

INDOOR AND OUTDOOR RADON CONCENTRATION LEVELS IN LEBANON

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Abstract—Lebanon's lung cancer rates, among the highest in the Arab region, contribute to the burden of noncommunicable diseases. A number of studies have shown that lung cancer risk increases when smokers vs. nonsmokers exposed to elevated radon levels are compared. This research employs indoor and outdoor space and time concentration surveys across Lebanon, where the smoking rate among the population is among the highest in the world. The distributional properties of measured radon concentration were shown to be lognormal with median indoor and outdoor concentrations of 17 and 10 Bq m⁻³, respectively. Standard deviation for indoor concentrations was 1.2 times smaller than its outdoor counterpart, suggesting that weather-related patterns affect outdoor radon concentration variability. No significant spatial association was detected across seasons for indoor and outdoor radon concentrations. Geographical location, proximity to faults, and housing construction material had no significant impact on outdoor and indoor radon concentration variations. When lognormal distributions were used to determine exceedance probability of the recommended reference radon concentration, they were smaller than 0.1%. While exhibiting high seasonal variability, the study shows that radon does not appear to be a public health concern in Lebanon.

Health Phys. 115(3):344–353; 2018

Key words: E-PERM; indoor radon concentrations; outdoor radon concentrations; spatial association; seasonal variation; Lebanon

INTRODUCTION

LEBANON'S LUNG cancer rate is about 33 per 100,000 for men and 15.5 per 100,000 for women (Ministry of Public Health 2011), which is 1.3 times higher than the rate for men (26 per

100,000) and twice the rate for women (7 per 100,000) in the eastern Mediterranean region (GLOBOCAN 2012). These rates contribute to the high burden of noncommunicable diseases in the country. Determining the chain of causality for such high cancer rates is a complex undertaking requiring long-term and expensive studies to examine the interplay between behavioral, social, and environmental factors. To explore concentrations of certain carcinogenic agents so as to confirm or exclude their possible contributions to these high cancer rates, space and time concentration surveys become necessary. Here, indoor and outdoor radon concentrations, a well-known carcinogen as classified by the International Agency for Research on Cancer (IARC 1988), are measured across Lebanon for the first time with the goal of establishing a baseline level and quantifying the causes of its variations.

Globally, radon is considered an important cause of lung cancer after smoking. A number of studies reviewed elsewhere (WHO 2009) have confirmed that even low concentrations of radon—as may be found indoors—contribute to lung cancer occurrence. The World Health Organization (WHO) estimates an increase in lung cancer of 16% per 100 Bq m⁻³ radon.

Other studies have also shown that lung cancer risk increases by some 25 fold when comparing smokers vs. non-smokers exposed to elevated radon levels irrespective of sex (Kim et al. 2016; Peterson et al. 2013). These findings suggest that elevated radon levels may disproportionately impact the population of Lebanon, where smoking is quite prevalent. In fact, adult smoking has been estimated at 38.5% in Lebanon and is on the increase among youth (Saade et al. 2008; Shamseddine et al. 2014). Hence, this indoor-outdoor radon study is warranted given the cancer and smoking rates in the Lebanese population.

After conducting the national sampling campaign, exceedance probabilities for the 300 Bq m⁻³ recommended reference level for radon concentration set by the International Commission on Radiological Protection (ICRP) in dwellings (ICRP 2009) are computed. Prior indoor sampling of radon in Lebanon was conducted in 2010, but the study focused on only one town and three villages in southern Lebanon (Kobeissi et al. 2014). The study reported that radon levels ranged from 30 to 120 Bq m⁻³. The goals of the

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The authors declare no conflicts of interest.

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(Manuscript accepted 11 March 2018)

0017-9078/18/0

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DOI: 10.1097/HP.0000000000000888

aforementioned study were to explore differences in radon concentration between various locations within dwelling areas with a focus on (1) ventilation patterns across the season, and (2) the presence of granite countertops in kitchens. The specific objectives here are to explore connections between indoor and outdoor radon concentrations in relation to seasonal variations, geographic locations, and living habits in Lebanon. The work here also aims at establishing baseline values and variations of radon concentration instead of offering the final word on indoor radon hazard assessment. To address these specific objectives, four hypotheses are framed and tested that consider whether geographical region, proximity to fault lines, construction material of houses, and seasonality explain the space and time variations in indoor and outdoor radon concentrations. To place these results in a broader context, the measurements reported here are compared to regions that share either geologic or climatological characteristics of Lebanon.

BACKGROUND INFORMATION

Ambient radon concentrations generally depend on two main factors: geological formations and meteorological conditions. Almost all the rock structures in Lebanon are sedimentary rocks, and most of these are pale limestone. Despite the vast thicknesses of the limestone layer, the variation in limestone types is rather limited and fine grained. The most varied sequence of sediments extends from Late Jurassic to the Middle Cretaceous and shows a considerable variety of limestone, sandstones, clays, and volcanic ashes. The igneous rocks are basaltic flows and intrusions of a variety of ages. The metamorphic rocks are confined to narrow bands around the edges of the intrusions (Dubertret 1945, 1975; Walley 1997). The Bekaa is full of deposits from many small rivers that prehistorically flowed from the rising Lebanon and Anti-Lebanon Mountains with more recent lake deposits occasionally above that. Basaltic rocks exist only in the extreme south and the extreme north. There exist many intrusions of different types in Lebanon (for example, volcanic ashes in limestone) so that the local geologic picture may be quite different from the general picture. While Lebanon's climate varies across the landform belts, most of the country has a Mediterranean climate characterized by warm, dry summers and cool, wet winters (Lebanese Meteorological Service 1966; Ministry of Environment 2011). The coastal plain is subtropical with a yearly rainfall of 900 mm. In the capital Beirut, the average summer temperature is around 27°C, and the average winter temperature is 14°C. In the Lebanon Mountains, temperatures decrease and precipitation increases with elevation with the higher altitudes receiving annual precipitation of over 1,200 mm including significant snow above 1,500 m. On the other hand, situated in the rain shadow of the Lebanon Mountains, the

Bekaa Valley and the Anti-Lebanon Mountains have hot, dry summers and cold winters with reduced rain anywhere from 200 mm to a maximum of 900 mm.

MATERIALS AND METHODS

Radon measurement device

Indoor and outdoor radon concentration measurements were carried out using a conventional electret passive environmental radon monitor (E-PERM) electret ion chamber (EIC) system manufactured by Rad Elec Inc., which is described elsewhere (Kotrappa et al. 1988, 1990). The E-PERM was found to be accurate, low cost, and convenient for long-term monitoring activities (Abdallah et al. 2007). The disadvantages of the E-PERM include the following: (1) radon concentrations require corrections for cosmic and terrestrial radiation background, and (2) the E-PERM system requires a surface free of dust and fibers, which can be problematic for some outdoor monitoring stations.

The radon concentration using the E-PERM is given by Kotrappa et al. (1990):

$$C = \left(\frac{V_1 - V_2}{T} \right) \times \frac{1}{CF} - b_R, \quad (1)$$

where V_1 and V_2 are the initial and final voltage readings at times t_1 and t_2 , $T = t_2 - t_1$ (d), b_R is the background gamma radiation (described later), and

$$CF = B + A \times MPV; \quad MPV = \frac{V_1 - V_2}{2}. \quad (2)$$

CF is a conversion factor with $A = 0.00125$ and $B = 1.5692$ (for concentration in Bq m^{-3}), and MPV is the mid-point voltage (V). The values of A and B are generic to all E-PERM systems and are taken from Kotrappa et al. (1990). The value of b_R was measured using a portable Eberline radiation monitor consisting of an E-600 meter and an SHP-270 compensated Geiger-Muller (GM) detector (Transcat, Rochester, NY, U.S.). The measured range of gamma radiation across all station locations and seasons varied from a minimum of 6.1 to a maximum of $12.2 \mu\text{R h}^{-1}$.⁵

Selection of measurement locations

Various countries have already carried out radon concentration surveys for public exposure purposes (UNSCEAR 2000). In some studies, the measurements were completed over a number of years (Oikawa et al. 2003), while in others, it was conducted over a period of 1 mo (Sarrou and Pashalidis 2003). These differences in sampling density and duration reflect inherent trade-offs between space and time. Denser spatial coverage in sampling comes at the

⁵Although *Health Physics* Journal policy requires the use of International System (SI) units, the instruments used in this work provide measurements only in traditional units, such as $\mu\text{R h}^{-1}$.

expense of shorter sampling durations and vice versa. With regard to the temporal dimension, precipitation and air temperature are out of phase with each other in this Mediterranean region; hence, it was deemed appropriate to divide the year into three seasons: warm (above mean annual) and low (below mean annual) precipitation, cold (below mean annual) and high (above mean annual) precipitation, and a transition. Spring and autumn seasons are brief, and their manifestations are short lived. Hence, the concentration measurements were carried out nationwide with data categorized into (1) the cool and somewhat wet and unsettled autumn season, (2) the wet and relatively cold winter season, and (3) a combined spring and summer warm-to-hot season characterized by low rainfall.

In terms of the spatial dimension, indoor and outdoor sampling was conducted at 24 measurement locations as shown in Fig. 1 (panel a). These locations were selected by dividing the country into the six official administrative regions (or muhafazat) corresponding to: Beirut (B), Mount Lebanon (ML), north Lebanon (NL), south Lebanon (SL), Nabatiyeh (NB), and Bekaa Valley (BK). Within each region, at least three locations (numerical suffixes in Fig. 1) were chosen based on geological background, convenience of installation and security of the E-PERMs, habitation, altitude, and local information. In certain instances (e.g., BK1), the E-PERM station was not operational and as such data could not be reported in Table 1.

To reduce statistical error, two E-PERMs were used to measure radon concentrations concurrently at each location, and the reported radon concentrations are the arithmetic

means of the two E-PERM measurements. Indoor readings were taken by placing the E-PERM sufficiently above the ground and away from windows in an undisturbed location in the dwelling’s main living area. In many cases, especially in winter, this was an extended kitchen area; otherwise, it was a bedroom. For outdoor measurements in the immediate surroundings of the dwellings, the two E-PERMs were positioned at a height of 1 m from the ground surface under a fabricated wooden awning to protect them from rain and snow (Fig. 1 panel b). The sampling was conducted over a 2 y period commencing in September 2004. The sampling durations at each location ranged from 78 to 186 d. It is to be noted that 24 locations may be viewed as a sample size that does not provide coverage for the entire country. However, it is worth repeating here that these measurements were intended for long-term assessments and thus the aforementioned trade-off between space and time is necessary to adequately sample seasonality.

THE DATA SET

The radon concentration measurements (after averaging the two E-PERM per location) are summarized in Table 1. The overall range for the entire data set spanned two orders of magnitude (0.2 to 79.3 Bq m⁻³). In the following sections, causes of these variations are first addressed using the four hypotheses. Exceedance probabilities of safe radon concentration set by the ICRP (2009) are then calculated so as to

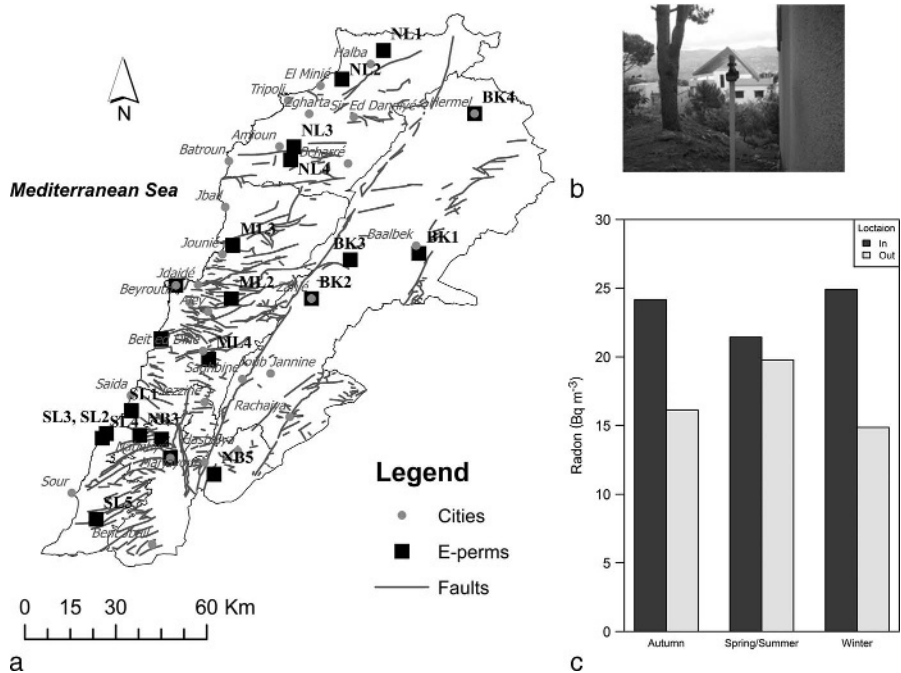


Fig. 1. Panel a: Map of Lebanon showing sites of homes where radon was measured—note the geological fault lines and major cities. Panel b: The E-PERM system placed under a protective canopy for outdoor radon measurement near a home in Mount Lebanon. Panel c: Averaged indoor and outdoor radon concentration by season.

Table 1. Outdoor and indoor air radon concentrations across Lebanon (Bq m^{-3}). Note that $1 \text{ pCi L}^{-1} = 37 \text{ Bq m}^{-3}$. The station map location (Fig. 1) of each point is also provided.^a

Location		Autumn		Winter		Spring/Summer	
		IN	OUT	IN	OUT	IN	OUT
Beirut							
Mar Elias	B1	6.88	11.12	4.17	0.15	27.09	19.13
Hamra	B2	79.26	3.73	n.a.	n.a.	n.a.	n.a.
Ashrafieh	B3	3.97	3.45	25.88	0.18	2.36	n.a.
Bekaa							
Zahle	BK2	16.46	6.33	8.42	12.45	47.48	20.49
Shmistar	BK3	13.37	5.28	n.a.	n.a.	n.a.	n.a.
Hermel	BK4	13.59	18.02	40.11	4.94	10.07	47.62
Mount Lebanon							
Damour	ML1	12.31	6.96	5.45	n.a.	24.52	12.27
Ras El Matn	ML2	10.37	1.97	10.25	6.21	8.56	28.13
Chnanir	ML3	n.a.	n.a.	22.03	6.17	12.89	11.37
Bakaata	ML4	72.41	22.77	n.a.	n.a.	36.23	33.84
North Lebanon							
Rihanieh	NL1	7.83	5.67	11.61	5.49	2.35	19.36
Bebnine	NL2	27.36	15.33	25.57	4.13	39.25	43.51
Kousba	NL3	64.01	9.54	17.44	42.22	9.85	13.70
Mitrite	NL4	n.a.	2.34	47.04	5.47	37.27	32.67
Nabatieh							
Nabatieh	NB1	31.76	19.82	52.36	66.33	25.42	19.39
Dawdieh	NB2	15.42	5.62	32.41	7.94	35.14	3.22
Zefta	NB3	25.00	33.12	28.70	21.49	25.42	25.03
Deir Zahrani	NB4	22.18	19.25	57.28	8.22	24.21	11.90
Khiam	NB5	22.18	19.25	4.57	14.72	2.99	17.59
South Lebanon							
Al Ghazieh	SL1	17.14	13.18	15.07	14.15	16.21	10.93
Kinnareat	SL2	13.18	57.03	23.12	9.35	12.84	4.87
Sarafand	SL3	13.57	27.39	15.75	11.37	6.65	9.08
Saksakieh	SL4	21.33	13.08	47.59	12.03	32.12	9.73
Shaatyeh	SL5	21.94	50.64	28.34	14.70	32.12	20.80

^an.a.: Not available; data from BK1 were not available.

assess whether radon is a potential contributor to the high cancer rates in Lebanon.

Data summary

Nationally, outdoor radon during the warm/hot season (spring/summer) ranged from a low of 3.2 to a high of 47.6 Bq m^{-3} , for the cool season (autumn) from 2.0 to 57.0 Bq m^{-3} , and in the cold season (winter) from 0.2 to 66.3 Bq m^{-3} . Indoor radon concentration ranged from 3.0 to 47.5 Bq m^{-3} in the warm/hot season, from 4.0 to 79.3 Bq m^{-3} in the cool season, and from 4.2 Bq m^{-3} to 57.3 Bq m^{-3} in the cold season.

The annual dwelling-averaged radon level in Lebanon was found to be 23.5 Bq m^{-3} . This value is comparable to

the levels in many countries with sedimentary-type soils such as the United Kingdom (20.5 Bq m^{-3}) and the Netherlands (29 Bq m^{-3}) and lower than values in nations with dominant granitic soils such as Finland (123 Bq m^{-3}) and the Czech Republic (140 Bq m^{-3}) (WHO/ENHIS 2009). The overall average indoor concentration (23.5 Bq m^{-3}) is also lower than the arithmetic mean of the distribution of worldwide indoor radon concentrations (40 Bq m^{-3}) (UNSCEAR 2000). However, the overall outdoor average concentration (16.4 Bq m^{-3}) is higher than the worldwide outdoor concentration of 10 Bq m^{-3} (UNSCEAR 2000). Both indoor and outdoor average radon concentrations remain significantly lower than the 300 Bq m^{-3} reference level for radon concentration adopted by the ICRP (2009). None of the indoor levels exceed 80 Bq m^{-3} , and none of the outdoor levels exceed 60 Bq m^{-3} . The national (i.e., all locations) averaged indoor levels per season were higher than their outdoor counterparts. Fig. 1 summarizes the average radon concentration in autumn, winter, and the spring/summer seasons. The average winter concentration indoors is highest, although the difference from other seasons is not large. Higher winter concentrations have been confirmed by other investigators (Bahtijari et al. 2006; Denman et al. 2007; Orgun et al. 2008; Papaefthymiou et al. 2003) and have several explanations, among which is less frequent ventilation in the winter due to colder weather. In relation to the data collected for south Lebanon (including the Nabatieh region) by Kobeissi et al. (2014), their indoor concentration ranged from 30–120 Bq m^{-3} in 2010 (including data from kitchens with granite countertops), which is on the upper end of indoor concentrations measured here that ranged from 3–53 Bq m^{-3} . However, both surveys agree that indoor radon concentrations in south Lebanon are well below the 300 Bq m^{-3} limit recommended by ICRP for dwellings (ICRP 2009).

Probabilistic structure of the radon concentration

When combining all data points sampled at all times and locations, the resulting probability density functions $p(x)$ for indoor or outdoor radon concentration (x) appears approximately lognormal as shown in Fig. 2, expressed as

$$p(x) = \frac{1}{x\sqrt{2\pi\sigma^2}} \exp\left(-\frac{[\ln(x)-\mu]^2}{2\sigma^2}\right), \quad (3)$$

where σ is the standard deviation and μ is the mean of the log-transformed variable. Similar lognormal distributions were reported in radon surveys (McLaughlin and Wasiolek 1988). Fig. 2 presents the empirically determined distributions along with the lognormal fit (using the method of moments) to all indoor and outdoor radon concentration measurements. The median for the indoor concentrations is 17.8 Bq m^{-3} , which is about 1.7 times larger than its

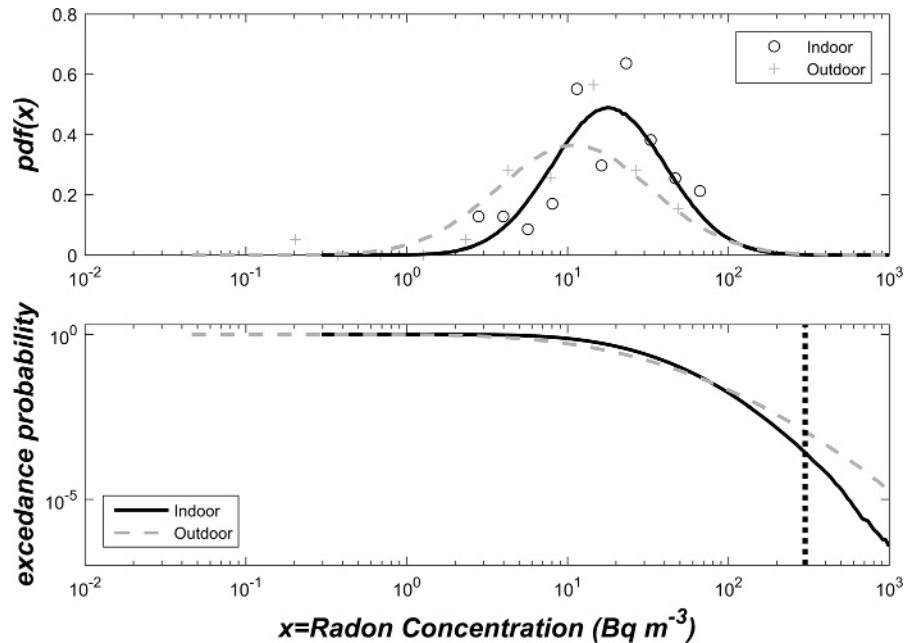


Fig. 2. Top: The measured (symbols) and the corresponding lognormal (lines) probability distribution function (pdf) fitted for indoor (open circles, black solid line) and outdoor (cross, grey dashed line) radon concentrations, using moment matching. Bottom: Computed exceedance probabilities derived from the lognormal model. The vertical dashed line is the 300 Bq m⁻³ concentration limit recommended by ICRP 103 (ICRP 2007).

outdoor counterpart (11.0 Bq m⁻³). The indoor standard deviation of the radon concentration (23.9 Bq m⁻³) is about 1.23 times smaller than its outdoor counterpart (30.5 Bq m⁻³). The fact that the standard deviation for outdoor radon concentrations is larger by some 23% than its indoor counterpart suggests that weather-related patterns are contributing to the large variability in outdoor radon concentrations.

The fitted lognormal distribution was then used to formulate exceedance probabilities. The exceedance probability can be computed from the cumulative lognormal distribution as shown in Fig. 2 along with the ICRP-recommended reference level of 300 Bq m⁻³ (bottom panel). Based on these lognormal extrapolations, ICRP exceedance probabilities for outdoor and indoor concentrations were both below 0.1%. Note here that the larger σ for outdoor concentrations (Fig. 2) leads to slightly higher exceedance probabilities for large radon concentrations (exceeding 50 Bq m⁻³) when compared to its indoor counterpart (less variable).

Because the lognormal distribution describes the radon concentration, log transformation of the radon concentration is employed for all statistical hypothesis testing unless stated otherwise.

Spatial structure of the radon concentration

The spatial variation of indoor and outdoor radon concentrations across the three seasons are shown in Fig. 3. Moran's I and Geary's C statistics are commonly employed to explore spatial association among samples. Moran's I and Geary's C statistics are given by Banerjee et al. (2004); Geary et al. (1954); and Moran (1950):

$$I = \frac{1}{\sum_i \sum_j \omega_{i,j}} \frac{\sum_i \sum_j \omega_{i,j} (c_i - \bar{c})(c_j - \bar{c})}{\tau^2} \quad (4)$$

$$C = \frac{1}{2 \sum_i \sum_j \omega_{i,j}} \frac{\sum_i \sum_j \omega_{i,j} (c_i - c_j)^2}{\tau^2} \quad (5)$$

where c_i and c_j are the log-transformed radon concentrations at spatial locations indexed by $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$, \bar{c} is the spatially averaged mean log-transformed radon concentration, $\tau^2 = \sum_{k=1}^n (c_k - \bar{c})^2 / n$ is the associated spatial concentration (log-transformed) variance, n ($= 24$) is the sample size, and $\omega_{i,j}$ is the matrix of spatial weights determined here using an inverse-distance rule given by:

$$\omega_{i,j} = \frac{(d_{i,j})^{-1}}{\sum_i \sum_j (d_{i,j})^{-1}} \quad (6)$$

when $i \neq j$ and zero otherwise, $d_{i,j}$ is the distance between two station locations i and j , and the normalization of the weights is global ensuring that $\sum_i \sum_j \omega_{i,j} = 1$. While both statistical measures are commonly used to assess spatial autocorrelation, Moran's I describes global correlations while Geary's C is sensitive to local spatial autocorrelations. Fig. 4 shows the comparison between Geary's C and Moran's I for all six maps. As expected, Geary's C is inversely related to Moran's I. The z-score used in assessing statistical significance of spatial association or autocorrelation in Fig. 4 points to similar conclusions; namely that the spatial association among the log-transformed seasonal radon concentration

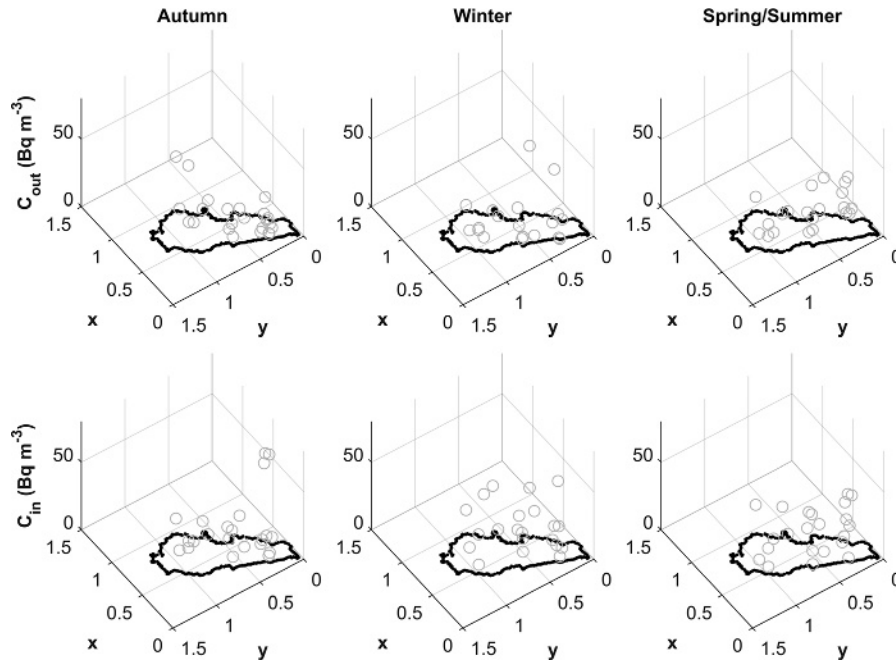


Fig. 3. The spatial variations in outdoor (top, C_{out}) and indoor (bottom, C_{in}) concentration across seasons (not log transformed). The x and y values are relative (arbitrary units) and are needed to compute ω_{ij} . The solid lines trace the borders of Lebanon (Fig. 1 shows station locations). The spatial variances τ^2 of outdoor and indoor log-transformed concentrations are, respectively, as follows: autumn (left panels), 0.86 (top) and 0.57 (bottom); winter (middle panels), 2.15 (top) and 0.63 (bottom); and spring/summer (right panels), 0.45 (top) and 0.85 (bottom).

is weak. A consequence of this finding is that these data sets can be analyzed using conventional statistical methods for hypothesis testing without concerns arising from spatial autocorrelation.

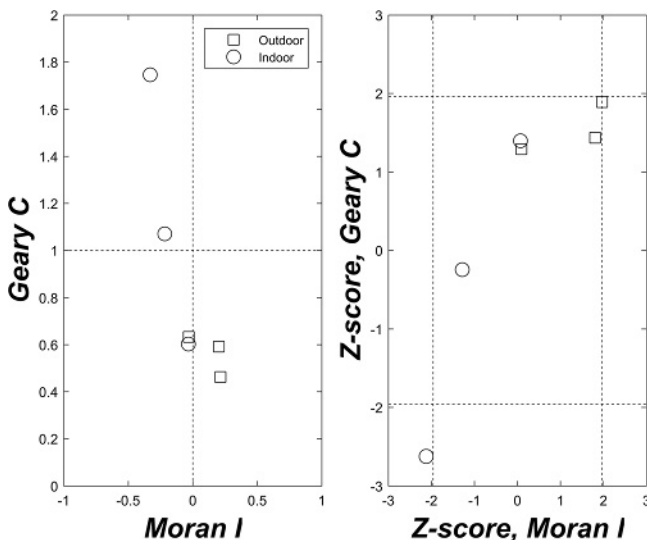


Fig. 4. Left: A comparison between Geary's C and Moran's I used to assess spatial autocorrelation for the log-transformed radon concentration maps shown in Fig. 3. Moran's I of zero and/or Geary's C of unity signifies no spatial structure (shown as dashed lines). Right: The associated z -scores for each of the spatial statistics are shown. The dashed lines outline the regions of statistical significance at the 95% confidence level.

HYPOTHESIS TESTING AND DISCUSSION

As noted earlier, four hypotheses were explored to explain the spatio-temporal variations in indoor and outdoor radon concentrations. These hypotheses include the role of geographic location (i.e., muhafaza), proximity to geologic fault lines, construction material of houses, and seasonal weather patterns.

Hypothesis 1: Geographic location impacts radon concentration

Using the geographic location or region (e.g., Beirut, Bekaa, Mount Lebanon, north Lebanon, Nabatieh, and south Lebanon) as a single factor in an analysis of variance (ANOVA) test on the log-transformed radon concentration, outdoor radon concentrations appear significantly impacted by this factor (Table 2). However, this finding is not statistically robust, as upon excluding the stations situated within the Beirut region, the ANOVA test fails to suggest that outdoor radon concentrations are significantly affected by location (Table 2). For the station in Beirut excluded here (B2, Hamra), the indoor radon was more than 21 times higher than the corresponding outdoor concentration (79.3 vs. 3.7 Bq m^{-3}); in fact, that was the highest reading. This result is not quite understood since indoor concentrations are normally higher than outdoor concentrations but not by 21 times. More typical differences do not exceed a factor of 3. Regrettably, not all winter and spring/summer data for the B2 location were retrieved to further assess this

Table 2. Summary of hypotheses tested and the main findings. Concentrations were log transformed and the confidence interval was set at 95%. ANOVAs and t-tests are two-tailed unless stated otherwise.

Hypothesis (alternate hypothesis)	Reject null	<i>p</i> value
Effect of location on radon concentration (ANOVA, prob > <i>F</i>)		
Location affects outdoor concentration	Yes	2.7×10^{-3}
Location affects outdoor concentration (excluding Beirut)	No	0.71
Location affects indoor concentration	No	0.54
Proximity to faults across seasons (t-test, prob > <i>F</i>)		
Proximity to fault affects outdoor concentration (total)	No	0.18
Proximity to fault affects outdoor concentration (autumn)	No	0.26
Proximity to fault affects outdoor concentration (winter)	No	0.13
Proximity to fault affects outdoor concentration (spring/summer)	No	0.35
Proximity to fault affects indoor concentration (total)	No	0.26
Proximity to fault affects indoor concentration (autumn)	No	0.48
Proximity to fault affects indoor concentration (winter)	No	0.33
Proximity to fault affects indoor concentration (spring/summer)	No	0.79
Effect of the building material across seasons (t-test, <i>p</i> value)		
Building material affects indoor concentration (total)	No	0.76
Building material affects indoor concentration (autumn)	No	0.28
Building material affects indoor concentration (winter)	No	0.98
Building material affects indoor concentration (spring/summer)	No	0.77
Outdoor vs. indoor concentrations (t-test, <i>p</i> value)		
Indoor concentration is larger than outdoor concentration (total)	Yes	0.0076
Indoor concentration is larger than outdoor concentration (autumn)	Yes	0.0223
Indoor concentration is larger than outdoor concentration (winter)	Yes	0.0121
Indoor concentration is larger than outdoor concentration (spring/summer)	No	0.5392
Seasonal patterns in outdoor and indoor concentrations (t-test, <i>p</i> value)		
Outdoor concentration in summer is significantly larger than outdoor concentration in winter	Yes	0.046
Indoor concentration in winter is significantly larger than indoor concentration in summer	No	0.2235

anomaly. One plausible explanation is that the measurement in Beirut was conducted on elevated floors, while samples in other geographic locations were taken near ground level. Radon is a heavy gas with an expected mean concentration profile that rapidly decreases with increasing height from the ground. Outdoor radon samples on balconies of tall buildings in Beirut may be biased toward lower concentration values because of this height dependency rather than their geographic location.

Hypothesis 2: Proximity to a fault line impacts radon concentration

A study in a neighboring country (Jordan) found that proximity to fault lines increases radon concentrations by factors of 3 to 10 (Al-Tamimi and Abumurad 2001). Given the similar geologic formation in Lebanon, it was hypothesized that proximity to fault lines will also play a role in explaining variations in outdoor radon concentrations. No statistical difference (Table 2) in log-transformed indoor and outdoor radon concentrations was found as a

function of the planar distance to a fault line at the 95% confidence interval.

Hypothesis 3: Building material impacts radon concentration

Influx of radon into homes could cause elevated indoor radon in areas with granitic rock (McLaughlin et al. 1988). Such rock formations are rare in Lebanon and certainly not known to be present in the studied areas (Table 3). No excessively high levels of outdoor or indoor radon (i.e., $>100 \text{ Bq m}^{-3}$) were measured in any of the studied locations including basaltic areas such as Khiam (NB5) thereby precluding any strong geologic sources. If the locale's geology does not warrant any suspicion of ground emanation (due to radium-bearing rock), then house walls may explain some of the spatial variations in indoor radon concentration. There are two major types of building materials for homes in Lebanon (Table 3). The first is a hollow concrete block (HCB, a mixture of sand and cement), and the second is limestone rock blocks. Cement being derived

Table 3. Predominant geologic bedrock in sampled areas and building materials used in sampled buildings and dwellings.^a

Geographic area	Sample ID	Area mother-rock	Building feature/material
Beirut			
Mar Elias	B1	Quat	Building upper floor/ Hollow concrete block (HCB)
Hamra	B2	Quat	As above
Achrafieh	B3	Meocene	As above
Bekaa			
Baalbek	BK1	Quat	Single story/HCB
Zahle	BK2	Miocene	As above
Shmistar	BK3	Miocene	As above
Hermel/Sharbin	BK4	Lwr Mid Cret	As above
North Lebanon			
Rihaniyeh	NL1	(not available)	Single story/ Limestone block
Bebnine	NL2	Miocene (Tert)	As above
Kousba	NL3	Up Cret Senonian-neogene	As above
Mitreet	NL4	As Kousba	As above
Mount Lebanon			
Damour	ML1	Quat	Single story/HCB
Ras-El-Maten	ML2	Lwr Mid Cret	Single story/ Limestone block
Chnanir	ML3	Lwr Mid Cret	As above
Bakaata	ML4	Lwr Mid Cret	As above
Nabatieh			
Nabatieh	NB1	UpCret/Lwr Mid Cret	Single story/HCB
Dawdieh	NB2	Quat	As above
Zefta	NB3	Lwr Mid Cret	As above
Deir El Zahrani	NB4	Lwr Mid Cret	As above
Khiam	NB5	Jurassic Quat, Up Cenozoic/Basaltic Volcanics	As above
South Lebanon			
Al Ghazieh	SL1	Quat/deposits	As above
Kinnareat	SL2	Quat	As above
Sarafand	SL3	Quat	As above
Saksakieh	SL4	Quat	As above
Shaatyeh	SL5	Tert Miocene/ Limestones	As above

^aQuat: Quaternary; Lwr: Lower; Cret: Cretaceous; Up: Upper; Tert: Tertiary.

from crushed limestone, both materials may contain radon precursors. At the most basic level, the dwelling's building material type can affect indoor radon levels (Kobeissi et al. 2014). Such an effect is best assessed in winter when windows and doors are usually closed as a result of cold weather, thereby minimizing ventilation. The reduced ventilation minimizes flushing of indoor emanated radon from

the ground or walls. For most cases, the winter indoor values are greater than the outdoor (16 out of 24 cases). A one-tailed student t-test confirms the hypothesis that indoor radon concentrations in the winter are significantly higher than the outdoor concentrations (Table 2). Few cases show the reverse situation with winter outdoor radon greater than indoor—for example, Kousba (NL3) values are 17.4 Bq m⁻³ indoors vs. 42.2 Bq m⁻³ outdoors.

Hypothesis 4: Seasonality plays a significant role in radon concentration variation

At the national level, outdoor radon concentrations appear to be lowest in winter (13.4 Bq m⁻³) and highest in spring/summer (19.7 Bq m⁻³), with autumn concentrations being intermediate (16.1 Bq m⁻³). To explore whether seasonality plays a statistically significant role in explaining radon concentrations, a one-tailed student t-test was conducted comparing whether outdoor summer concentrations exceed their winter counterpart. The outcome of this paired t-test revealed that outdoor summer concentrations are significantly higher than winter concentrations. This seasonal pattern is consistent with a number of studies that already showed outdoor radon concentration to be lowest in the winter and highest in the summer with autumn and spring intermediate (Denman et al. 2007; Orgun et al. 2008; Papaefthymiou et al. 2003). An exception to the above pattern was reported in Japan (Oikawa et al. 2003), where winter had the highest outdoor readings. The Japanese study suggested that these higher readings in the winter may be due to air mass movement resulting from dominant high pressure across the continent. In Lebanon's case, the warm dry season is predominantly calm with relatively high pressure, while the cool wet season is characterized by significant cyclonic systems moving in from the Mediterranean Sea to the west. This appears to indicate that the low outdoor radon level in the cool season may be due to a large-scale weather flushing action. The results here are consistent with other observations found in small (nonvolcanic) island nations that generally have a relatively low outdoor radon level. Indeed, the cases for Cyprus (Sarrou et al. 2003) as well as for Okinawa (Oikawa et al. 2003) support this view.

Repeating the same t-test for indoor radon concentrations with the hypothesis that winter concentrations exceed those of their summertime counterparts was not statistically supported at the 95% confidence level (Table 2). This negative outcome is rather intriguing. As noted earlier, in the warm spring/summer period, the difference between indoor and outdoor radon concentrations are small, and this is a manifestation of the frequent opening of windows for ventilation or the use of air-conditioning units with external air being chilled. Frequent opening of windows for ventilation is also common in most locations in rural Lebanon, where air conditioning is rarely used. With enhanced house ventilation

in the summer, indoor radon concentrations become more elevated primarily because of elevated outdoor concentration. During winter months, indoor radon concentrations do exceed their outdoor counterparts because ventilation is suppressed.

CONCLUSION

Four hypotheses aimed at explaining the spatio-temporal variations of indoor and outdoor radon concentrations in Lebanon formed the basis of this work. It was shown that geographic location, distance to fault lines, and building material were not significant factors in explaining the spatial variation of radon concentration in all seasons, whether indoor or outdoor. Seasonal variations were the most significant patterns to emerge, with outdoor summer concentrations significantly exceeding winter concentrations. Nonetheless, radon levels in Lebanon, while exhibiting high variability, remain well below the recommended limit suggested by ICRP and are not a public health concern. This finding was based on a single-year measurement at 24 locations, which is a limitation of the study. Moreover, the aforementioned conclusions, while necessary, are not sufficient to inform epidemiological research about the causes of the high rate of lung cancer in Lebanon. Such an undertaking requires accounting for exposure to cigarette smoking, particulate matter, and other environmental variables associated with lung cancer.

Acknowledgment—The authors thank Malek Chatila and Mohammad Chbaro for their technical assistance and for obtaining the measurements. The authors also thank the Safadi Foundation and the University Research Board at the American University of Beirut for partially supporting this research. We are also grateful to the people who allowed us to place E-PERMS on their property.

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