of 5 pCi/L, or below both MCLs. Second, systems were also categorized based on equivalents of radium-228. The radium-228 equivalents metric used the following formula:

(Radium-228 x 1.0) + (Radium-226 x 0.35) + (Radium-224 x 0.16)

where the weights are the relative cancer potencies listed in Federal Guidance #13. (Cancer potencies per Bq for radium-228, radium-226 and radium-224 are given as 2.8×10^{-8}, 1.0×10^{-8}, and 4.5×10^{-9}, respectively (USEPA, 1999).) Computed radium-228 equivalent levels were categorized into four levels. The lowest exposure level included populations in CWSs in which the radium-228 equivalent level was < 0.5 pCi/L. Two additional exposure level cutpoints (2 and 4 pCi/L) were selected such that the remaining population was divided into three approximately equal populations.

Osteosarcoma incidence rates were calculated for each exposure group based on the number of cases and population by age and sex. Rate ratios (RRs) were calculated relative to the lowest exposure group, and 95 percent confidence intervals (95% CI) were calculated using Poisson probability tables (Breslow and Day, 1987). RRs were computed by sex and age group (0 to 24 years, and 25 years and older at time of diagnosis).

RESULTS

A total of 75 osteosarcoma cases were included in this study. The distribution of cases in the study by age group and sex is presented in Table 1.

The 117 systems or subsystems in the study are tabulated by exposure category in Table 2. Individual radium-226, radium-228, and 48-hour gross alpha radioactivity levels in samples from these systems were as high as 6, 7.5, and 100 pCi/L, respectively. Averaged by system, 48 hour gross alpha radioactivity was as high as 70 pCi/L. Seventeen systems or subsystems had average levels that were above either the combined radium or the gross alpha radioactivity MCLs.

For all ages and both sexes combined, the annual osteosarcoma incidence rate in areas with drinking water above either the combined radium or gross alpha MCLs was 100% higher than in areas below both MCLs (4.8 cases per million vs. 2.4 cases per million) (Table 3). Among all males, the annual rates were 7.7 per million and 2.3 per million, respectively, and the RR was 3.3 (95% CI 1.6, 6.0). Among males age 25 years and over, the RR was 5.8 (95% CI 2.3, 12), while among males under 25 there was a statistically nonsignificant RR of 1.7. Among females, there was little difference in rates between exposure groups, but among those under 25 years old there was a statistically nonsignificant RR of 2.4.

Categorization of exposure by radium-228 equivalents, the metric accounting for predicted cancer potency, demonstrated that overall annual incidence rates among those exposed to 2.0 to 3.9 pCi/L and to $\geq$ 4 pCi/L was 4.4 and 4.3 per million, respectively, which were 90% higher than in communities where tap water had < 0.5 pCi/L (2.3 cases per million) (Table 4). The elevated rate in the 2.0 to 3.9 pCi/L category was statistically significant (95% CI 1.0, 3.3), and after combining the top two exposure categories of the radium-228 equivalent metric, the RR of 1.9 (95% CI 1.2, 2.8) was also statistically significant. The exposure-related elevation in incidence of osteosarcoma occurred entirely among males. The RRs for all males in the two highest exposure categories compared to the lowest category were 3.1 (95% CI 1.3, 6.0) and 3.4 (95% CI 1.5, 6.7). Among males under 25, the RRs in the two highest exposure categories compared with the lowest category were 1.9 (95% CI 0.4, 5.5) and 2.0 (95% CI 0.4, 5.8), while for males 25 and over, RRs were 5.5 (95% CI 1.8, 13) and 6.2 (95% CI 2.0, 14).

By restricting the analysis only to cases occurring as a first primary cancer diagnosis, seven cases (6 males and 1 female) are lost, leading to small change in RRs. Among all males living in areas with water over the MCL, the RR is 3.0. In males age 25 and over, the RR rises to 6.9, but in the 0-24 year age category the RR drops to 1.2. The RRs for all males in the 2.0 to 3.9 pCi/L and $\geq$ 4 pCi/L radium-228 equivalents exposure categories compared to the lowest category were 3.2 and 3.6, respectively. Among males under 25 the RRs were 2.0 and 1.5, while for males 25 and over, the RRs were increased to 6.6 and 9.3.

DISCUSSION

Study Interpretation

This study has found an association between naturally occurring radioactivity levels in drinking water and the incidence of osteosarcoma, among males but not among females. The osteosarcoma incidence rate for males over age 25 years was 5.8 times higher in areas served by CWSs with radioactivity levels above either the gross alpha or combined radium MCLs. For males under age 25 years, the rate was approximately 70% higher. Similar results were observed when exposure was estimated in terms of radium-228 cancer potency equivalents. Because osteosarcoma is a rare cancer, confidence intervals around RR estimates were wide, despite the large size of population in the study area and the long (20 year) period of case ascertainment.

It is unlikely that the results are confounded by other known risk factors for osteosarcoma, since their distribution in the population is not likely to correlate with the specific measures of radioactivity in drinking water. Excluding cases when the osteosarcoma was not the first primary cancer diagnosis, thereby limiting the possible effects of cancer treatment, resulted in higher RRs for all males. Because of the possibility of confounding due to fluoridation, CWSs that added fluoride were excluded from the study area.

Exposure estimates for this study were based on systematic surveys of radiological activity in CWSs. Because the surveys employed methods of sample collection and analysis that allowed for the measurement of short-lived isotopes (such as radium-224), the data are likely to be the most accurate estimates of exposure potential available. Because this study was conducted with a simple exploratory design that did not include interview data, exposure levels among cases and the populations served by CWSs were assigned based on the radioactivity levels in the drinking water at the residence at diagnosis. This is limited by the absence of information on individual tap water consumption, the ingestion of water away from the residence, the time spent at previous residences, and whether a water softener was present. In addition, a small percentage of residents within system boundaries used a private well instead of water from the system.

The results of this study are generally consistent with the previous studies in Iowa/Illinois and Ontario, but are not consistent with the Wisconsin studies. In Iowa and Illinois, the bone cancer mortality rate (1950 to 1962) in communities with ≥ 3 pCi/L radium-226 was 25 percent higher than in communities with < 1 pCi/L ($p = 0.08$). In contrast to this New Jersey study, the rate ratios were more elevated in the younger population. In the 20 to 29 year age group, the relative rate was 4.8 ($p = 0.03$). The association was also observed in both males and females in the Iowa/Illinois study.

In the Ontario exploratory case-control mortality study (Finkelstein, 1994) residential histories were assembled from birth and death certificates in the period 1950 and 1983. Based on estimated exposure to radium-226 in drinking water at the address at birth, the odds ratio (OR) was 1.4 (95% CI 0.8-2.4) for those with radium above 7 mBq/L (0.2 pCi/L). The OR for males was 1.9 (95% CI 0.9, 3.8), while for females the OR was 0.8. Subsequently, a case-control incidence study of persons diagnosed before age 26 years between 1964 and 1988 was conducted in Ontario, based on interviews supplemented by birth certificates (Finkelstein and Kreiger, 1996). In this study, the OR for incident osteosarcoma among those whose birthplace had water above 7 mBq/L compared to those with less, was 1.8 (95% CI 1.0, 3.0). However, based on estimated cumulative exposure, the OR was 1.3 (95% CI 0.8-2.2) and there was no trend for increasing cumulative exposure. Analysis was also presented that combined the results of the two Ontario studies, which had separate sets of participants. The OR of those whose birthplace had water above 7 mBq/L was 1.5 (95% CI 1.1, 2.2), while above 30 mBq/L (equal to 0.8 pCi/L; up to a maximum of 4.3 pCi/L) the OR was 2.0 (95% CI 0.8-5.1). The observation of an association among males but not females in the Ontario studies is interesting because similar results were found in this New Jersey study.

In the Moss et al. (1995) case-control study in Wisconsin, using other cancer cases as controls, an overall adjusted OR of 1.5 (95% CI 0.8, 2.8) was observed. The association was primarily found among females (adjusted OR=2.1, 95% CI 0.8, 5.0) and among those less than 45 years of age (adjusted OR=2.0, 95% CI 0.9, 4.5). No associations were observed in the second Wisconsin study (Guse et al. 2002).

Implications for Risk Assessment

As noted in the Introduction, the current federal MCL for combined radium-226 and radium-228 is 5 pCi/L. Based on extrapolation of risks observed at the higher exposure levels in occupational and medically-exposed cohorts, the USEPA (2000) has estimated that the lifetime increase in overall cancer mortality risk at the MCL is 0.7 in 10,000 (0.7×10^{-4}) to 2 in 10,000 (2×10^{-4}), predominantly due to bone cancer. The risk of increased overall lifetime cancer incidence at the MCL, weighted by the isotopic potency for radium-226 and radium-228 (USEPA, 1999), would be approximately 42% higher than the mortality risk, or 1.0-2.9 in 10,000. This epidemiologic study of drinking water exposure in New Jersey provides an opportunity to compare the USEPA's extrapolated risk estimate with estimates made from community incidence data.

If the differences in rates observed in this study are attributable to radium exposure, then the average annual added risk among the overall population from exposure at levels greater than either or both the combined radium or gross alpha MCLs (annual incidence among the exposed minus annual incidence among the unexposed) was 2.4×10^{-6} (2.4 per million). Average added lifetime risk in the overall population can be estimated by multiplying the annual risk difference by 70 years, yielding a total risk increase of 1.7×10^{-4} (1.7 in 10,000) with a lifetime of exposure (Table 5).

Based on the radium-228 cancer potency equivalent exposure measure, the average annual added risk in the overall population was 2.1×10^{-6} and 2.2×10^{-6} for the two highest categories of radium-228 equivalents, 2.0 to 3.9 pCi/L and ≥ 4.0 pCi/L, respectively. The average added lifetime risk of osteosarcoma incidence in the overall population at these exposure levels would both be 1.5×10^{-4}. The results of this study produce estimates of excess risk that are comparable to the USEPA estimates of cancer risk based on extrapolations from the radium dial and ankylosing spondylitis cohorts (Table 5).

Similar risk estimates can be made from the other studies of drinking water radium and bone cancers or osteosarcoma. The Iowa/Illinois study used an exposure cutpoint of 3 pCi/L radium-226, which was the 1962 Public Health Service guideline at the time of the study. This level is roughly equivalent to the current MCL for combined radium-226 and radium 228 of 5 pCi/L. Annual added mortality risk of bone cancer in the exposed group overall was 2.7×10^{-6} and, assuming lifetime exposure, the added lifetime risk of death was 1.9×10^{-4}. This estimate is close to the incidence risk of cancers predicted by USEPA at the current MCL (Table 5).

Added annual risk cannot be directly calculated from the Ontario studies since these used the case-control design. However, multiplying the attributable risk ((OR-1)/OR) for the highest exposure category ((2 –1)/2 = 0.5) by the average annual incidence rate for the 0 to 24 year age group in the New Jersey study population (3.8 per million) results in an annual excess incidence risk of 1.9×10^{-6}. Cumulative risk (through age 26 years in the Ontario study) can then be estimated by multiplying 1.9×10^{-6} by the mean number of years before diagnosis in the study, approximately 14 years, to yield 0.3×10^{-4}. Alternatively, multiplying 1.9×10^{-6} by 70 years would result in a lifetime excess risk of 1.3×10^{-4} (Table 5).

Similarly, the attributable risk computed from the overall association in Moss et al. study in Wisconsin would be 0.33. Applying this fraction to the overall annual incidence of approximately 3 per million in the New Jersey study population results in an annual excess cancer risk of 1×10^{-6}. Lifetime excess risk would then be 0.7×10^{-4} (Table 5).

The New Jersey Drinking Water Quality Institute is currently examining state and federal regulations on radiological activity in drinking water, in light of new scientific information on sampling, testing and risk estimates of radium exposure. The Institute will recommend to the NJDEP what changes, if any, are needed to the existing approach.

* * *

In summary, the results of this study, viewed in the context of previous studies of radium in drinking water and osteosarcoma, and biological knowledge of radiation effects, provide further evidence that exposure to radium at levels found in drinking water poses a measurable added risk of this bone cancer. The findings are quantitatively consistent with risk estimates based on linear extrapolation from studies of higher level occupational and medical exposures, which have provided the basis for regulatory actions. This consistency supports the use of such risk estimation methods for the regulation of environmental hazards.

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Table 1. Number of osteosarcoma cases by age group and sex, 1979-1998, in the study area.

Age Group	Males	Females
0-4	0	0
5-9	0	1
10-14	7	11
15-19	9	4
20-24	5	0
25-29	1	1
30-39	2	2
40-49	1	3
50-59	3	3
60-69	3	4
70-79	6	3
80+	2	4
Total	39	36

Table 2. The distribution of systems by exposure group.

Exposure Group	Number of Systems/Subsystems	Total Population
Gross alpha radioactivity and combined radium MCLs		
< both MCLs	100	1,287,336
≥ either MCL	17	135,638
Radium-228 equivalents, pCi/L		
≤0.5	76	979,001
0.5-1.9	14	168,229
2.0-3.9	12	147,272
≥4	15	128,472

Notes:

The 15 systems in the highest radium-228 equivalents category are all included in the ≥ either MCL category.

The MCL for gross alpha is 15 pCi/L and for combined radium-226 and radium-228 is 5 pCi/L.

Table 3. Incidence rates and population in systems categorized by exposure above or below either the gross alpha or combined radium MCLs.

Demographic Group	Exposure Group	Population	No. cases, 1979-98	Annual Incidence Rate, Per Million	Rate Ratio (95% Confidence Interval)
All	<MCL	1,287,336	62	2.4	1.0
	≥MCL	135,638	13	4.8	2.0 (1.1, 3.4)
All males	<MCL	617,223	29	2.3	1.0
	≥MCL	65,257	10	7.7	3.3 (1.6, 6.0)
Males 0-24	<MCL	222,716	18	4.0	1.0
	≥MCL	22,214	3	6.8	1.7 (0.3, 4.9)
Males 25+	<MCL	394,507	11	1.4	1.0
	≥MCL	43,043	7	8.1	5.8 (2.3, 12)
All females	<MCL	670,113	33	2.5	1.0
	≥MCL	70,381	3	2.1	0.9 (0.2, 2.5)
Females 0-24	<MCL	214,872	13	3.0	1.0
	≥MCL	20,887	3	7.2	2.4 (0.5, 6.9)
Females 25+	<MCL	455,241	20	2.2	1.0
	≥MCL	49,494	0	zero	zero

Table 4. Population, incidence rates, and rate ratios in systems categorized by exposure based on total isotope weighted radium cancer potency, as radium-228 equivalents.

Demographic Group	Exposure Group (pCi/L)	Population	No. cases, 1979-98	Annual Incidence Rate, Per Million	Rate Ratio (95% Confidence Interval)
All	< 0.5	979,001	45	2.3	1.0
	0.5-1.9	168,229	6	1.8	0.8 (0.3, 1.7)
	2.0-3.9	147,272	13	4.4	1.9 (1.0, 3.3)
	≥ 4.0	128,472	11	4.3	1.9 (0.9, 3.3)
All males	< 0.5	471,462	18	1.9	1.0
	0.5-1.9	80,907	5	3.1	1.6 (0.5, 3.8)
	2.0-3.9	68,213	8	5.9	3.1 (1.3, 6.0)
	≥ 4.0	61,898	8	6.5	3.4 (1.5, 6.7)
Males 0-24	< 0.5	170,311	12	3.5	1.0
	0.5-1.9	30,553	3	4.9	1.4 (0.3, 4.1)
	2.0-3.9	22,780	3	6.6	1.9 (0.4, 5.5)
	≥ 4.0	21,286	3	7.0	2.0 (0.4, 5.8)
Males 25+	< 0.5	301,151	6	1.0	1.0
	0.5-1.9	50,354	2	2.0	2.0 (0.2, 7.2)
	2.0-3.9	45,433	5	5.5	5.5 (1.8, 13)
	≥ 4.0	40,612	5	6.2	6.2 (2.0, 14)
All females	< 0.5	507,539	27	2.7	1.0
	0.5-1.9	87,322	1	0.6	0.2 (0.0, 1.2)
	2.0-3.9	79,059	5	3.2	1.2 (0.4, 2.8)
	≥ 4.0	66,574	3	2.3	0.8 (0.2, 2.5)
Females 0-24	< 0.5	163,831	13	4.0	1.0
	0.5-1.9	29,711	0	zero	zero
	2.0-3.9	22,289	0	zero	zero
	≥ 4.0	19,928	3	7.5	1.9 (0.4, 5.5)
Females 25+	< 0.5	343,708	14	2.0	1.0
	0.5-1.9	57,611	1	0.9	0.4 (0.0, 2.4)
	2.0-3.9	56,770	5	4.4	2.2 (0.7, 5.0)
	≥ 4.0	46,646	0	zero	zero

Table 5. Estimates of excess cancer risk from exposure to radium in drinking water.

Data Source	Outcome	Exposure Level	Risk Estimate
Extrapolation from occupational and medically-exposed cohorts (USEPA, 2000)	Total cancer mortality (predominantly bone) Total cancer incidence	5 pCi/L combined radium-226 and radium-228	0.7×10^{-4} to 2×10^{-4} 1.0×10^{-4} to 2.9×10^{-4}
Iowa/Illinois (Peterson et al., 1966)	Bone cancer mortality	$\geq$ 3 pCi/L radium-226	1.9×10^{-4}
Ontario (Finkelstein, 1994; Finkelstein and Kreiger, 1996)	Osteosarcoma incidence or mortality	$\geq$ 0.8 pCi/L	1.3×10^{-4}
Wisconsin (Moss et al. 1995)	Osteosarcoma incidence	$\geq$ 9 pCi/L gross alpha radioactivity	0.7×10^{-4}
Wisconsin (Guse et al. 2002)	Osteosarcoma incidence	2.5 – 4.9 pCi/L or > 5 pCi/L combined radium-226 and radium-288	No increased risk
New Jersey study	Osteosarcoma incidence	> 15 pCi/L gross alpha or > 5 pCi/L combined radium-226 and radium-228 2.0 – 3.9 pCi/L radium-228 equivalents $\geq$ 4 pCi/L radium-228 equivalents	1.7×10^{-4} 1.5×10^{-4} 1.5×10^{-4}

Figure 1. Community water supply system and subsystem boundaries.