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Assessing exposure to granite countertops—part 1: Radiation

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Humans are continuously exposed to low levels of ionizing radiation. Known sources include radon, soil, cosmic rays, medical treatment, food, and building products such as gypsum board and concrete. Little information exists about radiation emissions and associated doses from natural stone finish materials such as granite countertops in homes. To address this knowledge gap, gross radioactivity, γ ray activity, and dose rate were determined for slabs of granite marketed for use as countertops. Annual effective radiation doses were estimated from measured dose rates and human activity patterns while accounting for the geometry of granite countertops in a model kitchen. Gross radioactivity, γ activity, and dose rate varied significantly among and within slabs of granite with ranges for median levels at the slab surface of ND to 3000 cpm, ND to 98,000 cpm, and ND to 1.5E−4 mSv/h, respectively. The maximum activity concentrations of the ^{40}K, ^{232}Th, and ^{226}Ra series were 2715, 231, and 450 Bq/kg, respectively. The estimated annual radiation dose from spending 4 h/day in a hypothetical kitchen ranged from 0.005 to 0.18 mSv/a depending on the type of granite. In summary, our results show that the types of granite characterized in this study contain varying levels of radioactive isotopes and that their observed emissions are consistent with those reported in the scientific literature. We also conclude from our analyses that these emissions are likely to be a minor source of external radiation dose when used as countertop material within the home and present a negligible risk to human health.
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Introduction

Humans are constantly exposed to low levels of ionizing radiation, including emissions from soil, cosmic, and internal sources (Shapiro, 2002). Gypsum board, concrete, natural stone, and other building materials are among the many other ubiquitous sources of background radiation found in buildings (Ingersoll, 1983; NCRP, 2009).

Natural stone (i.e., natural rock) such as granite and marble is commonly used in residential settings as countertops in kitchens and bathrooms (hereafter collectively referred to as "granite"). A number of studies have reported on the concentrations of natural radionuclides (i.e., activity concentrations) for granite samples obtained from Egypt, Saudi Arabia, Pakistan, South Korea, China, Brazil, Kenya, and Finland (Mustonen, 1984; NCRP, 1987a; Mustapha et al., 1997; Chowdhury et al., 1998; European Commission, 1999; Lee et al., 2001; IAEA, 2003; Kumar et al., 2003; Arafa, 2004; Ahmed, 2005; ICRP, 2005; Al-Saleh and Al-Berzan, 2007; El-Taher et al., 2007; Lu et al., 2007; Ghosh et al., 2008; Kitto et al., 2008; Mujahid et al., 2008). Although the activity concentrations for the majority of those samples were below health-based screening levels and exposure guidelines used in the US, Europe, and elsewhere, a portion of the granite samples had a radiation hazard index that exceeded the European Commission (EC) screening value for limited use as superficial building materials (external dose of 0.3 mSv/a) (European Commission, 1999).

Although radioactivity associated with granite building materials has been evaluated in the literature, there is less information regarding the potential radiation doses from granite intended for use as a counter, table, or other surface finish indoors. This may be in part because granite was not commonly used as a countertop at the time that the National Council on Radiation Protection (and related organizations) evaluated radiation emitted from consumer products (NCRP, 1987b). In addition, exposure scenarios for granite countertops do not seem to be considered explicitly in existing screening models for radiation dose from building materials (NCRP, 1987b; Markkanen, 1995). Moreover, the degree to which the granite included in extant radiological evaluations represent in-use inventories of granite sold as countertops in North America and other markets is not

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known. Improving the knowledge base regarding the potential risks of granite countertops is important because of the prevalence of this material as a surface material inside the home.

We determined activity concentrations, γ ray emissions, and effective dose for a diverse sample of granite slabs intended for sale as countertops in the United States. Our investigation considered variability of radiation emissions between different types of granite, among slabs of the same type of granite, and within individual slabs of granite. In addition, our study included estimates of effective dose based on both direct measurements and calculations from validated models for a range of exposure scenarios. Finally, we evaluated potential health risks of countertop-related radiation emissions by comparing the dose estimates to relevant health-based benchmarks.

Methods

Overview

We measured the natural radioactivity of 39 full (3 m × 1.8 m × 3.2 cm) slabs of natural stone intended for sale as granite countertops in the United States. The collection of slabs comprised 27 different varieties that are estimated to account for approximately 30% of the US market share, based on recent sales data from 13 large suppliers of granite in the US. For a subset of granite varieties, we collected measurements from three slabs that allowed for an evaluation of variation across slabs of the same type. In addition, we assessed radiation dose with direct-reading dose meters for each slab and with models based on activity concentration measurements for a subset of the slabs.

Radiation measurements were taken on each slab of granite countertop using three instruments: a Geiger–Müeller (GM) counter, a γ scintillator, and a MicroRem Survey Meter. This array of instruments was selected to obtain measures of total radioactivity, γ ray emissions, and external dose rate. The measurements were collected at pre-determined and evenly spaced sampling locations on the polished surface of upright slabs. To assess the background radiation dose in the building housing the slabs, a comprehensive background survey was conducted in which dose rate measurements were collected in 21 locations throughout the building. Measured radiation dose rates were then background-corrected to ascertain the dose rate attributable to non-background sources.

Activity Concentrations

γ spectroscopy with a high purity germanium detector (Canberra Reverse Electrode High Purity Germanium System, Meriden, CT, USA) was used to measure the activity concentrations of selected isotopes (^{238}U, ^{232}Th, ^{40}K, and ^{226}Ra) in two 80-cm^2 samples cut from opposite corners of each slab. Each sample was placed in contact with the detector and counted over 8 h. The system was calibrated with a standard source of similar dimensions to the granite samples (Eckert & Ziegler Analytics, Atlanta, GA, USA). The detector was shielded with lead (Model 747, Canberra) to reduce any interference from background radiation.

The specific activities were averaged from the γ ray photopeaks at several energies to determine the activity concentrations of the relevant decay series. For each slab, the specific activity for the uranium and thorium series activities were determined using a weighted average of the daughter isotopes identified in the series. The ^{238}U series, which contains ^{226}Ra and ^{222}Rn, was determined using the ^{234}Th, proctactinium-234 m (^{234m}Pa), lead-214 (^{214}Pb), and bismuth-214 (^{214}Bi) γ ray lines. The thorium-232 (^{232}Th) series specific activity was determined using actinium-228 (^{228}Ac), lead-212 (^{212}Pb), and thallium-208 (^{208}Tl) γ ray lines. The specific activity of the ^{40}K was determined directly using its own γ ray line at 1461 keV. The minimum detectable specific activity of ^{40}K was 14 Bq/kg, ^{232}Th was 2 Bq/kg (based on ^{208}Tl) and 3.5 Bq/kg for ^{238}U (based on ^{214}Pb daughter-specific activity). A weekly quality assurance check was performed on the instrument for peak resolution, energy calibration, and activity estimates.

α, β, and γ radiation measurements were made with a GM counter (Model 3, Ludlum Measurements, Sweetwater, TX, USA) at 14 grid points distributed approximately uniformly across each stone and the two corners in which activity concentrations were assayed. Measurements at each sampling point were collected at the surface of the slab, 2.5 cm from the slab surface, and 2.5 cm from the surface with a 2.5 cm thick α/β absorber, to measure only γ rays. In addition to measurements at the 16 grid points, the GM was used to scan the entire slab for potentially enriched areas, which were defined as areas with greater than 500 cpm above background.

γ ray emissions were also measured using a γ scintillator (Model 44-10, Ludlum Measurements) at six locations on each slab, a subset of the 14 grid points. The scintillator uses a 5.1 cm × 5.1 cm sodium-iodide detector that responds to high-energy emissions (> 100 keV) that are not reflected in the GM measurements.

Radiation dose rate (mSv/h) was measured at each of the grid points and two corners using a MicroRem Survey Meter (Bicron Radiation Measurement Products, Solon, OH, USA). The measurement range of the instrument is 0–2 mSv/h, with an accuracy of ± 10% for readings of ^{137}Cs between 20% and 100% of the instrument range. Measurements were collected at the surface, as well as 15 and 30.5 cm from the surface at each location. Radiation dose was also measured in areas identified as potentially enriched from the GM measurements. The analysis of within-slab variability of radiation is presented for the dose measurements at 15 cm. Variability of radiation dose among the surface and 30.5 cm locations was similar.

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Dose Modeling

The radiation dose rate (mSv/h) from countertops in a model kitchen was estimated for several types of granite countertop to provide an estimate of dose in an actual residence. The nine different granite types used in the modeling analysis were selected to represent the range of measured activity concentrations, including the highest, lowest, and seven intermediate values ranked according to the activity concentration index (ACI, discussed below). The computer software program MicroShield (Version 7, Grove Software, Lynchburg, VA, USA) was used to generate the estimates of dose using activity concentrations and dimensions of granite countertops as the primary model inputs.

The model kitchen included over 4.6 m^2 (50 $feet^2$) of stone distributed between an L-shaped border counter and a rectangular island countertop (Figure 1). The model was run with homogeneous activity concentrations for the countertops. Additional modeling was conducted in which two 5 cm × 5 cm areas of elevated activity concentrations were incorporated into the slab with the highest ACI value. The two areas were modeled with activity concentrations of $^{40}K = 1997$ Bq/kg, $^{232}Th = 4179$ Bq/kg, and $^{226}Ra = 15972$ Bq/kg (Bordeaux type granite, analyzed by ARS International, Port Allen, LA, USA. McCarthy, personal communication); the highest value reported for granite building materials to date based on our review of the scientific literature.

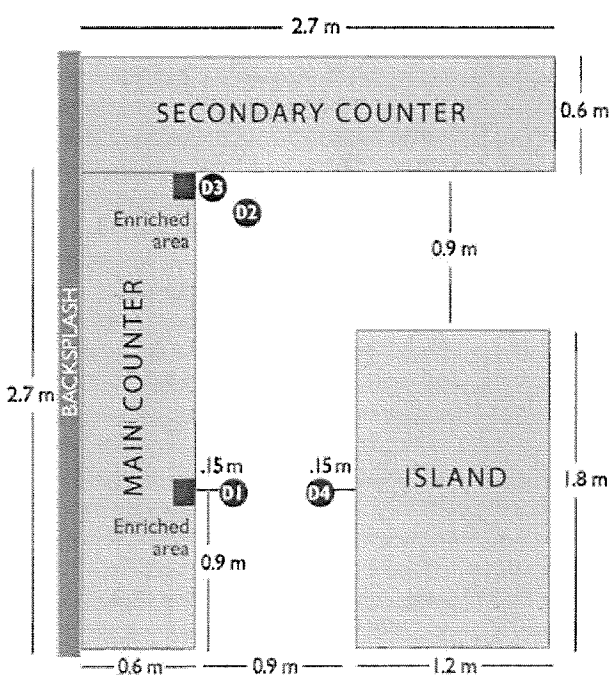

Figure 1. Layout of kitchen, stone countertop, and dose-point (D1-D4) locations for dose modeling.

Dose rate was modeled at four locations chosen to represent places where people spend time in the kitchen. The locations ranged from direct contact to 15 cm from a countertop. Dose was calculated at three heights (counter height, 0.3 m above the counter, and 0.6 m above the counter) selected to represent the height of the waist, chest, and head of an individual. Dose was also modeled for slabs oriented vertically and the results were used to assess the extent of agreement between the modeled and measured dose rates.

Risk Characterization

Measured activity concentrations were used to calculate an ACI for each of the granite slabs following a method recommended by the EC. The ACI is used as a screening tool to identify materials of potential concern for radiation and radon exposure (European Commission, 1999), and assumes that a person is standing in the center of a rectangular room in which the material being evaluated covers the interior surface of the floor, ceiling, and all four walls (Markkanen, 1995). The ACI is calculated from the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K expressed in units of Bq/kg as shown in equation (1).

$$ACI = \frac{C_{Ra}}{300\,\mathrm{Bq\,kg^{-1}}} + \frac{C_{Th}}{200\,\mathrm{Bq\,kg^{-1}}} + \frac{C_K}{3000\,\mathrm{Bq\,kg^{-1}}} \quad (1)$$

where C_{Ra}, C_{Th} and C_k are the radium, thorium, and potassium activity concentrations, respectively. According to the European Commission (1999), appropriate dose assessments should be performed for superficial building materials such as tiles and boards with an ACI greater than two, a value where the annual dose may exceed 0.3 mSv. Likewise, an ACI greater than six is indicative of a potential dose in excess of 1.0 mSV/a, a level that warrants controls according to the EC (European Commission, 1999).

Measured and modeled hourly dose rates were used to estimate annual radiation doses that can be compared with health-based guidelines. For measured dose rates, the median background-corrected slab dose rate measured 15 cm above the slabs was used, whereas for the modeled values we used the average dose among the four locations in the model kitchen. To obtain a conservative estimate of exposure duration, we used the upper bound values (~95th percentile) from the distributions of daily time spent in the kitchen reported in a cross-sectional study of time–activity patterns in the United States in our exposure calculations (Tsang and Klepeis, 1996). On the basis of an exposure of 4 h/day, we assumed an exposure duration of 1460 h/year. Measured and modeled annual dose estimates were compared with the EC building material exemption level of 0.3 mSv/a and the 1.0 mSv/a radiation dose limit attributable to a specific source recommended by US and international standards (NCRP, 1993; European Commission, 1999; IAEA, 2003; ICRP, 2005).

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Statistical Analysis

Statistical analyses were performed using SAS Statistical Software (SAS 9.1. 3, Cary, NC, USA) and included summary statistics and Spearman rank correlation. Linear mixed effect models, assuming a compound symmetry covariance matrix, were used to test for the significance of radiation dose levels measured among the three distances from the slab, controlling for potential correlation between measurements on the same slab (SAS PROC MIXED).

Results

Radioactivity Measurements

The activity concentrations for the two corner samples from each slab are summarized in Table 1 (individual slab results are presented in Supplementary Table S1). Maximum concentrations of the ^{40}K, ^{232}Th, and ^{226}Ra series were 2715 Bq/kg (Namibian Gold), 278 Bq/kg (Crystal Gold), and 939 Bq/kg (Nile Gold 3), respectively. The distribution of activity concentrations was similar for the two corners. Activity concentrations in pairs of samples from slabs were moderately to strongly correlated ($r = 0.37$ for ^{40}K; $r = 0.73$ for ^{232}Th; and $r = 0.87$ for ^{226}Ra). Of the 27 types of stones tested, six had an ACI greater than two for at least one of their two samples. Both samples from the slab of Juparana Bordeaux had ACI values greater than two. The highest ACI, 4.8, was calculated for a Nile Gold (designated Nile Gold 2). This slab also had the greatest difference in ACI values between the two samples (Left sample = 1.4 and Right sample = 4.8).

Measurements obtained with the GM for the 39 slabs ranged from background to 3000 cpm. As shown in Figure 2, GM readings were inversely correlated with the percentage of total external exposure attributable to γ rays (as measured by the GM with the α/β blocker). These results indicate that readings obtained from a GM are not a reliable indicator of dose from γ rays, a key limitation for use of a GM as a tool for radiation dose assessments of stones. Results from the γ scintillator ranged from undetectable for Galaxy Black and Copper Canyon to a slab median activity of 98,000 cpm for a slab of Nile Gold.

Dose Measurements

Dose rates measured at the three distances from the slabs, corrected for a background dose rate of 1E−4 mSv/h, are summarized in Table 2 (individual slab results are presented in Supplementary Table S1). The distributions of slab median values and individual values are presented to illustrate variation in the central tendency of dose rate among slabs

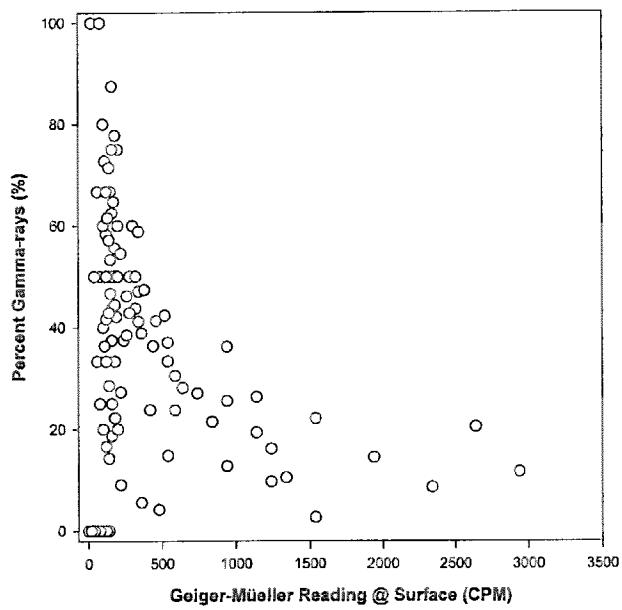

Figure 2. Geiger–Müeller (GM) readings in counts/min and the corresponding percent of radiation from γ rays.

Table 1. Summary of activity concentrations (Bq/kg) and activity concentration index (ACI, European Commission, 1999).

Corner	Series	N	Mean	Std	Min	Q1	Median	Q2	Max
1	^{40}K	38	1500	454	242	1246	1535	1798	2432
	^{232}Th	38	72	69	2	18	55	86	278
	^{226}Ra	38	145	193	9	41	67	165	939
	ACI	38	1.3	0.8	0.4	0.9	1.1	1.6	4.8
2	^{40}K	39	1532	474	244	1235	1522	1716	2715
	^{232}Th	39	62	56	3	15	51	86	231
	^{226}Ra	39	112	118	7	28	84	124	450
	ACI	39	1.2	0.5	0.2	0.8	1.1	1.7	2.1

Table 2. Summary of slab median and individual dose rate measurements (mSv/h) obtained at the surface and above 39 slabs of granite countertop.

Distance	N	Mean	Std	Min	Q1	Median	Q2	Max
Slab median								
Surface	39	3.9E−05	3.9E−05	<	1.0E−05	3.0E−05	5.0E−05	1.5E−04
15 cm	39	2.8E−05	2.8E−05	<	5.0E−06	2.0E−05	4.5E−05	1.0E−04
30 cm	39	2.2E−05	2.6E−05	<	<	1.5E−05	3.0E−05	1.0E−04
Individual measurements								
Surface	677	5.8E−05	9.9E−05	<	1.0E−05	3.0E−05	6.0E−05	1.0E−03
15 cm	677	3.7E−05	4.8E−05	<	<	2.0E−05	5.0E−05	3.0E−04
30 cm	676	2.7E−05	3.6E−05	<	<	2.0E−05	4.0E−05	2.5E−04

< Less than the background dose rate in air of 1E−4 mSv/h.
Minimum of eight measurements/slab plus additional measurements over spots that exceeded 500 cpm at the surface with a Geiger–Müeller (GM) detector.

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and variation of individual sampling points within and among slabs. Slab median dose ranged from less than background to 1.5E−04 mSv/h. At a distance of 15 cm from the slab, 26% of all the dose measurements were less than the background rate, whereas at 30.5 cm, 35% of the measurements were below background. An inverse relationship between dose rate and distance was observed, with a statistically significant difference in dose rate between measurements on the surface, at 15 and 30.5 cm ($P<0.001$) for both the distributions of slab median and individual measurements. As expected, dose rate was strongly correlated with γ activity (Spearman's $r=0.8$, $P<0.01$).

As shown in Figure 3, slabs with lower median dose rates had relatively low within-slab variability, with variability increasing as the slab median dose rate increased. Areas of enriched radioactivity were identified in the Namibian Gold, Nile Gold, and Shiva Pink types of granite, all of which had some of the highest within-slab variability. Nile Gold, which had the highest density of enriched areas, exhibited an area of approximately 10% of the surface area with activity greater than 10,000 cpm with maximum counts above 118,000 cpm. Granite types with high within slab variability, such as Kashmir Gold and Nile Gold, also exhibited high inter-slab variability, whereas other types with lower dose rates were more uniform between the slabs tested.

Dose Assessment: Modeled Dose

The modeling results at 15 cm and the corresponding dose rate measurements collected at 15 cm were in good agreement (Spearman's $r=0.91$, $P<0.01$; median difference <2.5E−5 mSv/h), indicating that the model provides a reasonably accurate estimate of dose rate associated with emissions from granite countertops. The estimated annual dose in the model kitchen ranged from 0.005 mSv/a for the Galaxy Black granite to 0.07 mSv/a for the Nile Gold 3 granite (Table 3). When the model results that incorporated two areas with elevated activity concentrations were used to estimate annual doses, the maximum annual dose increased from 0.07 to 0.18 mSv/a.

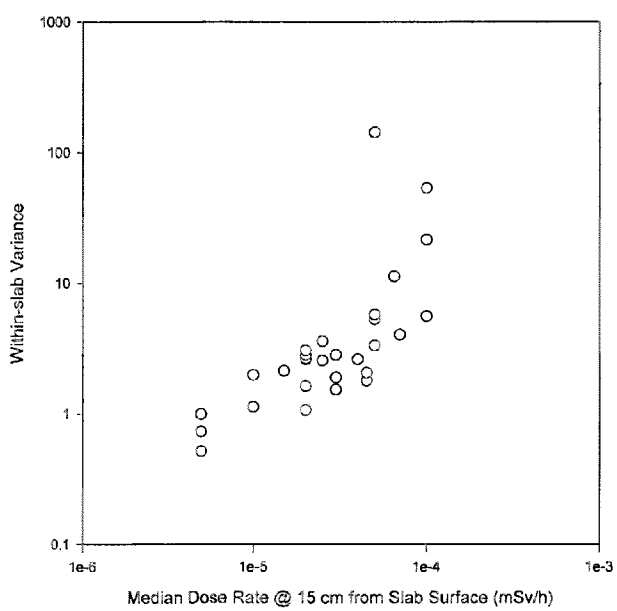

Figure 3. Within-slab variance of radiation dose measured at 15 cm from vertically oriented slab by slab median dose.

Risk Characterization

Conservative estimates of annual dose derived from the measured dose rates and an assumed exposure duration of 4 h/day for 365 days were all below the exemption threshold of 0.3 mSv/a established by the EC for building materials, and the 1 mSv/a criterion published by the NCRP and other organizations (NCRP, 1993; IAEA, 2003; ICRP, 2005) (Figure 4). The NCRP also has a recommendation that when a single source has the potential to cause an exposure that exceeds 25% of an individual's annual effective dose of 1 mSv/a, an additional assessment be made to ensure that the annual exposure from all man-made sources does not exceed 1 mSv/a for that individual. The dose assessment results obtained from the maximum exposure estimates in this study were well below this exemption limit of 0.25 mSv/a, requiring no further dose assessment to be made (NCRP, 1993).

The maximum annual dose derived from the modeled doses without areas of elevated activity concentrations was one-fourteenth of the 1 mSv/a criterion and approximately one-fourth of the 0.3 mSv/a EC exemption level for building materials, and the 0.25mSv/a exemption requiring further assessment. When areas of elevated activity concentration were incorporated into a countertop with the maximum ACI, the annual dose was approximately 1.5 times lower than both the 0.25 and 0.3 mSv/a criterion used for evaluation. Dose rates estimated in the model kitchen were lower than the dose rate measurements made at the slab faces. The difference reflects the more realistic geometry between the source and

Table 3. Modeling of exposure rate and annual dose in a model kitchen and an assumed high exposure scenario.

Stone color no.	Granite type	Annual dose (mSv/a)[a]
22	Arandis	0.031
5	Baltic Brown	0.040
8	Galaxy Black	0.005
7	GreenButterfly	0.056
20	Mascarello	0.011
24	Nile Gold 3	0.071
2	New Venetian Gold	0.034
27	Shiva Pink2	0.026
13	Shivakashi	0.036

mSv/a, millisievert/annum (year).
[a]Annual dose based on exposures at each of the four dose locations for 1 h/day for 365 days.

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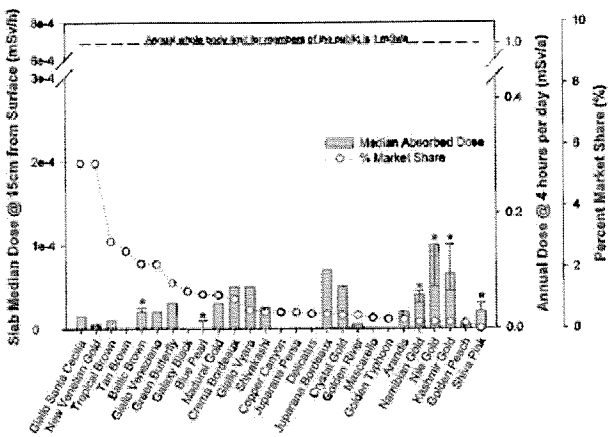

Figure 4. Distribution of annual doses (mSv/year) based on median parallel plane exposure measurements at 15 cm above the surface and assuming 4 h/day of exposure for 365 days/year. Stones denoted with a star (*) represent the range of test results from three slabs of that stone type.

receptor (perpendicular orientation) considered in the model in comparison with the measurements (parallel plane orientation).

Discussion

The potential for exposure to naturally occurring radioactive materials in granite marketed as interior surface finishes is relevant to public health because of their prevalence as work surfaces in homes and the relative lack of empirical information about their radioactivity. Other than this study of 27 types and 39 full slabs of granite countertop, we are not aware of an empirical evaluation of radiation exposure and dose published in the scientific literature for these types of materials. Average estimates of effective dose derived from the measurements included in this evaluation ranged up to 0.18 mSv/a, approximately one-fifth of the relevant health-based benchmarks, indicating that granite countertops are a minor component of exposure to natural and anthropogenic background levels of ionizing radiation.

We observed variability of radioactivity and radiation dose among and within slabs of granite countertop. The slab median dose rate measured at 15 cm ranged from zero to 1E−4 mSv/h and exhibited an approximately log-normal distribution. Variability within slabs was directly and strongly related to the average activity for the entire slab. The Nile Gold and Kashmir Gold types of granite had the highest degree of variability. The variability within a slab is of special interest considering that the γ activity in some areas of a slab was as much as six times greater than the average for the slab. These enriched areas were typically isolated and approximately 0.6 m^2 in size. Intra-slab and inter-slab variability, as well as enriched areas of radioactivity were incorporated into the estimates of effective dose presented here. Using these high-end estimates of effective dose that assumes a countertop with the highest ACI from this study combined with two supplementary enriched areas, the maximum dose was 0.18 mSv/a; a value that is approximately one-fifth the value of relevant benchmarks. As the dose estimates are well below relevant health-based benchmarks, the results show that a small area of enriched radioactivity on a granite countertop discovered during a radiological survey is not a specific indicator of an environmental hazard.

We found that gross measurements of radioactivity obtained with a GM detector did not agree well with the corresponding measurements of γ activity and external dose. This observation indicates that GM measurements cannot be translated into radiation dose with any degree of confidence. This disparity may exist because typical GM detectors measure α and β emissions in addition to some γ activity, which are less important for external dose than effectively measuring total γ activity.

The maximum annual dose estimated for slabs without areas of elevated activity concentrations in a model kitchen was 0.07 mSv/a, approximately one-fourteenth of the dose estimate based on the measurements collected 15 cm directly above the flat plane of a slab (i.e., an exposure scenario in which a person was lying down 15 cm above the countertop). The difference indicates that distance and geometry must be incorporated into refined dose assessments. The modeling accounted for a more realistic spatial orientation between a person and a granite countertop, and maintained the assumption that a person was either in contact with or within 15 cm of the counter, 4 h a day, for 365 days/year. The conservative dose modeling for the slab with the maximum observed ACI with the addition of two hypothetical areas of highly elevated activity concentration at the edge of the countertop also confirmed that the slabs evaluated in this study are not a source of radiation dose that is likely to exceed health-based limits. The dose modeling conducted in this study is assumed to be conservative, and therefore unlikely to have underestimated the actual upper end doses for these stones due to a number of considerations. First, the exposure duration was approximately the 95th percentile of the distributions of daily time spent in the kitchen and bathroom. Second, the time spent in the kitchen was all within 15 cm of a countertop. Third, the areas of elevated activity concentration were both located on the edge of the countertop, directly adjacent to a dose measurement point. Finally, the areas of elevated activity concentration had an ACI value of 37, over five times greater than any ACI for granite building material identified in the peer-reviewed scientific literature.

Our results indicate that a screening approach based on an ACI as used in the EU is a reasonably reliable and

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conservative method of screening stones intended for use as granite countertops. Of the granites tested in this study, two had an ACI value that according to EC criteria warrant a more refined dose assessment such as those conducted here. Dose assessments with a set of conservative assumptions show that all the granites, including those with ACI values greater than two, were below the EC exemption level of 0.3 mSv/a for building materials (European Commission, 1999), and well below the national and international standard for a radiation dose of 1 mSv/a (NCRP, 1993; IAEA, 2003; ICRP, 2005). Our finding indicates that the EC index performs reasonably well in classifying granite slabs that should be exempted from further consideration (two false positives), although more slabs would need to be evaluated to estimate the false positive rate with high confidence. However, false positives are plausible, given that the assumptions used to derive the ACI criteria include a large surface area of stone (approximately 90 m^2 (970 $feet^2$)) in a room with dimensions of 4 m × 5 m × 2.8 m (European Commission, 1999). The assumption of the entire room finished in granite is clearly an overestimate surface area for a granite countertop or tabletop exposure scenario. The ACI is also limited by reliance on a single activity concentration for a stone. If radioactivity is heterogeneous across a slab, the ACI could either under- or overestimate dose for the entire slab. Additional research on the applicability of the ACI to granite countertops is warranted.

In addition to the effective doses estimated here being below national and international evaluation criteria, exposure estimated from granite countertops is also low relative to natural background sources of radiation. An average person receives a total annual dose equivalent from natural sources of radiation of approximately 6 mSv/a, of which approximately 50% is due to "ubiquitous background" (NCRP, 2009). Variation in doses of natural radiation due to factors such as altitude (e.g., Atlantic coast *versus* Denver, CO) can be in the range of 0.5 mSv/a, an amount substantially greater than the upper bound doses estimated from exposure to granite countertops (~0.03–0.18 mSv/a). The estimates of annual dose from external exposure to radiation associated with a typical granite countertop is also comparable with doses attributed to other natural materials that comprise common products. Familiar building materials such as concrete and gypsum board have been reported to produce a dose of about 0.07 mSv/a (NCRP, 1987b).

The implications of our findings are based in part on the scope of the evaluation, the methods, and associated assumptions. The study included measurements of 39 slabs representing 27 types of granite estimated to account for approximately 30% of sales in the United States. In addition, the identity and geographic origin of the stones included in this study is not known precisely because naming practices for granite are not standardized (Anjos et al., 2005). Nonetheless, the activity concentrations for ^{40}K, and the ^{232}Th and ^{226}Ra series observed in these stones are within the range reported for granite building materials in the scientific literature (Mustonen, 1984; NCRP, 1987a; Mustapha et al., 1997; Chowdhury, Alam and Ahmed, 1998; European Commission, 1999; Lee, Kim, Lee and Kang, 2001; IAEA, 2003; Kumar, Sengupta and Prasada, 2003; Arafa, 2004; Ahmed, 2005; ICRP, 2005; Al-Saleh and Al-Berzan, 2007; El-Taher, Uosif and Orabi, 2007; Lu, Wang, Jia and Wang, 2007; Ghosh et al., 2008; Kitto, Haines and Diaz Arauzo, 2008; Mujahid et al., 2008). Therefore, these samples of granite intended for use as interior work surfaces contain amounts of naturally occurring radioactive materials that are similar to levels in other types of granite building materials reported in the literature for which larger numbers of samples have been examined. In addition, the measured dose rates at the surface of and short distances away from full slabs are similar to or below background levels of radiation dose associated with other building materials. To further account for uncertainty associated with the sample size, the estimates of annual effective dose derived from the measurements and models incorporated conservative assumptions about proximity to the slab and exposure duration.

In summary, our results show that the types of stones characterized in this study contain varying levels of radioactive isotopes and that their observed emissions are consistent with those reported in the scientific literature. We also conclude for our analyses that these emissions are likely to be a minor source of radiation dose when used as countertop material within the home and present a negligible risk to human health.

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