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A REVIEW OF RADON EQUILIBRIUM FACTORS FOR THE ASSESSMENT OF RADON DOSE TO THE LUNG

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The Basic Facts

- Radon (^{222}Rn) and thoron (^{220}Rn), as well as their progenies, are present in the indoor and outdoor atmosphere as attached and unattached fractions to the local aerosol particles.
- Radon and thoron gas contribute relatively little to the dose to the lung.
- It is the inhalation of the short-lived solid radon decay products and subsequent deposition on the walls of the airway epithelium of the bronchial tree, that delivers most of the radiation dose to human lungs.

Guidelines and Doses

- Radon guidelines or recommendations are established to reduce the risk of health effects. Health effects from radon arise from dose to the lungs.
  ICRP reference level for radon exposure: 10 mSv/y
- Radon guidelines or recommendations are expressed as radon gas concentration in the air.
  Canadian indoor guideline: 200 Bq/m^3
- It is, then, necessary to link radon gas concentration to radon dose.

Lung Dosimetry

- This requires the use of a bronchial dose model.
- Dose models do not use measured radon gas concentration as input, because the same radon gas concentrations can have different decay product concentrations under different environmental conditions.
- Instead, dose models use the radon equilibrium equivalent concentration, *EEC*, as the input parameter.

$$EEC(^{222}\mathrm{Rn}) = 0.105(^{218}\mathrm{Po}) + 0.516(^{214}\mathrm{Pb}) + 0.379(^{214}\mathrm{Bi})$$
$$EEC(^{220}\mathrm{Rn}) = 0.91(^{212}\mathrm{Pb}) + 0.087(^{212}\mathrm{Bi})$$

Equilibrium Factor

- The equilibrium factor, F_{eq}, is defined as the ratio of *EEC* and C_{Rn}, the radon gas concentration.

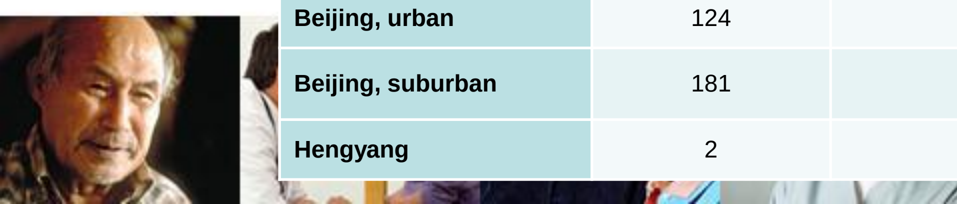
$$F_{eq} = EEC/C_{Rn}$$

- To assess radon bronchial dose, accurate information on the equilibrium factor is required.
- Many environmental and physical parameters determine the extent of equilibrium between radon gas and its progenies.
- Published measurement results of F_{eq} from more than 20 countries were reviewed.

Review Results

- A total of 14593 measurements in China showed the overall average of F_{eq}=0.5 for various types of dwellings in broad geographic locations and diverse environmental conditions.

Location in China	No. of houses	Radon Bq/m^3	F_{eq}	reference
17 provinces/cities (1983-1998)	5638	24 (1, 374)	0.48 (0.25, 0.67)	Pan, 2003
26 provinces/cities (1984-1990)	8528	23 (<DL, 387)	0.47 (0.20, 0.60)	Cheng et al. 2002
Kaohsiung, Taiwan	20	9.6 (1.7, 23)	0.49 (0.24, 0.79)	Chen et al., 1998
Hong Kong	62	27 ± 9	0.24 ± 0.13	Yu et al. 1999
Hong Kong	11	40 (26, 66)	0.52 (0.13, 0.89)	Yu et al. 2008
Yangjiang (HBRA)	31	48 ± 25	0.43 (0.19, 0.81)	Yuan et al. 2000
Yangjiang (Control Area)	5	18 ± 8	0.58 (0.55, 0.60)	Yuan et al. 2000
Baotou	6	N. A.	0.43 (0.24, 0.65)	Liu et al. 2010
Beijing	5	19 (10, 33)	0.39 (0.28, 0.55)	Li et al. 2011
Beijing, urban	124	19	0.60 (0.25, 0.95)	Hou et al. 2015
Beijing, suburban	181	123	0.57 (0.28, 0.92)	Hou et al. 2015
Hengyang	2	N. A.	0.43 (0.24, 0.59)	Wu et al. 2016



Review Results

- A total of 1265 measurements in India showed the overall average of F_{eq}=0.37, varied from 0.1 to 0.5.

Location in India	No. of dwellings	Radon, Bq/m^3	F_{eq}	Reference
Punjab	230	53 (25, 84)	0.44 (0.15, 0.80)	Saini et al. 2017
Punjab	32	55 (21, 94)	0.47 (0.25, 0.8)	Bangotra et al. 2015
Punjab	36	GM=45, GSD=1.39	GM=0.35 (0.17, 0.70)	Kumar et al. 2012
Uttarakh Himalaya	35	34 ± 22	0.42 (0.10, 1.33) [a]	Joshi et al. 2016
Uttarakh Himalaya	25	89 (75, 123)	0.39 (0.32, 0.46)	Kandari et al. 2016
Garhwal Himalaya	78	38 ± 40 (4, 174)	GM=0.40, GSD=2.43 [a]	Prasad et al. 2016a
Garhwal Himalaya	87	99 ± 59 (13, 291)	0.42 (0.23, 0.80)	Prasad et al. 2016b
Garhwal Himalaya	122	55 ± 59 (4, 198)	0.40 (0.10, 0.62)	Ramola et al. 2016
Garhwal Himalaya	100	71 (12, 191)	0.28 (0.02, 0.9)	Ramola et al. 2011
Garhwal and Kumaun	150	54 (7, 191)	0.28 (0.02, 0.90)	Ramola et al. 2003
Kumaun Himalaya	100	36 (11, 64)	0.24 (0.07, 0.9)	Ramola et al. 2011
Kumaun Himalaya	52	GM=100 (41, 208)	GM=0.36 [a]	Singh et al. 2016a
Himachal Pradesh	96	64 (26, 209)	0.50 (0.12, 0.77)	Singh et al. 2016b
Assam	30	123 ± 53 (48, 245)	0.39 (0.33, 0.52)	Baroah et al. 2014
Karnataka	74	104 (18, 300)	0.094 (0.011, 0.71)	Sannappa et al. 2014
Kerala (HLNRA)	18	N.A.	0.51± 0.16	Mayya et al. 2012

Review Results

The review of F_{eq} from 20 countries gives a mean of F_{eq}=0.41 with a standard deviation of 0.11 and a median of F_{eq}=0.40.

Measured F_{eq} values vary widely from as low as 0.1 to as high as 0.8.

In the indoor environment, F_{eq} values are significantly higher in poorer ventilated houses and also higher in homes with smokers.

Location	No. of dwellings	Radon, Bq/m^3	F_{eq}	reference
18 cities in Canada	**12576 (grab sampling)**	**GM=20, GSD=4.33**	**0.65 (0.20, 0.82)**	**Chen et al. 2011**
Ottawa, Canada	**6 (long-term meas.)**	**51 (28, 78)**	**0.71 (0.59, 0.86)**	**Harley et al. 2012**
Sweden	225 (short-term meas.)	N.A.	0.44 (0.19, 0.69)	Swedjemark 1983
Hazara, Pakistan	138 (short-term meas.)	132 (41, 254)	0.46 (0.29, 0.70)	Khan et al. 2012
Soum region, Jordan	21 (long-term meas.)	144 (22, 911)	0.40 (0.36, 0.42)	Abumurad and Al-Tamimi, 2005
Lithuania	8 (short-term meas.)	69 (18, 170)	0.47 (0.43, 0.52)	Jasaitis et al. 2011
6 regions in Poland	54 (short-term meas.)	300 (19, 1668)	0.32 (0.08, 0.64)	Mamont-Ciesla and Stawarz, 2012
Iowa, USA	98 (short-term meas.)	259 (11, 940)	0.25 (0.03, 0.70)	Sun et al. 2009
Czech	30 (short-term meas.)	N.A.	GM=0.36, GSD=1.32	Jilek et al. 2010
Germany	136 (short-term meas.)	32 (7, 370)	0.34 (0.07, 0.90)	Keller et al. 1984
Germany	10 (short-term meas.)	658 (112, 1726)	0.30 (0.15, 0.49)	Reineking et al. 1990
Serbia	43 (long-term meas.)	60 ± 40 (21, 230)	0.30 ± 0.20	Mishra et al. 2014
Balkan region	48 (long-term meas.)	AM=122, GM=71, GSD=2.7	0.50 (0.043, 0.93)	Gulan et al. 2012
Osijek, Croatia	37 (short-term meas.)	72 ± 44	0.44 (0.12, 0.89)	Planinic et al. 1999
Rome, Italy	4 (short-term meas.)	138 (97, 186)	0.34 (0.30, 0.37)	Bochicchio et al. 1994
Rome, Italy	6 (short-term meas.)	62 (15, 95)	0.48 (0.42, 0.55)	Bochicchio et al. 1996
Thessaloniki, Greece	25 (short-term meas.)	N.A.	0.47 ± 0.09	Clouvas et al. 2003
Thessaloniki, Greece	26 (short-term meas.)	34 (12, 516)	0.49 ± 0.10	Clouvas et al. 2006
Catalonia, Spain	4 (short-term meas.)	313 (10, 3000)	0.34 (0.06, 0.73)	Ortega and Vargas, 1996 Vargas et al. 2000
Mexico City, Mexico	12 (short-term meas.)	141 ± 173	0.42 ± 0.19	Martinez et al. 1998
7 cities in Argentina	91 (long-term meas.)	38 (7, 81)	0.34 (0.10, 0.80)	Lopez and Canoba, 2003
El-Minia, Egypt	15 (short-term meas.)	123 ± 22 (20, 300)	0.35 (0.19, 0.62)	Mohamed, 2005
El-Minia, Egypt	25 (short-term meas.)	110 ± 20 (17, 330)	0.31 (0.11, 0.61)	Ei-Hussein, 2005
India	1265 (most long-term)	63 (4, 300)	0.36	see Table 2.
China	14593 (most short-term)	26 (<DL, 387)	0.48	see Table 1.

Conclusions

- The review demonstrated clearly that many environmental factors as well as human activities and habits affect the value of F_{eq}.
- For ^{222}Rn dosimetry, the UNSCEAR and the ICRP selected typical value of F_{eq}=0.4 for indoors.
- The typical value can be used if local environmental specific F_{eq} is unknown or not well known with the understanding that the variability in the value can be more than ± 50%.
- If more accurate ^{222}Rn dosimetry is required to assess either ^{222}Rn bronchial dose or ^{222}Rn risk, local environmental specific F_{eq} values are the preferred parameters to use.

Thanks for your attention!