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Estimation of residential radon exposure and definition of Radon Priority Areas based on expected lung cancer incidence

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ABSTRACT

Radon is a naturally occurring gas, classified as a Class 1 human carcinogen, being the second most significant cause of lung cancer after tobacco smoking. A robust spatial definition of radon distribution in the built environment is therefore essential for understanding the relationship between radon exposure and its adverse health effects on the general population. Using Ireland as a case study, we present a methodology to estimate an average indoor radon concentration and calculate the expected radon-related lung cancer incidence. We use this approach to define Radon Priority Areas at the administrative level of Electoral Divisions (EDs).

Geostatistical methods were applied to a data set of almost 32,000 indoor radon measurements, sampled in Ireland between 1992 and 2013. Average indoor radon concentrations by ED range from 21 to 338 $Bq\,m^{-3}$, corresponding to an effective dose ranging from 0.8 to 13.3 $mSv\,y^{-1}$ respectively. Radon-related lung cancer incidence by ED was calculated using a dose-effect model giving between 15 and 239 cases per million people per year, depending on the ED. Based on these calculations, together with the population density, we estimate that of the approximately 2,300 lung cancer cases currently diagnosed in Ireland annually, about 280 may be directly linked to radon exposure. This figure does not account for the synergistic effect of radon exposure with other factors (e.g. tobacco smoking), so likely represents a minimum estimate. Our approach spatially defines areas with the expected highest incidence of radon-related lung cancer, even though indoor radon concentrations for these areas may be moderate or low. We therefore recommend that both indoor radon concentration and population density by small area are considered when establishing national radon action plans.

1. Introduction

Radon is a natural radioactive gas present in all soils (Cothern and Smith, 1987), representing a significant source of ionizing radiation (WHO, 2009). When radon reaches the outdoor atmosphere it is diluted to lower concentrations. In confined places (e.g. dwellings, workplaces, caves and underground mines) however, radon may accumulate to higher concentrations where it may pose a substantial health risk (e.g. UNSCEAR, 2000a; US-EPA, 2003; WHO, 2009). Radon exposure is principally linked to lung cancer (e.g. Catelinois et al., 2006; ICRP, 1987; Pérez-Ríos et al., 2010), but may also be a contributing factor for other diseases such as skin cancer, Non-Hodgkin's Lymphoma, stomach cancer and brain cancer (Ha et al., 2017; López-Abente et al., 2018; Vienneau et al., 2017).

Globally, lung cancer is one of the most common cancer types, resulting in approximately 1.6 million annual deaths worldwide (Sugawara and Nikaido, 2014). In Ireland, lung cancer is the fourth most common cancer type, and with approximately 2,300 new cases every year is currently the primary cause of cancer deaths (about 20% of total cancer deaths; NCRI, 2015). Survival rates are normally low, < 20% after five years (e.g. Drolet and Martel, 2015; Jemal et al., 2010; NCRI, 2015), indicating that any reduction in the number of lung cancer cases will therefore have a significant positive impact on the health of the general population. Smoking has an overwhelming influence on lung cancer (i.e. up to 90% may be attributed directly to smoking; NCRI, 2011), and it may be difficult to identify any increase in the risk due to other factors (e.g. radon, occupational exposure, air pollution). Darby et al. (2005), however, estimated that the risk of lung cancer increases by about 16% for each 100 $Bq\,m^{-3}$ increase of radon exposure, and that between 3% to 14% of lung cancer fatalities globally may be attributed to inhalation exposure of radon (WHO, 2009). Radon is therefore the second cause of lung cancer after tobacco smoking (WHO, 2009).

The number of annual lung cancer fatalities related to radon

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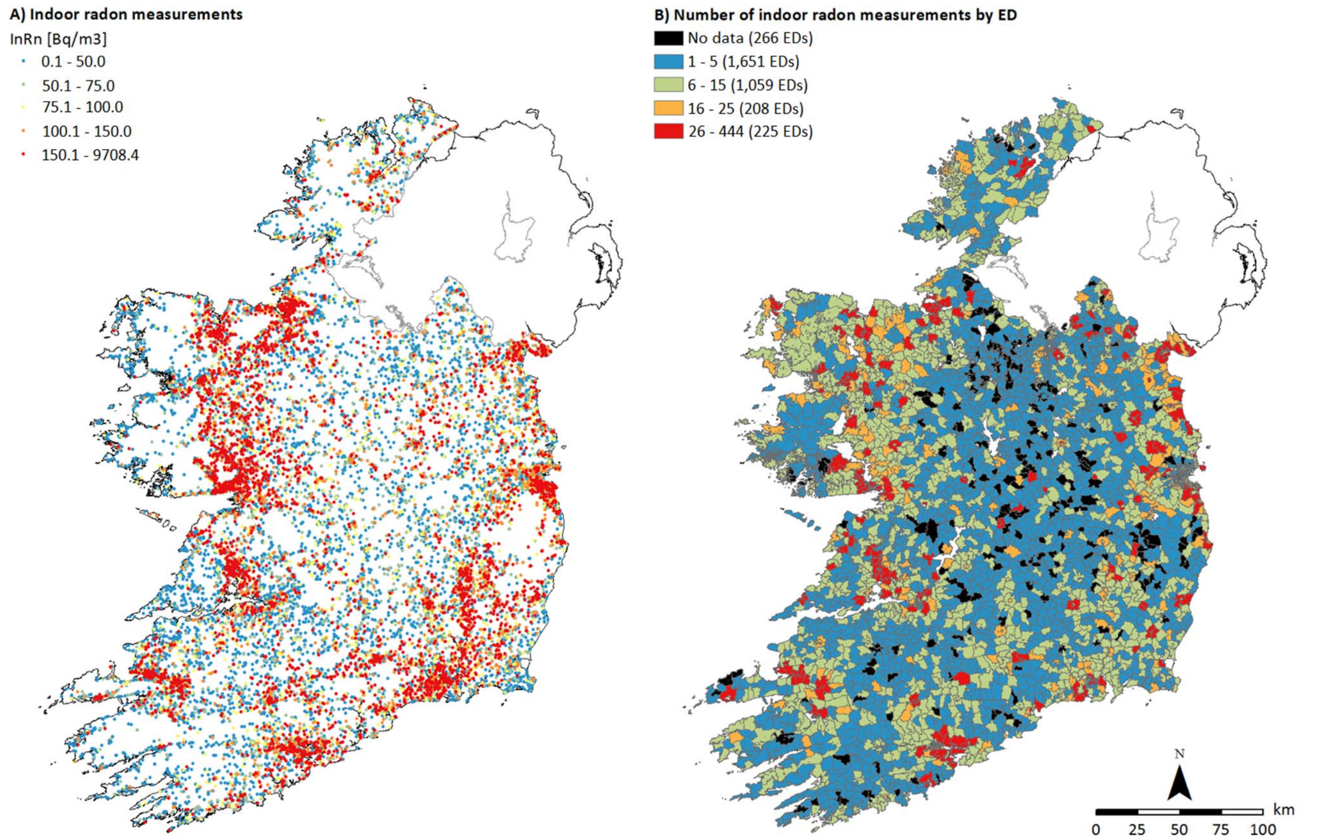

Fig. 1. Indoor radon measurements in Ireland between 1992 and 2013; a) location of indoor measurements (n = 31,910), and b) number of dwellings sampled by Electoral Division (ED).

exposure (e.g. around 18,000 in Europe, Gray et al., 2009; 21,000 in the USA, Casey et al., 2015) indicates that radon is an important health issue globally. Radon exposure can however be mitigated if appropriate measures are implemented. In this context, for example, the EU developed Council Directive 2013/59/EURATOM, in which the strategies to reduce exposure to ionizing radiation are defined. The EU Directive especially defines radon as one of the risks that Member States should address, and mentions that each Member State must identify areas (i.e. Radon Priority Areas) where a high radon exposure is probable (i.e. "*areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level*"). The efficacy of national strategies has been demonstrated in Ireland where the national average indoor radon concentration has been reduced from 89 Bq m^{-3} to 77 Bq m^{-3} since the introduction of building regulations in 1997 (Dowdall et al., 2017a, 2017b).

Although in this definition of priority areas the health effects are not tacitly mentioned, the EU Directive clearly remarks that the long-term goal is to reduce the lung cancer risk attributed to radon exposure, and therefore the main objective of a National Radon Action Plan is to reduce the adverse health effects resulting from radon exposure. It is therefore beneficial to include the expected number of lung cancer cases linked to radon exposure in the definition of Radon Priority Areas. Such a classification will have significant impact on the implementation of a cost-effective and spatially targeted Radon Action Plan (e.g. Bochicchio et al., 2017). Population density is consequently an important consideration in a Linear No-Threshold scenario as described by Darby et al. (2005), since it is understood that there is no lower limit for a safe radon exposure and that exposure to low indoor radon concentrations may also cause lung cancer. In this sense, for example, in terms of lung cancer prevention it could be more effective to reduce the average indoor radon concentration in a highly populated area by 5–10 Bq m^{-3} than attempting to do so by 15–20 Bq m^{-3} in areas with a lower population density. Estimation of the number of lung cancer cases due to radon exposure by administrative level, as proposed in this study, will therefore allow a focussed effort in reduction of indoor radon concentrations in areas where more inhabitants are exposed to radon and, consequently, more lung cancer cases would be expected.

Data pertaining to adverse health effects are often aggregated at administrative levels (e.g. Electoral Divisions, Municipalities; e.g. Bivand et al., 2008; Hansell et al., 2014), hence analysis of possible adverse health effects of a contaminant requires estimation of its concentration at the same domain. In this regard, for radon risk assessment the objective is to estimate an average indoor radon concentration in an administrative area, based on indoor radon concentrations measured from individual houses (Borgoni et al., 2010). Different methods have been proposed in the literature, including geostatistical methods (e.g. Borgoni et al., 2010; Ha et al., 2017; Hauri et al., 2012; Vienneau et al., 2017). The advantage of geostatistical methods is that they take into account the spatial correlation between the data (modelled by the variogram) to predict a value in a non-sample point.

In this paper, we apply a novel and robust method to define Radon Priority Areas, using Ireland as a case study. We estimate an average indoor radon concentration by Electoral Division (3,409 EDs, with total population ranged from 66 to 38,900 and an average of 1,400 inhabitants, and areas ranged from 0.04 km^2 to 162 km^2; Census 2016 Central Statistics Office Ireland), and then estimate the number of annual lung cancer cases attributed to this carcinogen. Data collected by the National Cancer Registry are also at this level (NCR/NICR, 2011). The methodology described in this study represents an important advance in the field of radiological protection, helping to define Radon Priority Areas based on a combination of indoor radon concentration and human population distribution, thereby contributing to a cost-effective national radon action plan.