Comprehensive analysis of household radon gas levels and risk factors in Southern Alberta

Fintan K. T. Stanley, BSc, Siavash Zarezadeh, Colin D. Dumais, BSc, Karin Dumais, BSc, Renata MacQueen, Fiona Clement, PhD, Aaron A. Goodarzi, PhD*

Author Affiliations:

Robson DNA Science Centre, Arnie Charbonneau Cancer Institute, Departments of Biochemistry & Molecular Biology and Oncology, Cumming School of Medicine, University of Calgary, Calgary, Alberta, Canada (Stanley, Zarezadeh, Goodarzi); Canadian Association of Radon Scientists and Technologists, Calgary, Alberta, Canada (Dumais, Dumais, MacQueen); Health Technology Assessment Unit, O'Brien Institute for Public Health, Department of Community Health Sciences, Cumming School of Medicine, University of Calgary, Calgary, Alberta, Canada (Clement).

*Correspondence to: Aaron Goodarzi, A.Goodarzi@ucalgary.ca

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ABSTRACT

Background: Radon (^{222}Rn) gas is a naturally occurring radioactive isotope arising from uranium decay in soil and bedrock, escaping and often concentrating in indoor air. Radon undergoes radioactive disintegration, precipitating as solid radioisotopes and emitting cancer-causing alpha particles. The inhalation of radon exposes lung tissue to alpha particle bombardment, a highly mutagenic form of ionizing radiation that damages DNA and increases the lifetime risk of lung cancer by 16% per 100 Bq/m^3. **Methods:** In this study, we analyzed household radon concentrations and risk factors in the greater metropolitan area of Calgary, the 3rd largest Canadian metropolis. **Results:** 2,382 households were tested between 2013-2016, with an average indoor air reading of 126 Bq/m^3 radon, equating to an effective absorbed radiation dose of 3.2 mSv/yr. 48% of households were ≥100 Bq/m^3 and 12.4% were ≥200 Bq/m^3, with homes measuring as low as <15 Bq/m^3 and as high as 3,441 Bq/m^3. Maximum observed radon concentrations were 3-fold higher in properties built in the past 25 years compared to older homes, suggesting that modern building practices are increasing indoor air radon accumulation. Health economic analysis suggest that lung cancers associated with high indoor radon levels cost the regional economy $17 million annually in direct and indirect medical costs. **Interpretation:** This work demonstrates that radon is a genuine public health concern in Southern Alberta, legitimizes efforts to understand the consequences of radon exposure to the public, and suggest that radon testing and mitigation is likely to be an impactful cancer prevention strategy.

KEYWORDS:
Radon, Radiation, Cancer, Air Quality, Lung Cancer, Calgary, Alberta, Canada, Building Practice, Home Age, Home Size, Alpha Particle, DNA damage

INTRODUCTION

Radon (^{222}Rn) gas is formed naturally by the radioactive decay of radium, thorium and uranium-bearing soils and bedrocks, and is prevalent in the North American Prairies. Radon gas permeates under high pressure through the soil towards low or negative pressure areas such as basements and cellars. In winter, radon is actively drawn up as homes are heated and thermal stack effects (hot air rises) generates pressure differentials that draw upon foundations. Poorly-ventilated and well-insulated homes can experience profound radon buildup. Radon inhalation is the single greatest source of lifetime radiation exposure[1] and is estimated to be responsible for 2% of all cancer deaths[2]. High radon also correlates with increased rates of myeloid leukemia, melanoma, kidney cancers and certain childhood cancers[3,4]. Atomic ^{222}Rn has a half-life of 3.8 days, with 50% decaying in that time to solid radioactive polonium and emitting alpha (α) particle radiation, which is, dose-for-dose, substantially more dangerous to health than x- or γ-rays[5,6]. Radon decay within lungs leads to α-particle bombardment of tissue and precipitation of solid polonium within lung mucosal linings. These decay products emit another 3x α-particles and 2x $\beta-$particles before becoming solid ^{210}Pb (Lead). Precipitated polonium attached to household dust can also be inhaled[3]. Alpha particles carry enough energy to dislodge electrons from other molecules, leading to ionization. Human DNA is easily ionized by α-particles, and will break apart as they travel through tissue, generating difficult-to-repair DNA damage that has a significantly higher dose effect than γ-rays[5-7]. DNA damage leads to genetic mutation that increases cancer risks with each new α-particle emission.

Radiation is measured in Becquerels (Bq) that equal one radioactive decay event per second. Radon concentrations in air are captured as Bq/m^3 with 100 Bq/m^3 increasing lifetime lung cancer risk by 16%[8]. Health Canada indicates that 200 Bq/m^3 represents the maximum acceptable amount before certain and serious health risks. For context, a year of inhaling 200 Bq/m^3 radon is the radiation exposure equivalent of 500 dental x-rays. Anyone chronically inhaling radon gas between age 0-65 is at risk of lung cancer in their lifetime, with children and teens most at risk[2,9-11]. Globally, 25% of lung cancer patients are non-smokers, with most cases in developed countries caused directly by radon inhalation in homes and workplaces[12-14]. 2,150

Albertans are diagnosed with lung cancer yearly, with mortality at 1,610 deaths/year. Cancer prevention is preferable to the physical, emotional, social and economic cost of cancer diagnosis and therapy. In the case of radon, exposure is uncomplicated by addiction and prevention represents an effective way to reduce cancer burden. Motivated by this, our objective was to measure household radon levels and correlate these with home metrics in the greater Calgary metropolitan area, the third most populous urban area in Canada.

METHODS

DATA COLLECTION - From October 2013 to January 2016, ~3,000 homeowners in the greater metropolitan area of Calgary purchased 'alpha track' radon detectors ($45/unit) as part of a study entitled the "Citizen Scientist Radon Testing Project". Outreach to the general public was achieved through print, online and TV/radio media. Participants consented to long term average radon readings and home metrics to be provided to researchers in a semi-anonymous manner, with data only associated with their postal region. The survey collected foundation type, construction year and room of deployment. 80% tests (n = 2,382) were returned and eligible for analysis. The remaining tests were either not deployed during the appropriate testing window or, for a small minority, spoiled by homeowner error. Rigorous care was taken to educate participants in the correct test deployment methods through personal communication with C-NRPP (*Canadian National Radon Protection Program*)-certified professionals, online video demonstrations and phone-calls. Radon tests were closed passive etched track detectors made from CR-39 plastic film inside an antistatic holder (Radtrak2, Landauer Radon, Inc., Glenwood, IL, USA) and enclosed in housing composed of electrically conductive material with filtered openings to permit gas diffusion, with a typical linear range of 15 Bq/m^3 to 25,000 Bq/m^3. To be read, CR-39's are etched in 5.5N NaOH at 70°C for 15.5 min and counted automatically using TrackEtch® software at Landauer laboratories in the USA (ISO 17025 certified). Labs and detectors are C-NRPP accredited to carry out alpha track device analysis. Controls submitted to the lab included duplicates to ensure device reproducibility, spiked positives (to ensure accuracy) and non-deployed negatives (controlling for transport and storage prior to analysis). All readings were calculated in Bq/m^3 rounded to the nearest whole number and are represented as such throughout this study. The 'greater metropolitan area' of Calgary, included the entire City of Calgary and towns/hamlets of Cochrane, Okotoks, Airdrie, Canmore, Bragg Creek, Chestermere, High River, De Winton, Redwood Meadows and surrounding rural 'municipal districts'. There were a total of 2,018 homes within Calgary city limits and 364 in surrounding townships. Commercial buildings, apartment blocks and mobile homes were excluded. Single Family detached homes represented the overwhelming majority of properties tested (n = 1,819). The median test duration was 103 days and >99.5% of were deployed from October-April, as recommended by national and international agencies.

RESULTS

OVERALL HOUSEHOLD RADON LEVELS IN THE CALGARY METROPOLITAN AREA - The indoor air radon levels for each home, grouped by postal code district, are shown in ***Figure 1***. The average reading across all tests in the region was 126 Bq/m^3, with a minimum reading of <15 Bq/m^3 and maximum of 3,441 Bq/m^3. ***Figure 2*** shows a map of radon readings by geographical subdivision. While some regions trended slightly higher on average than others, there were no areas with uniformly low household radon levels. All areas monitored contained homes with high radon well above the national action level. The townships of Cochrane and Okotoks/High River displayed highest average household radon readings, at 261 Bq/m^3 for Cochrane and 194 Bq/m^3 for Okotoks/High River. The City of Calgary itself averaged at 122 Bq/m^3, ranging from 72-164 Bq/m^3 between smaller districts within city limits. These variances are relatively small, and we conclude that since exceptionally high radon readings have been observed all across the region, there are no guaranteed 'safe' areas and all neighborhoods are potentially at risk.

RELATIVE RISKS COMPARED TO CANADIAN AVERAGES - The *Cross-Canada Survey of Radon Concentrations in Homes*[15], most recently updated in 2012, determined that 6.9% of all Canadian homes exceeded 200 Bq/m^3. For the Calgary Health Region, based on a sample size of 86 homes that survey indicated that 8.1% of homes exceeded 200 Bq/m^3, with no homes exceeding 600 Bq/m^3. Our data, based on 2,382 readings in the same region, reveals that 12.4% of homes are ≥200 Bq/m^3 with 1% of homes ≥600 Bq/m^3. The percentage of homes exceeding 200 Bq/m^3 in townships surrounding Calgary is greater, at 17% on average, with Okotoks/High River (27%) and Cochrane (25%) being the highest. This indicates that Southern Albertan homes contain radon levels far higher than Canada as a whole, bringing the percentage of Albertan homes ≥200 Bq/m^3 in line with estimates for Manitoba (19%) and Saskatchewan (9%)[15]. The 2015 population of the City of Calgary was 1.23 million, with ~200,000 people in surrounding townships. Census data estimates this area to contain 463,682 single family residences and, so, the 12.4% of homes exceeding 200 Bq/m^3 equates with ~57,500 homes or, taking into account the average occupants per household (2.6), roughly 150,000 residents - a substantial population whose lifetime risk of lung cancer is increased by an avoidable health risk. This also indicates that the percentage of population at risk from radon (12.4%) is comparable to those at risk of tobacco-related cancer, as smoking rates in Alberta are 19%[16].

RADON LEVELS BY HOME AGE AND ENGINEERING FEATURES - The home metrics survey distributed with detectors allowed us to examine factors that associated with high radon levels (***Table 1***). The strongest correlation was with date of home construction, with newer homes trending towards higher readings. An independent-sample t-test indicated that radon levels were higher in houses built in the last 25 years (mean 142 Bq/m^3, n=995) than homes built before 1992 (mean 108 Bq/m^3, n=1,134), with a statistically significant difference of 34 Bq/m^3± 7[mean ± standard error], $t(2127) = 4.9$, $p<0.001$. One way ANOVAs were carried out to test for potential associations between home metrics and radon readings, unreported sets were excluded. Based on Bonferroni post-hoc testing, tests carried out in basements demonstrated significantly ($p \leq 0.001$) higher radon vs those conducted at ground or 1st floors; tests carried out in utility spaces were also more like to be higher compared to living spaces ($p<0.001$) (***Figure 3***). This suggests that individuals occupying basement-suites (common practice in the region) are especially at risk.

Figure 4A shows all homes across the region measuring ≥200 Bq/m^3 separated into those built within the past 25 years (1992-2016) and earlier (1890-1991). A striking increase in the maximum observed radon levels is evident for newer homes, suggesting that millennial building, insulation and/or ventilation practices are creating indoor air environments that accumulate radon to higher levels compared to homes built through most of the 20th century. This could be due to:

(i) ***Energy-efficient home insulation*** practices have improved substantially in the past 25 years, reducing heat-loss but also suppressing overall indoor and outdoor air exchange. Indeed, increasing the air-tightness increases home mean radon concentrations by 56.6%[17]. In newer homes with the energy efficient insulation and no additional ventilation to compensate, maximum radon levels are expected to rise to substantially higher levels.

(ii) ***Home floor plan sizes*** in Canada have steadily increased over time. Since concrete contracts as it dries in a fixed ratio with the overall size of the slab being poured[18,19], larger floor plans equate with a greater net shrinkage around the perimeter and, consequently, a larger floor-to-foundation gaps, enabling more radon to enter. This is likely exacerbated by the fact that the overall concrete shrinkage has increased significantly in the past 25 years, reportedly due to a scarcity of good quality aggregates and subsequent use of recycled aggregates and higher mineral additives (such as fly ash)[20]. An unbiased survey of 1,632 Calgary metropolitan area homes listed for sale in the summer of 2016 demonstrates that average floor plans have doubled over the past 65 years (***Figure 4B-C***). Plotting reported home ft^2 values by construction year indicates a clear trend towards larger floor plans, with those built from 1992-2016 being an average 2,384.9 ft^2 (n = 914 homes), 51% (806 ft^2) larger than homes built in the previous 90 years (1,578.9 ft^2 on average, n = 725).

(iii) ***Ceiling height and the number of floors*** in homes has also increased over time, with vaulted two-story ceilings and three-level homes becoming the norm in the region in the past 25 years. Loftier homes, just like tall chimneys, demonstrate greater thermal stacking and pull air from lower levels with exceptional power. Roof-top vents and open upper-floor windows will exacerbate this effect, especially if lower floor vents, windows and doors are obstructed or closed, leading to poor air-intake. Heating tall homes creates more potent thermal stack effects generating powerful negative pressures at basement level that draw up ever more soil gas (radon) into the indoor air.

INDOOR RADON LEVELS PRE- AND POST-MITIGATION - We also collected data from households that were ≥200 Bq/m^3 and opted for mitigation, to understand how effective these procedures are at reducing radon in the region (***Figure 5)***. Most mitigations involved sub-slab depressurization, with a minority utilizing radon-impermeable membrane installation. Of 90 homes averaging 575 Bq/m^3 before mitigation, radon suppression successfully reduced levels to an average of 32.5 Bq/m^3 (max = 88 Bq/m^3; min = 7 Bq/m^3). The most striking case was the home at 3,441 Bq/m^3 that was successfully reduced to 86 Bq/m^3 – a 97.5% reduction. When viewed by percentages, mitigation typically achieved a 92% radon reduction. Thus, we conclude that for the greater Calgary metropolitan area, radon mitigation is generally extremely effective. We speculate that this is due to the porous gravel that lies beneath most homes in the region, enabling soil gas flow across foundations to mitigation devices. It is worth noting that homes that rest upon less permeable, compacted clay may not be so amenable to radon mitigation.

THE ECONOMIC COST OF RADON - Radon is an avoidable cause of a cancer type with serious economic consequences to health care systems, individuals and society. 2,150 new cases of lung cancer are diagnosed annually in Alberta and ~358 of those are never-smokers whose tumors are thought to be overwhelmingly attributed to radon. This is a conservative estimate, as some smoking-related cancers may also be attributed or worsened by radon exposure. The direct costs paid by the healthcare system for one case of lung cancer in Alberta are estimated to be $24,055/person[21]. Hence, the total direct cost of radon-induced lung cancer in Alberta is approximately $8,600,000/yr. Indirect costs of lung cancer in Alberta are unknown; however, other studies have estimated that, including lost productivity, informal care-giving and other costs borne outside the healthcare system, indirect costs are at least as much as direct costs[22]. Hence, when these are factored in, then total costs of radon-induced lung cancer to Alberta are estimated to be at least $17 million per year. If one also takes into account local annual inflation rate of 1-2% across a 10 year period[23], then universal radon protection has the potential in a decade to return $177-186 million to provincial economy, with $89-93 million being returned directly to the healthcare system.

INTERPRETATION

STRENGTHS and LIMITATIONS - This work represents one of the largest municipal studies of household radon in Canadian history, and has analyzed household radon levels not only by region (the historic norm for previous work[15]) but correlates radon levels with specific Canadian-built home metrics. While our data has statistical power with >2,000 data points within the city limits of Calgary, one limitation of our work we only have 364 data points in the surrounding smaller communities, and those areas will require further surveying in the future to improve the power of our findings. For some of the self-reported home metric data points within our survey, we fell short of 100% response rate, with an average 89% (lowest 85%) of desired information returned. Our work focused entirely on residences of a non-commercial nature and, in future years, it will be important to expand this analysis to encompass daycares, workplaces, etc. Nevertheless, our work represents the first major systematic examination of radon with community-level resolution for a major Canadian city.

RADON and RADIATION DOSAGES - In this study, we report radon concentrations in Bq/m^3, a measure of radioactive decay events. However, absorbed radioactive energy dose is measured typically by the Sievert (Sv), a weighted measure of radiation absorption by tissue, and factors in radiation quality and relative health risk. The ICRP (*International Commission on Radiological Protection*) uses an epidemiological approach to estimate radon exposure effects using risk estimates from uranium miner and A-bomb survivor studies. Based on this, 100 Bq/m^3 radon equates with 1.72 mSv/yr[24]. Other complex models take into account physical factors such as radon decay product exposure and physiological factors such as breathing. According to UNSCEAR (*United Nations Scientific Committee on the Effects of Atomic Radiation*) 100 Bq/m^3 equates to a 2.5 mSv/yr dose absorbed by adult lungs[25]. If we apply these to our most extreme case (3,441 Bq/m^3), occupants of that household received 59.2 mSv (ICRP model) to 86 mSv (UNSCEAR model) of α-radiation per year, equivalent to 6,000 dental x-rays and exceeding Canadian maximum limit for nuclear energy workers (100 mSv in 5 years) in 14-20 months.

***RADON and RADIATION QUALITY* -** Radiation 'quality' is also important to consider as α-particles are much more densely ionizing versus x-rays. Established systems[7] to estimate biological effects of different radiation qualities weight electromagnetic radiation (such as X-rays, γ-rays) as 1X dose equivalent and particle radiation (i.e. α-particles) at 20X. Radiobiologists estimate that 50 mSv of ionizing radiation produces approximately one DNA double-strand break (DSB) per cell, an event capable of shearing entire chromosomes and promoting cancer-causing mutations. A typical pair of adult human lungs is lined by 56 billion alveolar type I/II cells and 68 billion epithelial cells, the cells most exposed to radon[26]. If we consider an indoor air radon level of 200 Bq/m^3, equivalent to 3.44 mSv/yr using the *most conservative* estimate discussed above, then that equates with approximately 1 DSB for every 15 cells or, when on the scale of all lung alveoli cells, at least 7.36 billion DSBs per person. Even assuming that 90% of DSBs are repaired without causing genetic errors, then that means a minimum of 736 million genetic mutations per lung will occur per year in a person inhaling 200 Bq/m^3 radon. Thus, it is easy to see how, biologically, the difference between 199 Bq/m^3 and 200 Bq/m^3 is insignificant. Decisions as to whether or not to mitigate a home should be based on the principle of reducing radon to as low as reasonably achievable and the public should be wary of overvaluing somewhat arbitrary administrative action levels, as should policy makers be wary of overusing them.

CONCLUSION

Southern Alberta is a region of high geologic radon potential and home to ~1.4 million people, including Calgary, the 3rd largest Canadian census district[27]. Approximately 2,000 Albertans are diagnosed with lung cancer annually and 1 in 4 diagnoses are in never-smokers[12,28]. We demonstrate that 48% of 2,382 of greater Calgary metropolitan area homes contain indoor air radon above 100 Bq/m^3; 12.4% exceeded 200 Bq/m^3, the maximum acceptable limit and recommended action level in Canada. Homes built in the past 25 years have significantly higher radon compared to older homes. This study shows that radon – an established and potent carcinogen – is of genuine concern in Southern Alberta, and legitimatizes efforts to understand the consequences of exposure to public health. Our findings suggest that radon awareness, testing and mitigation is likely to be an impactful cancer prevention strategy.

FIGURE and TABLE LEGENDS

Figure 1. Indoor air radon concentrations by postal code district in the greater Calgary metropolitan area. 2,382 individual home readings for indoor air radon are grouped by the first three digits of Canadian postal code. Darker coloured circles indicate multiple overlapping radon readings. High radon concentrations are documented almost universally across the region. (1.Airdrie East, 2.Canmore, 3.Central Foothills, 4.Cochrane, 5. High River, 6. Kananaskis Improvement District, 7. Okotoks, 8. Redwood Meadows, 9. Chestermere, 10. Symons Valley.

Figure 2. Average indoor air radon concentrations by subdivision of the greater Calgary metropolitan area. The percentage of homes between 0-100 Bq/m^3, 100-200 Bq/m^3 or >200 Bq/m^3 for the four quadrants of Calgary and the surrounding towns, including number of homes tested in each region. Max = maximum observed radon reading in area; Min = minimum observed radon reading in area. In all cases, homes well above the maximum acceptable limit (200 Bq/m^3) for Canada are documented.

Figure 3. Average indoor air radon concentrations by home features. Box plots showing min/max spread and mean of indoor air radon tests within home descriptor groupings (*$p \leq 0.001$, Bonferroni Post hoc testing on one-way ANOVAs).

Figure 4. Maximum observed household air radon concentrations are significantly higher in homes built in the past 25 years. (A) Indoor air radon measured in homes built between 1992 and 2016 versus 1991 and earlier. (B) The reported square footage of homes constructed between 1945 and 2016. (C) Average home square footages across decades.

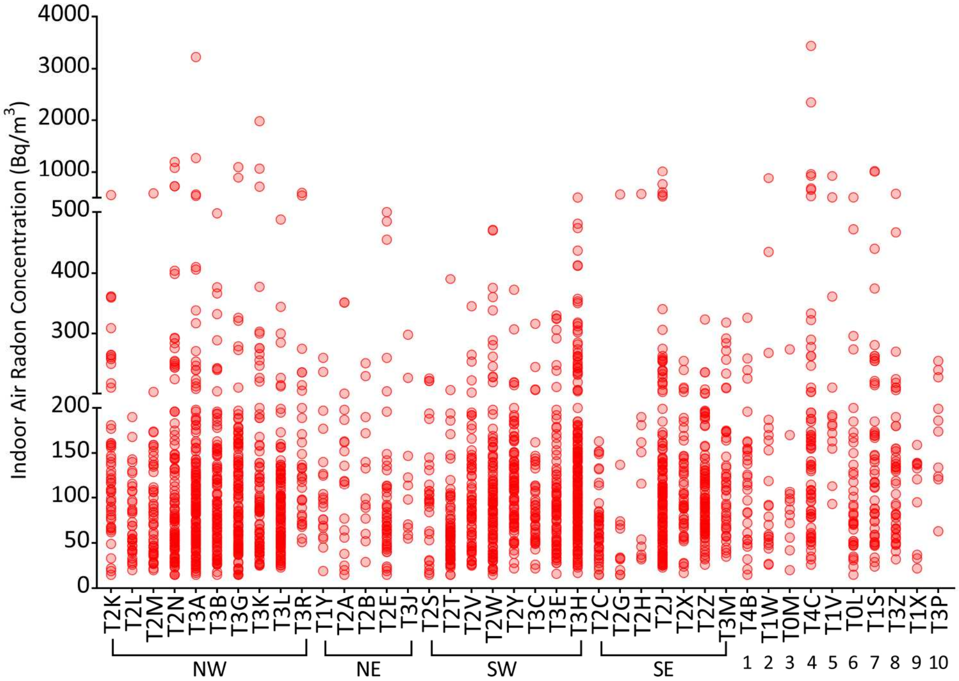
Figure 5. Pre- and post-mitigation household air radon concentrations for all homes initially measuring ≥200 Bq/m^3. Red bars indicate radon levels prior to mitigation. Blue bars are the corresponding post-mitigation radon level for that same household.

Table1: Radon levels by home metrics. 2,382 household air radon readings grouped according to reported building metrics with average indoor air radon concentrations, error of the mean, and range.

REFERENCES

1. Schauer DA & Linton OW. NCRP Report No. 160, Ionizing Radiation Exposure of the Population of the United States, medical exposure--are we doing less with more, and is there a role for health physicists? *Health Phys* **97**, 1-5 (2009).
2. Darby S, Hill D, Auvinen A et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *Brit. Med. J.* **330**, 223 (2005).
3. Henshaw DL, Eatough JP & Richardson RB. Radon as a causative factor in induction of myeloid leukaemia and other cancers. *Lancet* **335**, 1008-12 (1990).
4. Marsh JW & Bailey MR. A review of lung-to-blood absorption rates for radon progeny. *Radiat Prot Dosimetry* **157**, 499-514 (2013).
5. Edwards AA, Purrott RJ, Prosser JS et al. The induction of chromosome aberrations in human lymphocytes by alpha-radiation. *Int J Radiat Biol Relat Stud Phys Chem Med* **38**, 83-91 (1980).
6. Little JB, Kennedy AR & McGandy RB. Effect of dose rate on the induction of experimental lung cancer in hamsters by alpha radiation. *Radiat Res* **103**, 293-9 (1985).
7. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP* **37**, 1-332 (2007).
8. World Health Organization. *WHO handbook on indoor radon : a public health perspective*, xiv, 94 p. (World Health Organization, Geneva, Switzerland, 2009).
9. Lubin JH, Boice JD, Jr., Edling C et al. Lung cancer in radon-exposed miners and estimation of risk from indoor exposure. *J Natl Cancer Inst* **87**, 817-27 (1995).
10. Krewski D, Lubin JH, Zielinski JM et al. Residential radon and risk of lung cancer: a combined analysis of 7 North American case-control studies. *Epidemiology* **16**, 137-45 (2005).
11. Chen J. Canadian lung cancer relative risk from radon exposure for short periods in childhood compared to a lifetime. *Int J Environ Res Public Health* **10**, 1916-26 (2013).
12. Parkin DM, Bray F, Ferlay J et al. Global cancer statistics, 2002. *CA Cancer J Clin* **55**, 74-108 (2005).
13. Darby S, Hill D, Deo H et al. Residential radon and lung cancer--detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand J Work Environ Health* **32 Suppl 1**, 1-83 (2006).
14. Chen J. A Review of Radon Doses. *Radiation Protection Management* **22**, 27-31 (2005).
15. Health Canada. *Cross-Canada Survey of Radon Concentrations in Homes - Final Report*, 29 (Government of Canada, Ottawa, Ontario, 2012).
16. Health Indicators. in *CANSIM* Vol. 82-221-X (ed. StatsCan) (Government of Canada, 2016).
17. Milner J, Shrubsole C, Das P et al. Home energy efficiency and radon related risk of lung cancer: modelling study. *Brit. Med. J.* **348**, f7493 (2014).

18. Videla CC, Carreira DJ, Garner NJ et al. Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete. Vol. ACI 209.2R-08 (American Concrete Institute, Farmington Hills, MI, 2008).
19. Gilbert RI. Shrinkage, Cracking and Deflection-the Serviceability of Concrete Structures. *Electronic Journal of Structural Engineering* **1**, 2-14 (2001).
20. Silva RV, deBrito J & Dhir RK. Prediction of the shrinkage behavior of recycled aggregate concrete: A review. *Construction and Building Materials* **77**, 327-339 (2015).
21. Low dose computed tomography for the screening of lung cancer in adults. (Institute of Health Economics Edmonton AB, 2014).
22. Smetanin P, Stiff, D., Briante, C., Ahmad, S., Wong, L., and Ler, A. Life and Economic Burden of Lung Disease in Ontario: 2011 to 2041. . in *Risk Analytics, on behalf of the Ontario Lung Association* (2011).
23. Consumer Price Index, historical summary (1996 to 2015). in *CANSIM* Vol. 62-001-X and 62-010-X (ed. StatsCan) (Government of Canada, 2015).
24. Protection against radon-222 at home and at work. A report of a task group of the International Commission on Radiological Protection. *Ann ICRP* **23**, 1-45 (1993).
25. UNSCEAR. Effects of Atomic Radiation in *UNSCEAR 2000 Report to the General Assembly* Vol. I (2000).
26. Crapo JD, Barry BE, Gehr P et al. Cell number and cell characteristics of the normal human lung. *Am Rev Respir Dis* **126**, 332-7 (1982).
27. Census Profile - Census Program. in *2011 Census* Vol. Statistics Canada Catalogue no. 98-316-XWE. (ed. StatsCan) (Government of Canada, 2012).
28. 2012 Report on Cancer Statistics in Alberta. (Alberta Health Services Surveillance & Reporting, Edmonton AB, 2012).



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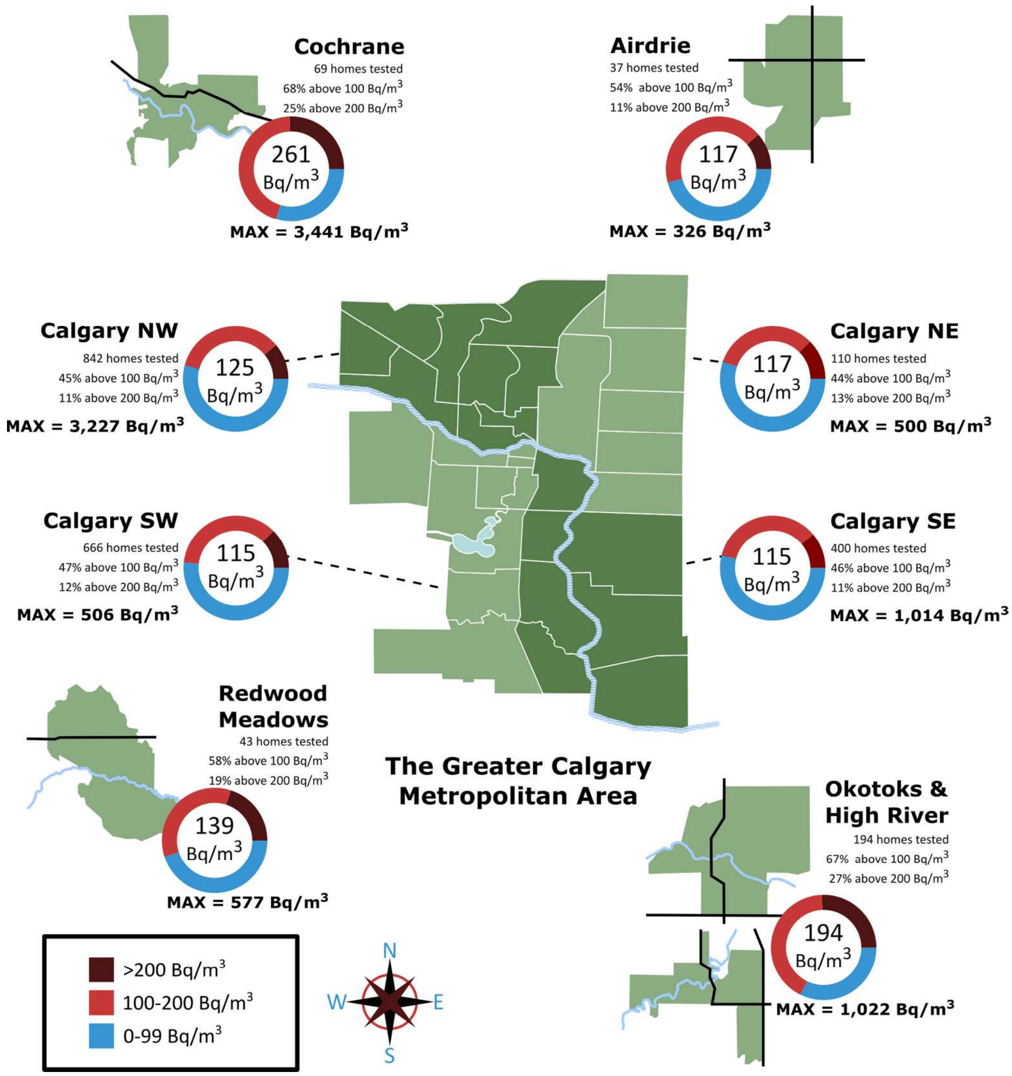

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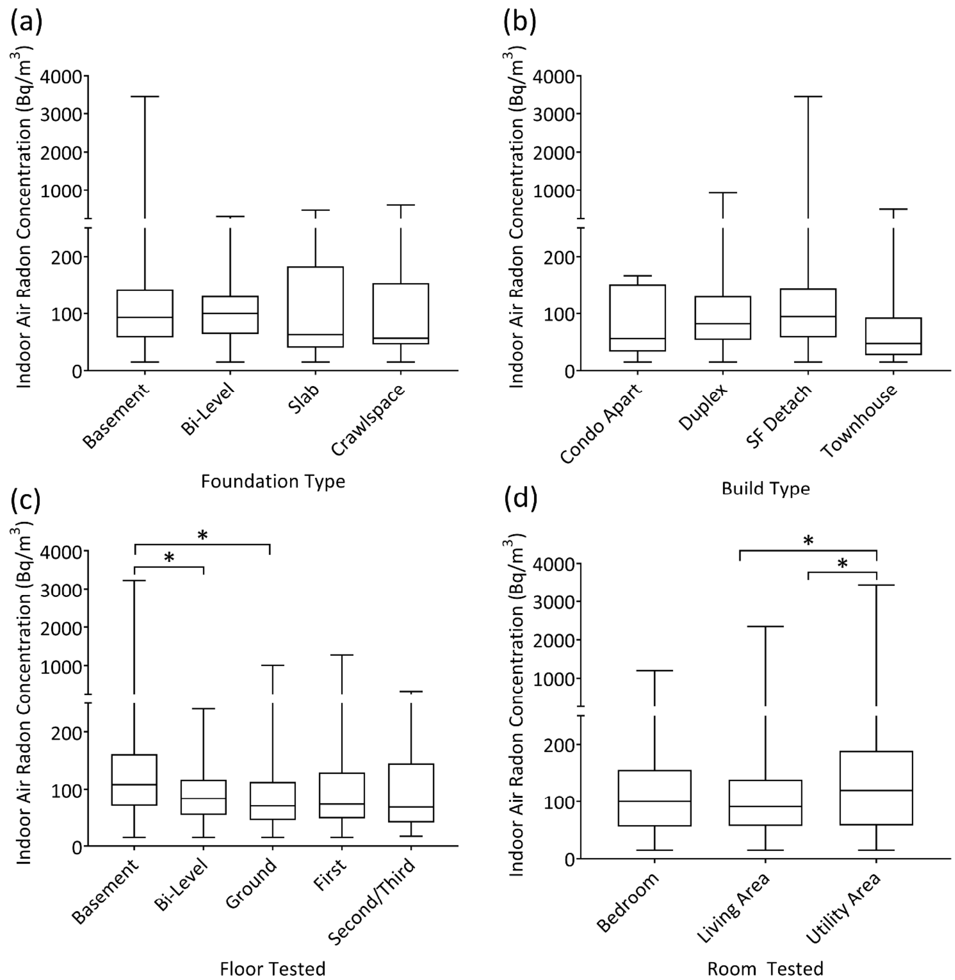

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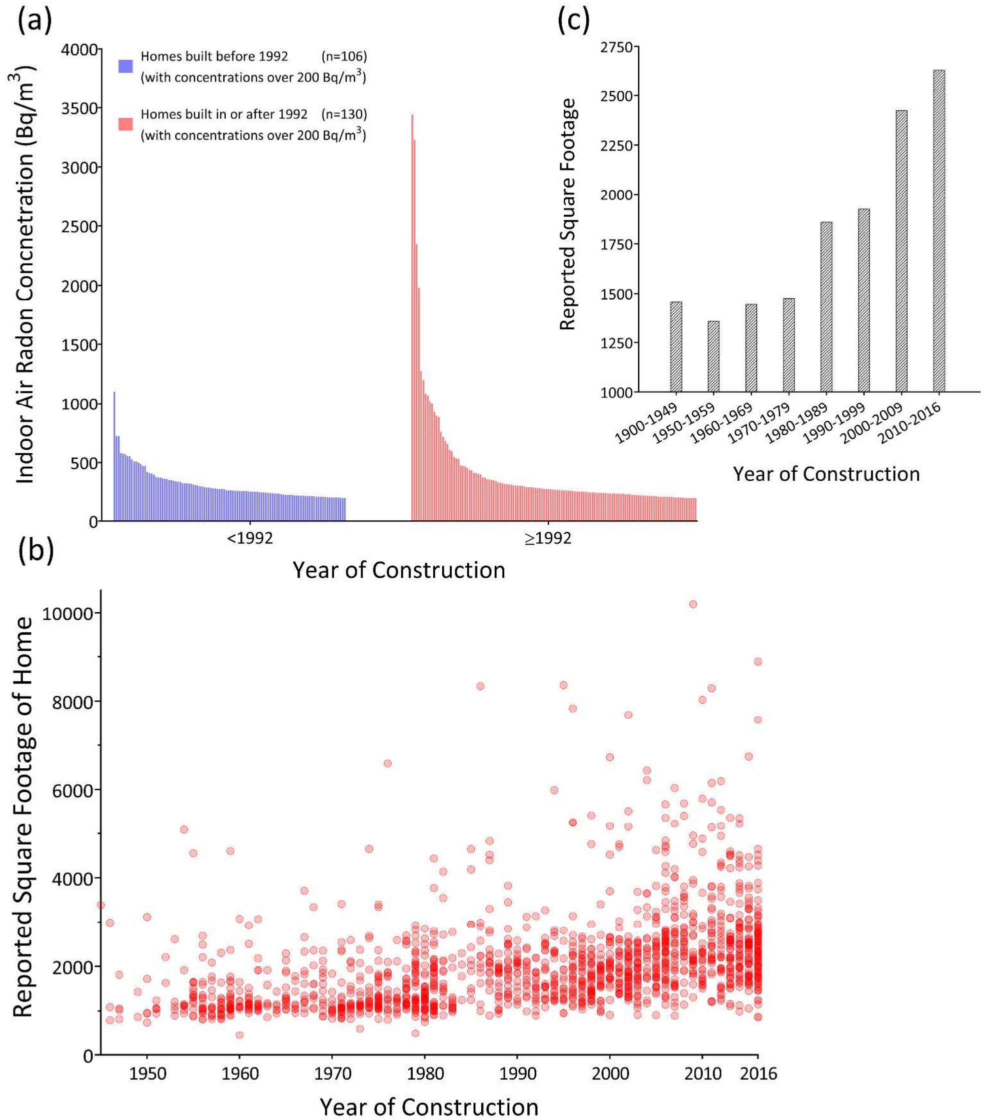

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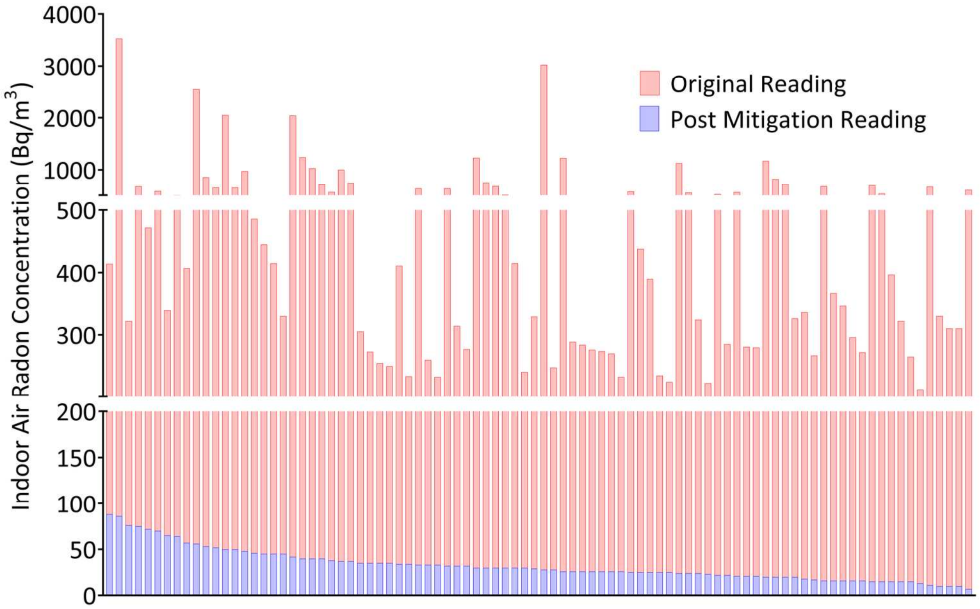

Figure 5. Pre- and post-mitigation household air radon concentrations for all homes initially measuring ≥200 Bq/m3. Red bars indicate radon levels prior to mitigation. Blue bars are the corresponding post-mitigation radon level for that same household.

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HOME ENGINEERING METRIC	NUMBER OF HOMES REPORTING	AVERAGE RADON LEVEL (Bq/M^3)	STD. ERROR OF MEAN	MIN.OBS. RADON LEVEL (Bq/M^3)	MAX.OBS. RADON LEVEL (Bq/M^3)
TOTAL	2382	126	± 3	<15	3441
AGE OF HOME					
1890-1990	1100	108	± 3	<15	1100
1991-2016	1029	140	± 7	<15	3441
BUILD					
CONDO/APAR	12	81	± 17	<15	167
SF DETACH	1819	126	± 4	<15	3441
DUPLEX	113	108	± 10	<15	925
TOWNHOUSE	50	76	± 12	<15	498
UNREPORTED	388	136	± 6	<15	1014
FOUNDATION					
BASEMENT	1973	125	± 4	<15	3441
SLAB	28	120	± 21	<15	472
BI-LEVEL	89	106	± 6	<15	309
CRAWL SPACE	30	95	± 20	<15	607
UNREPORTED	262	144	± 8	<15	1014
FLOOR					
BASEMENT	1360	137	± 4	<15	3227
BI-LEVEL	58	91	± 6	<15	240
GROUND	485	62	± 4	<15	1005
FIRST	246	101	± 7	<15	1274
SECOND/THRD	31	92	± 13	17	326
UNREPORTED	202	176	± 22	17	3441
ROOM					
BEDROOM	282	125	± 7	<15	1198
LIVING SPACE	1740	117	± 3	<15	2346
UTILITY SPACE	105	224	± 48	<15	3441
UNREPORTED	255	147	± 8	<15	1014

Table1: Radon levels by home metrics. 2,382 household air radon readings grouped according to reported building metrics with average indoor air radon concentrations, error of the mean, and range.