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METHODOLOGIES FOR IDENTIFYING HIGH-RADON AREAS: A BRIEF REVIEW

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ABSTRACT

Indoor radon concentrations are found to vary substantially among geographical areas, implying that homes with high concentrations may "cluster" to a significant degree. Programs for finding and fixing homes with high levels may thus be aided by identifying "high-radon" areas. This has usually been accomplished by simply monitoring indoor levels or by using information on physical factors - such as radium content and permeability of soils, building characteristics, and local meteorology - to map the "radon potential," either using physical models or scoring procedures. A third approach is to develop a statistical exposure model, based on correlation of measured indoor concentrations with data on physical factors, providing a mapping of estimated "actual" indoor concentrations. A preliminary regression analysis between county GM indoor radon concentrations from Minnesota and associated physical data yields an R^2 exceeding 0.5.

INTRODUCTION

Airborne decay products of radon in homes are estimated to cause significant risks of lung cancer among the general population, e.g., approximately 10,000 cases per year in the United States (1). A particular concern is long-term residence in homes having concentrations much higher than average, since the associated risk is thought to be proportional to lifetime cumulative exposure. In many countries, monitoring has yielded the frequency distribution of ^{222}Rn concentrations in homes, often indicating that a significant number have concentrations an order of magnitude greater than the average. Furthermore, the distribution differs not only from one country to another, but also from one area to another within a given country (2-4).

The variation of indoor Rn concentrations from one home to another, one area or region to another, or one country to another, can be understood in principle in terms of the causative factors discussed below. Although we might hope for a sufficient physical understanding to predict concentrations in individual homes, it is clear that - even if possible in principle - such a large amount of information on homes and sites would be required that it is easier simply to measure the indoor concentration. On the other hand, because concentration distributions vary substantially from one area or region to another, the preponderance of homes having concentrations substantially greater than the average for a particular country tend to occur in particular areas. The ability to characterize concentration distributions systematically and reliably from area to area would therefore have substantial value in focussing efforts to identify homes with unusually high concentrations and to reduce these levels.

For the United States, for example, where the average concentration in single-family houses is approximately 55 Bq/m^3, and perhaps 50,000 or 100,000 homes have concentrations greater than 740 Bq/m^3, we may estimate - based on data from Refs. 4 and 5 - that perhaps 90% of such homes occur in 10% of the country. Identifying these "high-radon" areas as a first priority, followed by intensive local monitoring, would lead to more rapid identification of the bulk of the individual homes having very high levels. Such characterization would also provide a substantive basis for choosing where to include Rn control techniques in the construction of new homes. Concentration of efforts into high-radon areas also has substantial financial implications, given the very large cost to the public of control efforts, estimated to be $10-1000 billion in the United States (6, 7).

GENERAL APPROACHES, PHYSICAL BASIS, AND AVAILABLE DATA

Past attempts to identify high-radon areas suggest three conceptually different, but potentially related, approaches to developing area estimators of indoor radon concentrations. One is to utilize monitoring data acquired in a representative sample of a region's housing stock; this approach is limited by the intensity of monitoring required to yield direct estimates for all areas or geographic scales of interest. The second is to use physical models or scoring procedures to predict indoor concentrations based on information characterizing the soils, housing, or other relevant physical features of the region (or nation) of interest. This approach is limited when the physical models or other procedures, or the data required, are not complete enough to yield reliable estimates, the situation in which we presently find ourselves. A third alternative is to use relevant physical data themselves, outside the context of a physical model, and together with available indoor monitoring data, as indicators of local indoor concentrations.

Approaches may differ in another important way, i.e., whether they are designed to yield estimates of the radon "potential" - in several possible senses - or whether they provide estimates of the actual radon concentrations occurring in existing, or even future, housing. For example, approaches based on physical parameters or models may be designed to indicate or estimate quantities ranging from soil-gas concentrations or entry rates to indoor concentrations (in the basement or primary living space) and may entail either "conservative" assumptions (in the sense of maximizing estimated quantities, and hence exposures, thus being "protective" of public health) or realistic assumptions, aimed at yielding estimates of the actual concentrations to which occupants are or would be exposed. Similarly, although in most countries indoor Rn monitoring is performed with the aim of estimating actual indoor concentrations, a protocol may be selected instead to indicate the "potential" for high concentrations; e.g., the "screening" protocol recommended until recently in the United States by the Environmental Protection Agency (EPA) used short-term sampling, in the basement if there was one (8).

The Rn concentration in a building may be described in steady state as the ratio of the entry rate per unit indoor volume to the space's ventilation rate, a balance between entry and removal. The bulk of the Rn found in single-family homes in many countries arises from Rn present in interstitial gas in underlying soil or rock, generated from naturally-occurring radium and entering the indoor space primarily by transport of the soil gas itself (9-11). The importance of pressure-driven flow implies that it is not only the amount of the parent, Ra, in underlying material, and the fraction of the newly-generated Rn that emanates into the interstitial air, that determine the Rn "availability," but also the permeability of the soil (or rock) to soil-gas flow. Rn entry also depends on the configuration of the building substructure, including the location and size of openings to the soil, though these are usually large enough that it is the permeability of the soil (rather than the impedance offered by the substructure) that controls the Rn entry rate (11). The ultimate simplification is instructive: To the extent that differing meteorological driving forces change entry and removal rates together by the same factor, it is not the ratio of these rates that ultimately determines the indoor concentration. Rather, it is the ratio of the product of the primary source parameters - Ra concentration, emanation fraction, and permeability - to the comparable removal parameter, the "leakage area" of the building shell - to which the home's ventilation rate is proportional in the simplest case (12).

The major classes of physical data therefore pertaining to estimation of indoor concentrations are geological, soils, housing, and meteorological. Occupant habits can also play a role in indoor concentrations (as well as affecting personal exposures), but this factor will be ignored here. It is important to emphasize that indoor concentration data themselves are essential to most efforts for estimating potential or actual Rn concentrations. Depending on the approach taken, different types of data might be thought to be suitable, but ultimately these need to be normalized to the parameter of principal interest, i.e., the concentration to which occupants are exposed. We have noted above the use of contrasting data in the United States, as well as the long-term data used more commonly in European countries (2-4, 8).

The earliest physical data used as indicators of radon potential, e.g., in Sweden and the United States, have been geographic radiometric data or geologic mappings of rock types known to have elevated Ra contents, supplemented by indications of soil-gas Rn concentrations or entry (10, 13-16). More recent efforts have considerably advanced the utility of U.S. aerial radiometric data (5, 17).

Sources of soils, housing, or meteorological information vary from one country or region to another. A review of the availability of such information has been completed for the United States (18), paying special attention to soils and climatological data. Soils information from U.S. Soil Conservation Service (SCS) maps and associated data include water permeability, grain sizes, and soil taxonomic class. The primary SCS mappings are prepared county by county in hard copy rather than digitized, making use for broad-scale analytical purposes difficult. In some cases, such as Minnesota (see below), useful maps have been prepared at other scales. Of more general interest is that the SCS is preparing a series of statewide generalized soil maps, mapping geophysically distinct soil regions digitally and describing each in terms of its average mixture of component soil types and associated physical information (19).

Climatic data may be found in various forms, typically derived in the United States from data of the National Oceanic and Atmospheric Administration. Useful mappings of relevant meteorological parameters may be developed by processing and interpolating typical meteorological data from more than 200 stations across the U.S. and Canada, as was done previously to develop a mapping of "infiltration degree days," as a basis for an infiltration standard (20). Data on housing characteristics exist in different forms and at different levels in different areas and countries, and general comments are not instructive in this brief paper.

RADON "POTENTIAL" MAPPING

The mapping of radon potential over regions or countries has included: 1) simple display of radiometric data (or of areas with rock types with typically high Ra concentrations); more complex display of geologic or radiometric information together with other types of information (such as soil types or permeabilities); and the development of maps on the basis of physical modeling. The Swedish maps referred to earlier, or the U.S. maps of surficial Ra (equivalent-uranium) content, are examples of the first class. An example of the second class is Sweden's use of mapped indicators of Ra content and soil permeability to classify soil for building purposes (21). A differing approach is taken in the U.S. Geological Survey (USGS) development of radon-potential maps of Montgomery County, Maryland (22), using underlying rock units as the template for developing potential classifications based on radiometric information as well as soil-gas monitoring data and on volunteer indoor monitoring data acquired using a "screening" protocol (cf. above). A comparable approach has been used to develop a radon potential map of the United States utilizing geologic, radiometric, soil permeability, and housing data, together with the EPA screening data, to develop rank scores that are converted to estimates of the average screening indoor concentration by county (23).

A more sophisticated extension of potential mapping could utilize physical representations to develop estimates, for example, of Rn entry rates based on physical data. The most basic form of this approach has been considered by several workers, basically to utilize a quantitative *index*, calculated from physical parameters such as surficial Ra concentration and soil permeability (9, 24). Various forms of this general approach - including fairly sophisticated modeling - have also been examined for use in characterizing the radon potential of prospective building sites (25). However, perhaps the most advanced use of *physical models* for developing area radon potentials is a program in Florida where soil and radiometric information is used in calculating radon entry rates into a standard housing unit as a basis for indicating the radon potential of small map units across the state (26). Such approaches are here considered mapping of radon "potential" because the models do not afford a quantitatively validated basis for calculating the actual entry rates or and do not transform this quantitatively to the concentrations to which occupants are actually exposed.

RADON "ACTUAL" MAPPING

Monitoring data can in principle provide direct estimates of the indoor concentrations of interest.. However, in view of the scale of significant geographic variability, very large monitoring efforts would be required to yield useful estimators at a fine enough scale to include most of the "high-radon" homes. We therefore turn immediately to a third general approach, i.e., the use of available monitoring *and* physical data in a statistical analytical framework yielding estimators of actual indoor concentrations by area in the region or country of interest. This approach uses much the same data as used in the other approaches, but it begins by examining the relationship between the monitoring and physical data (guided as much as possible by physical understanding), yielding a *correlation model* providing estimators that may be used for small areas where monitoring data are not available or are not intensive enough to yield useful estimates. Further, by utilizing suitable monitoring data in the analytical procedure, the results can be normalized to actual annual-average living-space concentrations, of more use than radon "potentials" for indicating occupant exposures.

A preliminary examination of this approach has been undertaken for Minnesota. Beginning with measured county geometric mean (GM) concentrations from the EPA-state survey, Lawrence Berkeley Laboratory (LBL) used county parameters developed for a radon entry potential index in a mobility and population exposure study (27) - including average surficial radium content and indicators (based on a state soils map) of permeability and emanation fraction - to examine the predictive power of such physical data or indicators (28). The correlation analysis was performed for all counties in Minnesota, as well as for the sets of counties having monitoring data from a minimum of 5 and 10 homes. For the latter set, Figure 1 shows the relationship between the measured GMs (from the 10 or more data) and the predicted GM concentrations, derived from a multiple regression for which R^2 was 0.5. The error bars indicate estimates of the standard error in the measured GMs arising purely from the limited number of monitoring data; we note that the deviations from the line shown are consistent with the correlation model being completely predictive. (Given the influence of other factors, this cannot of course be literally the case.) A comparable result is found for the full set of counties, although the deviations (and error bars) are substantially larger.

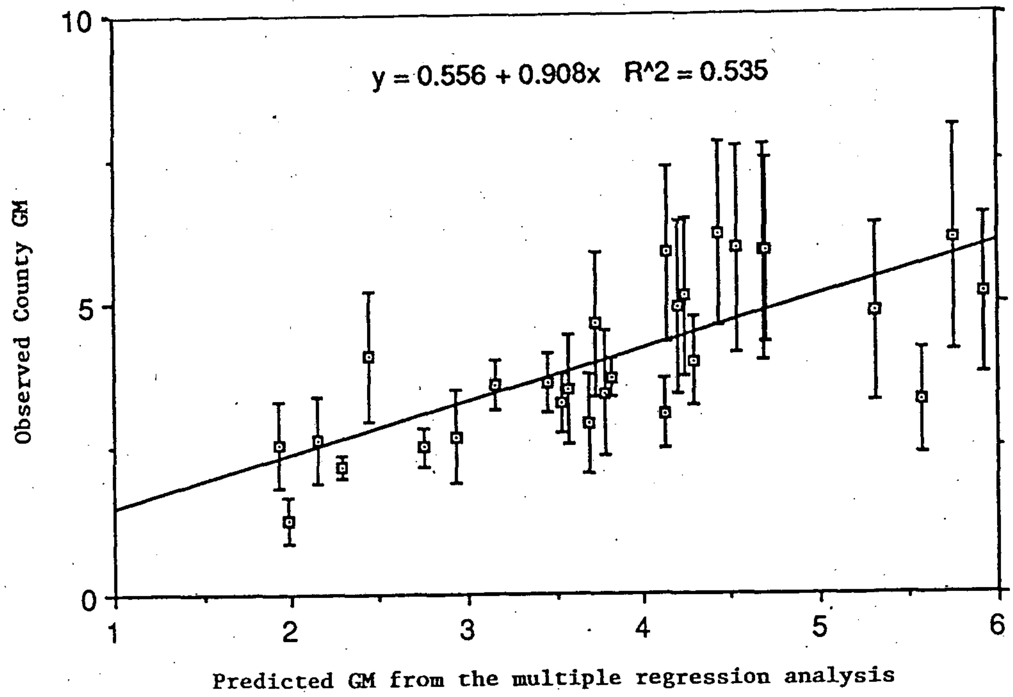

Fig. 1. Multiple regression results for county GM concentrations (in pCi/l = 37 Bq/m^3) for Minnesota counties with data from 10 or more houses (Ref. 28).

A fuller development of this approach would use different data, including long-term monitoring data taken in the primary living space and more precise spatial information. However, this initial success has led to a more substantial developmental effort, conducted jointly by LBL with the USGS and the Research Triangle Institute, which recently completed a national survey of radon for the EPA (29).

DISCUSSION

This brief review indicates several approaches to identification of high-radon areas, without attempting to indicate all the efforts of each type that have been undertaken. These approaches are conceptually different and, by their very nature, can be utilized for significantly different purposes. Given the present limitations of data and of physical modeling capabilities, it appears useful to utilize a statistically-based analytical approach to incorporate all the available data in a self-consistent way if the objective is to yield estimators that are normalized to the actual concentrations of primary interest.

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