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Systematic grid-based radon concentration measurements in the urban areas of Cyprus

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ABSTRACT

A comprehensive grid-based study of indoor Rn concentration in all accessible urban areas of the Republic of Cyprus, where 67.3% of the population resides, is presented. During the years 2004–2012, a total of 407 measurements of indoor Rn in the four highly-populated urbanised areas of Lefkosia, Lemesos, Larnaka, and Pafos districts were conducted, using high-sensitivity active Rn portable detectors. The four districts were subdivided into 189 grid cells, each of 1 km^2 in area. The grid cell mean indoor Rn concentration is in the range of 1.7 to 86.4 Bq/m^3, with an overall geometrical mean of 14.3 ± 10.0 Bq/m^3, and a median of 14.3 ± 3.9. The Rn mean in Cyprus is almost two-and-a-half times lower than the estimated world average of 39 Bq/m^3. The equivalent annual effective dose rate for each measurement was also calculated and compared to the corresponding world value. The spatial distribution and variation of Rn concentration values are also shown on maps of the urban areas of these districts. The conclusion of the present extensive and systematic Rn survey is that the Rn risk in the highly populated areas of Cyprus is low.

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1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive inert gas that is found in homes all over the world. Indoor Rn concentrations depend on a number of factors, including the geological characteristics of the ground underneath buildings, details of construction, and the habits of the occupants (e.g., USEPA, 1993; Appleton, 1995; Miles et al., 2007; Quindós et al., 2008; Demoury et al., 2013; Szabó et al., 2014). It is the decay product of the naturally occurring uranium-238 (^{238}U) decay series, which is present throughout the earth's crust. The half-life of Rn-222 is only 3.8 days and it directly decays into Polonium-218 (^{218}Po) by emitting alpha particles with an energy of about 5.5 MeV. Daughter nuclides following Rn decay, attached to microscopic dust particles, are inhaled and emit alpha particles, which effectively cause biological damage to the lung cells. Inhalation of air with high Rn concentration over a long period of time increases the risk of lung cancer (Field, 2001; Darby et al., 2005; Field et al., 2006). According to the World Health Organisation (WHO) the risk of lung cancer increases by 16% per 100 Bq/m^3 increase in long time average Rn concentration; the dose–response relation is linear, i.e., the risk of lung cancer increases proportionally with increasing Rn exposure (Zeeb and Shannoun, 2009). According to WHO, Rn is much more likely, however, to cause lung cancer in people who smoke. In fact, smokers are estimated to be 25 times more at risk from Rn than non-smokers.

The International Commission on Radiological Protection (ICRP, 2009), the International Atomic Energy Agency (IAEA, 2003), the European Commission (EC, 1997), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000a,b) refer to the health hazards due to Rn inhalation and emphasise the need for each country to define upper limits for Rn concentration in old and new buildings. The World Health Organisation recommends a national annual average concentration reference level of 100 Bq/m^3, but if this level cannot be reached under the prevailing country-specific conditions, the reference level should not exceed 300 Bq/m^3 (Zeeb and Shannoun, 2009).

The rock and soil mineral composition under a house affects the indoor Rn concentration. Atmospheric pressure differences between house and ground (rock or soil) can cause a slight under-pressure in a house that can draw up Rn gas from the soil or rock into the building. Radon moves more rapidly and further through permeable overburden, such as coarse sand and gravel, than through less permeable material, such as clay. Fractures in bedrock allow Rn to move more quickly (Otton, 1992; Appleton, 1995).

Radon gas can enter a house through cracks in concrete floors and walls, floor drains, sump pumps and construction joints (Appleton, 1995). Radon levels are generally higher in basements and ground floor rooms that are in direct contact with the rock or soil. The ability of Rn to be drawn into a house from the subsurface is influenced by the building design, construction quality, and ventilation preferences

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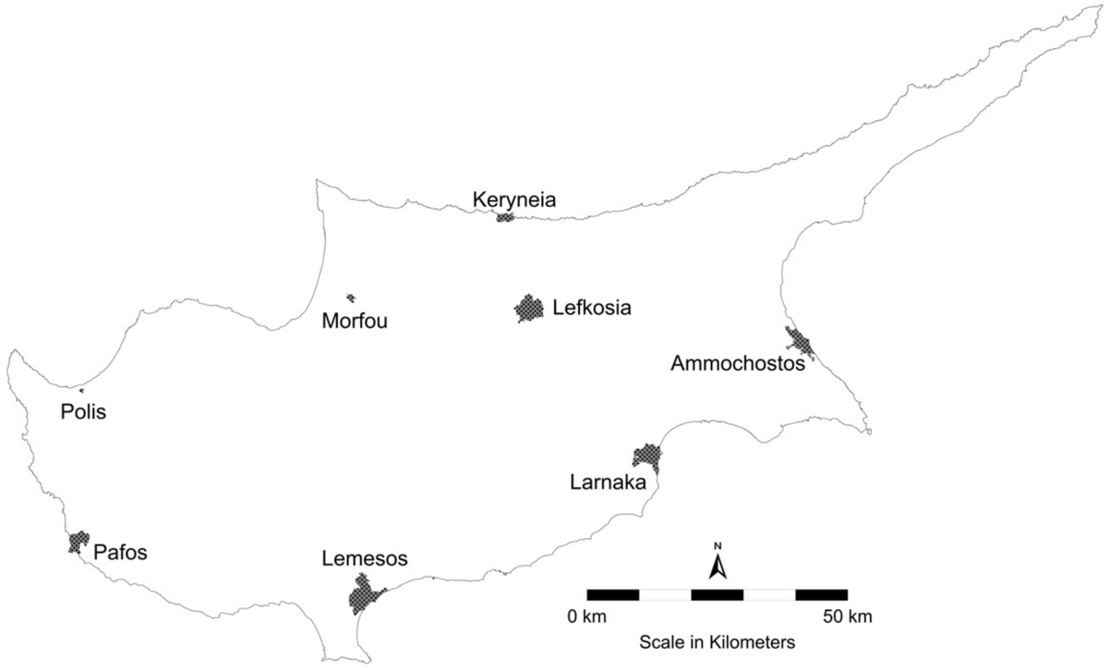

Fig. 1. Map of Cyprus showing the main towns and the location of Lefkosia (or Nicosia), Lemesos (or Limassol), Larnaka and Pafos (Source: Department of Lands and Surveys, Cyprus).

of the occupants. Building materials within the home environment are another source of indoor Rn gas (Abari et al., 2013; Cosma et al., 2013).

The concentration of uranium in the underlying rock or soil is the main factor that determines Rn levels. The investigated four urban areas of Lefkosia, Lemesos, Larnaka and Pafos (Fig. 1) are located on a sedimentary formation containing alluvium deposits, calcarenite, gravel, sand, marl and marly chalk (GSD, 1995; Tzortzis and Tsertos, 2004). The elemental uranium concentration measured in samples of surface soil from this formation is 0.78 ± 0.58 ppm (A.M. $\pm$ S.D.), and 1.69 ± 0.44 ppm in representative rock samples from the four sedimentary formations occurring in the accessible part of Cyprus, while the corresponding worldwide value is 2.8 ppm (Tzortzis and Tsertos, 2004; Tzortzis et al., 2003a).

In 1993, Christofides and Christodoulides (1993) from the Lefkosia General Hospital presented the results of the first indoor ^{222}Rn concentration measurements in Cypriot houses using alpha-track (CR-39) detectors. In 2001, the newly established Nuclear Physics Laboratory of the Department of Physics, University of Cyprus, began the "*Cyprus Radioisotopes*" project, aiming to measure indoor ^{222}Rn concentration in Cypriot public buildings and dwellings (Anastasiou et al., 2003), using high-sensitivity portable active Rn monitors of the type "RADIM3A" (Plch, 2001). Other research parts of the project included extensive and systematic measurements of naturally occurring radioisotopes in samples from different types of rock and soil, and building materials by means of standalone and in-situ high-resolution gamma-ray spectroscopy (Tzortzis et al., 2003a,b, 2004; Tzortzis and Tsertos, 2004, 2005; Michael et al., 2011; Svoukis and Tsertos, 2007). To date, only a few sporadic measurements of Rn concentration levels in Cyprus were reported (Sarrou and Pashalidis, 2003).

As a next step, our Laboratory has started systematic grid-based measurements on indoor Rn concentration throughout the main urbanised areas of Cyprus (Lefkosia, Lemesos, Larnaka and Paphos), using a constant grid cell of 1 km^2 in area, and high-sensitivity Rn portable detectors. The methodology and dose rate calculations are described by Theodoulou et al. (2012), together with the results in the densely-populated Lefkosia area. In the present study, besides the Lefkosia Rn data, the indoor Rn concentration grid-based measurements for the other three main residential areas of Lemesos, Larnaka and Pafos districts, together with the associated annual effective dose rates, are presented and compared to world average values. The measured Rn concentration in these four highly-populated districts is also presented on maps.

2. Methodology

2.1. Portable Rn detector

Indoor Rn measurements were obtained by two high-sensitivity portable monitors. The RADIM3A (Jiří Plch — SMM company) is a

Table 1
The population distribution in the accessible urban areas of the Republic of Cyprus (Statistical service, 2012). The number of measured grid cells and the corresponding number of measurements (N) in each district, the grid cell geometrical mean and standard deviation (SD) of the Rn concentration measurements (Rn), the annual effective dose rates (D) in each district, and the grid cell median and median absolute deviation (MAD) in each district.

Location	Population	No. of grid cells	N	Grid cell Rn (Bq/m^3)		Grid cell geometrical mean ($\pm$SD)		Grid cell median ($\pm$MAD)	
				Min.	Max.	Rn (Bq/m^3)	D (mSv/y)	Rn (Bq/m^3)	D (mSv/y)
Lefkosia*	245,900	54	108	6.4	86.4	17.9 ± 13.2	0.451 ± 0.333	18.8 ± 5.9	0.474 ± 0.149
Lemesos	184,600	33	66	6.3	51.6	11.8 ± 9.3	0.303 ± 0.235	10.4 ± 2.6	0.262 ± 0.066
Larnaka	86,400	57	143	1.7	47.8	12.7 ± 9.5	0.320 ± 0.240	12.5 ± 4.2	0.315 ± 0.106
Pafos	63,900	45	90	10.5	18.7	14.6 ± 2.1	0.368 ± 0.053	15.0 ± 1.3	0.379 ± 0.033
Total	580,800	189	407						
Grand geometric mean ($\pm$SD)						14.3 ± 9.97	0.360 ± 0.251		
Grand median ($\pm$MAD)								14.3 ± 3.9	0.361 ± 0.098

* Source: Theodoulou et al. (2012).

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