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Radon: Sources, Health Risks, and Hazard Mapping

INTRODUCTION

There are 3 naturally occurring radon (Rn) isotopes: ^{219}Rn (actinon), ^{220}Rn (thoron), and ^{222}Rn, which is commonly called radon. Radon-222 is a natural radioactive gas produced by the radioactive decay of radium (^{226}Ra), which, in turn, is derived from the radioactive decay of uranium. Uranium is found in small quantities in all soils and rocks, although the amount varies from place to place. Radon-222 or ^{222}Rn (radon) occurs in the uranium-238 decay series, has a half-life of 3.82 d, and provides about 50% of the total radiation dose to the average person. Radon concentrations (1) in outdoor air are generally low (4–8 Bq m^{-3}), whereas radon in indoor air ranges from less that 20 Bq m^{-3}, to about 110 000 Bq m^{-3} with a population-weighted world average of 39 Bq m^{-3}. Country averages range from 9 Bq m^{-3} in Egypt, 20 Bq m^{-3} in the UK, 46 Bq m^{-3} in the US, 108 Bq m^{-3} in Sweden, and 140 Bq m^{-3} in the Czech Republic (2). Radon in soil air (the air that occupies the pores in soil) commonly varies from 5 to 50 Bq L^{-1} but may be <1 Bq L^{-1} or more than 2500 Bq L^{-1}. The amount of radon dissolved in ground water ranges from about 3 to nearly 80 000 Bq L^{-1} (3).

This synopsis describes the kinds of rocks and unconsolidated deposits that radon is associated with, how radon moves through the ground and into buildings, the associated health risks, and how to produce radon hazard maps. It is an updated summary of Appleton, J.D. 2005. Radon in air and water. In: *Essentials of Medical Geology: Impacts of the Natural Environment on Public Health*. Selinus, O. (eds). Elsevier, Amsterdam, pp. 227–262.

GEOLOGICAL ASSOCIATIONS

Relatively high levels of radon emissions are associated with particular types of bedrock and unconsolidated deposits, for example, some granites, uranium-enriched phosphatic rocks, and shales rich in organic materials (3). Uranium concentrations also sometimes occur in limestones, sedimentary ironstones, and permeable sandstones. Rock types that are high radon sources in the US include *i)* uraniferous metamorphic rocks and granites, especially fault shear zones in these rocks in the Sierra Nevada, Rocky, and Appalachian mountain ranges; *ii)* marine black shales, especially in a belt from Ohio to Colorado; *iii)* glacial deposits derived from uranium-bearing rock and sediment, especially in the northwestern Midwest, where high radon emanation reflects large surface area and high permeability caused by cracking when dry; *iv)* uranium- and radium-enriched soils derived from carbonate, especially karstic terrain; *v)* uranium-mining residues and mine tailings in western US (e.g., Colorado); and *vi)* phosphate ore close to the surface and in mining waste on the surface, especially in Florida. Releases from coal residues and the burning of natural gas and coal complete the list of major contributors to atmospheric radon in the US (4).

High concentrations of radon in houses and soil gas in the UK are associated with *a)* rocks and weathering products that contain enhanced levels of uranium or radium, and *b)* permeable rocks, unconsolidated overburden, and their weathering products. Granites in southwest England are characterized by high uranium concentrations, a deep weathering profile, and uranium in a mineral phase that is easily weathered. Although the uranium may be removed during weathering, radium generally remains *in situ* (5). Radon is easily emanated from the weathered rock, and high values of radon have been measured in ground and surface waters (110–740 Bq L^{-1}) and in soil gas (frequently >400 Bq L^{-1}). There is a clear correspondence between areas where more than 30% of the house radon levels are above the UK Action Level (200 Bq m^{-3}) and the major granite areas (3, 5).

The depositional and diagenetic environment of many black shales leads to enrichment of uranium. For example, some Carboniferous shales in north England contain 5–60 mg kg^{-1} uranium. Weathering and secondary enrichment can substantially enhance uranium (U) levels in soils derived from these shales. Fifteen percent to 20% of houses sited on uraniferous shales with >60 mg kg^{-1} U and high soil-gas radon (32 Bq L^{-1}) are above the UK radon Action Level (6). Sedimentary ironstone formations in the UK, including the Jurassic Northampton Sand Formation and the Marlstone Rock Bed, are slightly uraniferous and permeable, so a relatively large proportion of houses underlain by these rocks are affected by high radon concentrations (3). High levels of radon occur in both soil gas and houses underlain by Carboniferous Limestone in the UK, as well as in caves and mines. Ten percent to more than 30% of houses built on the limestones have radon concentrations greater than the UK Action Level (7–9).

Similar associations between high radon and Lower Carboniferous limestones, Namurian uraniferous and phosphatic black shales, some granites, and highly permeable fluvioglacial deposits have also been recorded in Ireland (10).

In the Czech Republic, the highest indoor and soil-gas radon levels are associated with the Variscan granites, granodiorites, syenites, and phonolites of the Bohemian massif. Syenites contain 12–20 mg kg^{-1} U, phonolites have 10–35 mg kg^{-1} U, and soil-gas radon concentrations range up to more than 450 Bq L^{-1}. High radon is also associated with Palaeozoic metamorphic and volcanic rocks, and also with uranium mineralization in the Příbram area (11, 12).

In Germany, the highest radon occurs over the granites and Palaeozoic basement rocks. Median soil-gas radon for some granites ranges from 100 to 200 Bq L^{-1} (13). In contrast, the highest radon potential in Belgium is associated with strongly folded and fractured Cambrian to Lower Devonian bedrocks in which uranium preferentially concentrated in ferric oxyhydroxides in fractures and joints is considered to be the main source of radon (14). In France, some of the highest radon levels occur over peraluminous leucogranites or metagranitoids in a stable Hercynian basement area located in South Brittany (western France). These rocks are derived from uraniferous granitoids, with average uranium contents of over 8 mg kg^{-1} (15). High radon is associated with granite and alum shale in Sweden, Norway, and Belgium (16–18). In India, the soil-gas and indoor radon concentrations are controlled by lithology, structure, and uranium mineralization (19), whereas in Korea, high soil-gas radon is associated with granite gneiss and banded gneiss, and low concentrations occur in soils over shale, limestone, and phyllite schist (20).

The impact of unconsolidated deposits reflects their permeability and composition. In Sweden, fragments and mineral grains of uranium-rich granites, pegmatites, and black alum shales are dispersed in till and glaciofluvial deposits, leading to high radon in soils and dwellings, especially when the glaciofluvial deposits are highly permeable sands and gravels (21). In Norway, high radon is associated with highly permeable fluvioglacial and fluvial deposits derived from all rock types and with moderately permeable unconsolidated sediments (mainly basal till) that contain radium-rich rock fragments (17).

RELEASE AND MIGRATION OF RADON GAS

Most of the radon atoms formed from the decay of radium remain in the mineral grains. In soils, normally 20%–40 % (in clays up to 70%) of the newly generated radon atoms emanate to the pore space where they are mixed in the gas (soil air) or water that fill the pores. From the pore space, radon can be transported by diffusion or by flow in carrier fluids, such as gas (soil air) or water. The rate of release of radon from rocks and soils is largely controlled by their uranium and radium concentrations, grain size, and by the types of minerals in which the uranium occurs. The most important factors controlling its migration and accumulation in buildings include *i)* the transmission characteristics of the bedrock, including porosity and permeability; *ii)* the nature of the carrier fluids, including carbon dioxide gas, surface water, and groundwater; *iii)* weather; *iv)* soil characteristics, including permeability; *v)* house construction characteristics, and *vi)* life style of house occupants (22).

After uranium and radium concentration, the permeability and the moisture content of rocks and soils are probably the next most significant factors influencing the concentration of radon in soil gas and buildings. The maximum distance that radon can diffuse through water is about 5 cm. Thus, in unsaturated rocks and overburden with high fluid permeability, higher radon values are likely to result from a given concentration of uranium and radium than in less permeable or water-saturated materials. The fracturing of clays, resulting in enhanced permeability, combined with clays' relatively high radium content and its emanation efficiency may also result in higher radon concentrations in dwellings.

Radon containing soil air (or soil gas) is transported along natural pathways, which include planar discontinuities and openings, such as bedding planes, joints, shear zones, and faults, as well as potholes and swallow holes in limestone. Artificial migration pathways underground include mine workings, disused tunnels, and shafts, as well as near-surface installations for electricity, gas, water, sewage, and telecommunications services. For example, higher radon (average 480 Bq m^{-3}) was found in houses located $\pm$150 m from the surface projection of a closed uranium mine tunnel in Hungary compared with houses located further away [average 291 Bq m^{-3} (23)]. Radon is thought to migrate through fissures that intersect the mine tunnel and run up to the surface.

Out of doors, radon normally disperses in the air, whereas in confined spaces, such as buildings, mines, and caves, it may accumulate. Derived from soils and rocks underlying a building, radon in indoor air is transported into the building with soil gas through holes and cracks in the foundation. Normally radon transport by diffusion is not the cause of enhanced radon concentrations in dwellings, although diffusion may be more important in buildings with crawl spaces or those that lack a protecting concrete slab. Smaller amounts or radon may be released by degassing of domestic radon-containing water into the indoor air or from building materials. Soil gas represents the predominant source of indoor ^{222}Rn gas. Indoor radon concentrations are generally about 1000 times lower than radon in the soil underlying the house. Most houses draw less than 1% of their indoor air from the soil, although houses with low indoor air pressures, poorly sealed foundations, and several entry points for soil air may draw as much as 20% of their indoor air from the soil. Consequently, radon levels inside the house may be very high even in situations where the soil air has only moderate amounts of radon.

The design, construction, and ventilation of the home affect indoor radon levels. Radon-containing soil air can be transported into a home through cracks in solid floors and walls below construction level; through gaps in suspended concrete and timber floors and around service pipes; through crawl spaces, cavities in walls, construction joints, and small cracks or pores in hollow-block walls.

Radon decays in a few days, so water in rivers and reservoirs usually contains very little radon. Consequently, homes that use surface water do not have a radon problem from their water. Water processing in large municipal systems aerates the water, which allows radon to escape, and also delays the use of water until most of the remaining radon has decayed. However, in some parts of the US and Sweden, ground water is the main water supply for homes and communities. These small public water works and private domestic wells often have closed systems and short transit times that do not remove radon from the water or permit it to decay. In such situations, radon from the domestic water released during showering and other household activities could add radon to the indoor air. Areas most likely to have problems with radon from domestic water supplies include those with high levels of uranium in the underlying rocks. This association has been observed in the US, the UK, and Sweden (24, 25).

Building materials generally contribute only a very small percentage of the indoor air ^{222}Rn concentrations. However, in a few areas, concrete, blocks, or wallboard made by using radioactive shale or waste products from uranium mining will make a larger contribution to the indoor radon. (26–28).

EXPOSURE AND HEALTH RISKS

The average person in the UK receives an annual effective radiation dose of 2.8 millisieverts (29), of which about 85% is from natural sources: cosmic rays, terrestrial gamma-rays, the decay products of ^{220}Rn and ^{222}Rn, and the natural radionuclides in the body ingested through food and drink. About 60% of the total natural radiation dose is from radon isotopes (24, 27, 30). On an individual basis, the dose depends upon where one lives, ones' life style, and the nature and extent of any medical treatment. Most of the exposures to terrestrial gamma-rays and to ^{220}Rn and ^{222}Rn decay products result from living indoors. Most of the radon that is inhaled is exhaled again before it has time to decay and irradiate tissues in the respiratory tract. Radon (^{222}Rn), however, decays to form very small solid radioactive particles, including polonium-218, that become attached to natural aerosol and dust particles. These may remain suspended in the air or settle onto surfaces. When these particles are inhaled, they irradiate the bronchial epithelial cells of the lung with alpha particles, and this may increase the risk of developing lung cancer. Apart from lung cancer, there is no epidemiological proof of radon causing any other type of cancer (31, 32).

A large body of epidemiological data has accumulated over several decades relating to studies of the incidence of lung cancer in miners, and risk estimates have been derived from this data (33). A combined analysis of underground-miners epidemiological studies revealed an increase in relative risk from about 2% at a mean exposure of 250 WLM (1 WLM = working

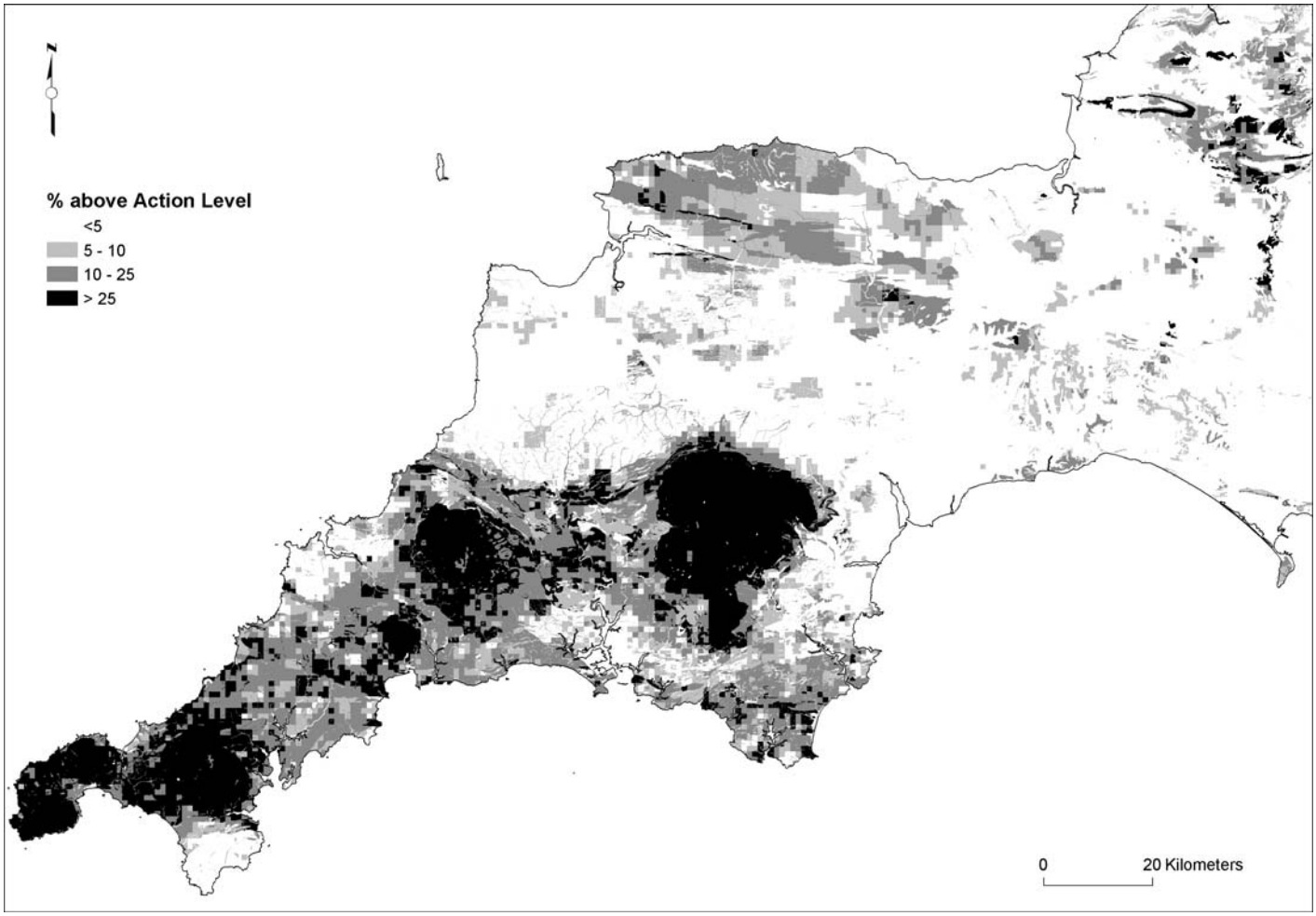

Figure 1. Provisional radon potential map of southwest England based on geology and indoor radon measurements.

level month, equivalent to an average annual exposure of 144 Bq m^{-3} y) to 10% at 2500 WLM (34).

Collaborative analysis of individual data from 13 case-control studies of residential radon and lung cancer in 9 European countries showed that the risk of lung cancer increased by 16% (95% confidence interval, 5%–31%) per 100 Bq m^{-3} increase in radon after correction for random uncertainties in measuring radon concentrations (35). The dose-response relation seemed to be linear, with no threshold and remained significant ($P = 0.04$) in analyses limited to individuals from homes with measured radon <200 Bq m^{-3}. The results suggest that radon is responsible for about 2% of all deaths from cancer in Europe. Systematic analysis of pooled data from 711 North American residential case-control radon studies showed that the odds ratios (OR) for lung cancer increased with residential radon concentration. The estimated OR after exposure to radon at a concentration of 100 Bq m^{-3} over a 25-y period was 1.11 (1.00–1.28), which is compatible with the estimate of 1.12 (1.02–1.25), predicted by downward extrapolation of the results from occupational studies of radon-exposed underground miners (36, 37).

The number of lung-cancer cases from residential radon exposure in the US is estimated to be 15 000 to 22 000, which is 10%–15% of lung cancer deaths. Radon causes 11% of lung cancer deaths among smokers (most of whom die of smoking) but 23% of persons who never smoked. Darby et al. (38) demonstrated that over 80% of the radon related deaths in the UK occur at ages of less than 75 and over 80% in smokers or ex-smokers. About 90% of radon induced deaths in the UK probably occur in response to exposure to radon concentrations below the currently recommended action level of 200 Bq m^{-3} of which 57.3% (1304 deaths) can be attributed to residential radon below 50 Bq m^{-3} (38). The total number of deaths from lung cancer in the UK is about 34 000, most of them directly from smoking. The cumulative absolute risk of lung cancer by age 75 years, at a residential radon concentration of 100 Bq m^{-3} is approximately 12% for smokers and 0.5% for nonsmokers. The US Environmental Protection Agency estimates that radon in drinking water causes about 168 cancer deaths per year, 89% from lung cancer caused by breathing radon released from water, and 11% from stomach cancer caused by drinking radon-containing water. In general, radon released from tap water and inhaled will present a greater risk than radon ingested through drinking water (30).

RADON HAZARD MAPPING

Accurate mapping of radon-prone areas helps to ensure that the health of occupants of new and existing dwellings and workplaces is adequately protected. Radon potential maps can be used *i)* to assess whether radon protective measures may be required in new buildings; *ii)* for the cost-effective targeting of radon monitoring in existing dwellings and workplaces; and *iii)* to provide a radon assessment for home buyers and sellers. It is important, however, to realize that radon levels often vary widely between adjacent buildings, because of differences in the radon potential of the underlying ground, as well as differences in construction style and use. Whereas, a radon potential map can indicate the relative radon risk for a building in a particular locality, it cannot predict the radon risk for an individual

building. In the UK, radon potential maps generally indicate the probability that new or existing houses will exceed a radon reference level, which in the UK is called the Action Level (200 Bq m^{-3}) (3, 30). In other countries, geological radon potential maps predict the average indoor radon concentration (US) or give a more qualitative indication of radon risk (Germany and the Czech Republic).

Two main procedures have been used for mapping radon-prone areas. The first is geological radon potential mapping in which each geological feature is assigned to a radon potential class based on the interpretation of one or more of the following types of data: *i)* radon concentrations in dwellings (indoor radon); *ii)* concentration, mineralogical occurrence, and chemical state of uranium and radium in the ground (radiometric and geochemical data); *iii)* rock and soil permeability and moisture content; *iv)* concentration of radon in soil gas, and *v)* building architecture (construction characteristics). The second uses radon measurements in existing dwellings to map the variation of radon potential between administrative or postal districts, or grid squares, or within geological polygons (39, 40).

Uranium and radium concentrations in surface rocks and soils are useful indicators of the potential for radon emissions from the ground. Uranium can be estimated by gamma spectrometry either in the laboratory or by ground, vehicle, or airborne surveys. The close correlation between airborne and ground radiometric measurements and indoor radon concentrations has been demonstrated in Virginia and New Jersey in the US, Nova Scotia in Canada, and also in parts of England (39, 41) although areas with high permeability have significantly higher indoor radon levels than would be otherwise expected from the e^{226}Ra concentrations, reflecting an enhanced radon flux from permeable ground (9, 42).

Sweden was the first country to make use of airborne gamma-ray spectrometry data to produce maps of radon potential. Radon potential is estimated and mapped on the basis of available data including *i)* geology; *ii)* airborne radiometric surveys (covering 65% of Sweden); *iii)* results from radiometric surveys of the ground; *iv)* results from radon surveys in buildings; *v)* results from earlier geotechnical investigations (e.g., permeability and ground water level); *vi)* field surveys, including gamma spectrometry; *vii)* orientation soil-gas radon measurements. Åkerblom (43) established a simple 3-fold radon risk classification based on geology, permeability, and soil-gas radon. A similar classification was used for the radon risk map of Estonia (44).

Radon risk mapping of the Czech Republic at a scale of 1 : 500 000 is based upon a number of data sets for airborne radiometry, geology, pedology, hydrogeology, ground radiometry, and soil-gas radon. Radon risk maps at the 1 : 50 000 scale are used for the identification of dwellings exceeding the guidance level to an accuracy of 70%–80% (11), although the maps are not recommended for the prediction of the requirement for radon protective measures in new buildings for which soil-gas radon site assessments are required (45).

It has been demonstrated in a number of countries, including Canada, Czech Republic, Germany, the UK, the US, and Sweden that soil-gas radon measurements combined with an assessment of ground permeability can be used to map geological radon potential in the absence of sufficient indoor radon measurements. Ten to 15 soil-gas radon measurements are generally required to characterize a site or geological unit. The Swedish National Board of Housing, Building, and Planning has adopted a ground classification based on geology, permeability, and soil-gas radon measurement (21). Similar procedures are used in Finland, Germany, and the Czech Republic (45). However, soil-gas radon data may be difficult to interpret because of the effects of large diurnal and seasonal variations in soil-gas radon close to the ground surface, as well as variations in soil-gas radon on a scale of a few meters.

Because the purpose of maps of radon-prone areas is to indicate radon levels in buildings, maps based on actual measurements of radon in buildings are generally preferable to those based on other data. Procedures for monitoring and surveys of radon in dwellings are described in (46) and (47). Requirements for mapping radon-prone areas by using indoor radon data are similar, whether the maps are made on the basis of grid squares or geological units. These requirements include *i)* accurate radon measurements made by using a reliable and consistent protocol; *ii)* centralized data holdings; *iii)* sufficient data evenly spread; and *iv)* automatic conversion of addresses to geographical co-ordinates. It appears that Great Britain is the only country that currently meets all of these requirements for large areas. In countries where lesser quality or quantity of indoor radon data is available, there is greater reliance on proxy data for radon potential mapping (e.g., Czech Republic, Germany, Sweden, and the US).

Radon measurements in existing dwellings have been used to map the radon potential of countries, administrative districts, or grid squares, without taking into consideration the geological controls on radon in dwellings. Because the factors that influence radon concentrations in buildings are largely independent and multiplicative, the distribution of radon concentrations is usually lognormal, so lognormal modeling was used to produce accurate estimates of the proportion of homes above a reference level in the UK (48, 49). Radon potential mapping that used indoor radon measurements have been carried out in other European countries, including Ireland, Luxembourg, and France (50).

Radon maps based on indoor radon data grouped by geological unit have the capacity to accurately estimate the percentage of dwellings affected together, with the spatial detail and precision conferred by the geological map data (51). Combining the grid square and geological mapping methods gives more accurate maps than either method can provide separately [(40); Fig. 1].

References and Notes

1. Radioactivity is measured by using the SI unit becquerel (Bq). One becquerel represents 1 atomic disintegration per second. The level of radioactivity in the air from radon is measured in becquerels per cubic meter (Bq m^{-3}) of air. Twenty radon atoms disintegrate every second in every cubic meter of air when the radon concentration is 20 Bq m^{-3}.
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29. The absorbed dose (measured in Gy or rad) is the energy absorbed by a unit mass of tissue, whereas the dose equivalent takes account of the relative potential for damage to living tissue of the different types of radiation. The dose equivalent is the absorbed dose multiplied by a "quality factor," which is 1 for beta and gamma rays and 20 for alpha particles. This is because alpha particles deposit their energy much more densely. In addition, alpha particles transfer all their energy in short distances so that a relatively small volume of tissue receives a high dose of radiation. The commonly used unit for dose equivalent is the sievert (1Sv = 1000 millsieverts; 1000 mSv). The dose equivalent indicates the potential risk of harm to particular tissues by different radiations, irrespective of their type or energy.
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